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Assessing Thermal Comfort in Office Buildings: A Parametric Study of Kinetic Louvers and Double-Skin Facades in Türkiye

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ABSTRACT

The optimization of building façades plays a crucial role in enhancing indoor thermal comfort and energy efficiency, particularly in climate-responsive design. This study investigates the impact of kinetic shading systems, glazing modifications, and non-ventilated double-skin façades (DSFs) on indoor thermal comfort in four distinct climatic zones of Türkiye: Zone 1- hot-summer Mediterranean (Antalya), Zone 2- temperate (Istanbul), Zone 3- semi-cold (Ankara), and Zone 4- cold (Erzurum). The analysis was conducted using computational simulations. A parametric simulation workflow was used to assess thermal comfort through the Percent of Comfortable Time (PCT) based on the PMV model under various façade configurations. The findings indicate that kinetic louvers significantly enhance summer thermal comfort, increasing PCT from 6.87% to 18.66% in Zone 1(Antalya), 24.05% to 47.02% in Zone 2 (Istanbul), 31.58% to 54.48% in Zone 3 (Ankara), and 42.56% to 57.05% in Zone 4 (Erzurum). When combined with double-pane Low-E glazing and reduced WWR (0.3), PCT reached its highest values: 40.32% (Zone 1), 79.59% (Zone 2), and 79.23% (Zone 3), indicating strong combined effect between dynamic shading and optimized envelope design. Double-skin façade (DSF) systems produced moderate but consistent improvements across the four climates. The non-ventilated DSF increased PCT from 6.87% to 17.17% in Zone 1 (Antalya), 24.05% to 39.20% in Zone 2 (Istanbul), 31.58% to 46.81% in Zone 3 (Ankara), and 42.56% to 48.34% in Zone 4 (Erzurum). When DSFs were paired with Low-E glazing, PCT further improved to 23.35% (Zone 1), 49.61% (Zone 2), 50.43% (Zone 3), and 41.35% (Zone 4). However, DSF performance remained lower than kinetic shading in extreme climates, reflecting the limited adaptability of non-ventilated cavities. Overall, the findings confirm that façade optimization must be climate-specific: dynamic shading and high-performance glazing yield the largest gains in warm and temperate regions, while cold climates benefit more from strategies that balance shading control with heat-retention properties.

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1. Introduction

In the contemporary world of architecture and construction, significant attention is given to the efficient use of fuel and energy resources (Sheliahovich 2011). However, many buildings are not designed to function in harmony with their surrounding environment, leading to increased energy demand and contributing to environmental pollution due to rising CO_2 emissions (Salah & Tuna Kayılı 2021). According to the United Nations Environment Programme (2020), buildings contribute nearly 40% of global energy-related CO_2 emissions, making energy-efficient architectural strategies indispensable in mitigating climate change impacts. Furthermore, ensuring the health and comfort of building occupants has always been a primary objective in architectural design (UNEP 2020). Within this framework, passive design strategies play a crucial role in achieving human comfort by allowing occupants to interact dynamically with their external environment (Manzano-Agugliaro et al. 2015). Incorporating bioclimatic architecture and adaptive thermal comfort principles enables buildings to respond dynamically to their climate, reducing dependence on mechanical heating and cooling systems (Givoni 1998; Nicol & Humphreys 2010).

Among various environmental factors, thermal comfort is one of the most critical components in determining Indoor Environmental Quality (IEQ) in buildings (Al Horr et al. 2016). Developing a comprehensive understanding of thermal comfort is essential not only for enhancing occupant satisfaction but also for minimizing energy consumption (Taleghani et al. 2013). Oseland (1994) emphasized that indoor thermal comfort is a key factor in how people regulate their indoor environment, influencing air quality and significantly impacting productivity and work efficiency. Studies indicate that suboptimal indoor thermal conditions can impair cognitive function, reduce concentration, and negatively affect decision-making, further emphasizing the need for optimized thermal comfort in workspaces (Lan et al. 2011; Seppänen, Fisk, & Lei 2006).

In this regard, research has shown that office buildings rank among the highest energy-consuming structures, with annual energy demands reaching up to 1000 kWh/m^2 (Panopoulos & Papadopoulos 2017). Given this high energy consumption, ensuring optimal indoor thermal comfort conditions is essential for maintaining workplace productivity while simultaneously reducing energy usage (Elzeyadi 2002). Green building rating systems such as LEED and WELL emphasize indoor thermal comfort as a key criterion for sustainability, advocating for designs that balance occupant well-being with energy efficiency (U.S. Green Building Council 2021).

This study underscores the necessity of implementing effective thermal comfort strategies in office buildings to enhance occupant well-being, boost productivity, and contribute to overall energy efficiency. By integrating sustainable and passive design principles, architects and building professionals can create environmentally responsible and energy-efficient workspaces that prioritize both human comfort and sustainability.

Numerous studies have explored indoor thermal comfort conditions across different climate zones. Some of these investigations have aimed to refine and develop models used in evaluating local thermal comfort conditions (Singh et al. 2015; Cao et al. 2016; Manu et al. 2016; Daemei et al. 2019; Ren et al. 2022). Meanwhile, other studies have examined the influence of design parameters on thermal comfort (Felix & Elsamahy 2017; Martinelli & Matzarakis 2017; Yang et al. 2019).

Daemei et al. (2019) proposed passive design strategies to enhance human thermal comfort in humid climate zones based on the Köppen climate classification. The study selected eight cities worldwide that shared similar climate characteristics and identified humidity and rainfall as the most influential climatic parameters in determining indoor comfort. Various passive design strategies were suggested and analyzed, with findings indicating that strategies adopted in specific regions could be successfully transferred to other locations with similar climatic conditions. The importance of adapting passive design strategies to local climatic conditions has been emphasized since Olgyay's seminal work on bioclimatic architecture (Olgyay 1963). More recent research has demonstrated that context-driven passive cooling techniques can significantly reduce energy consumption while maintaining indoor comfort levels (Prieto et al. 2018). These insights highlight the potential for scalable, climate-responsive architectural solutions that improve indoor thermal comfort while minimizing energy dependency (Daemei et al. 2019).

Taleghani et al. (2013) conducted a comprehensive review of thermal comfort models in buildings, focusing on adaptive models and steady-state models, specifically Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) models. The study also compared three major adaptive thermal comfort standards used at the time:

- ASHRAE 55-2010 (American Standard),
- EN15251 (European Standard),
- ATG Guideline (Dutch Standard).

The analysis revealed that the primary differences among these standards lie in the equations defining upper and lower thermal limits, reference temperatures, and acceptable temperature ranges. These variations stem from the different climatic datasets used to develop the standards, leading to regional discrepancies in their applicability (Taleghani et al. 2013). In line with this, De Dear & Brager (1998) introduced the adaptive thermal comfort model, which emphasized occupants' behavioral, physiological, and psychological adaptation to indoor climates. This model formed the foundation of modern adaptive comfort standards (ASHRAE 55, EN 15251), allowing for wider temperature ranges in naturally ventilated buildings.In the same context, Enescu (2017) reviewed thermal comfort models and indicators for indoor environments, presenting the most widely used thermal comfort frameworks and their variations. The study explored the evolution of thermal comfort concepts, models, and assessment indicators, alongside thermal comfort standards, control strategies, optimization techniques, and real-world applications.

These findings underline the importance of selecting appropriate thermal comfort models based on climatic conditions and building typologies. Recent advancements in Artificial Intelligence (AI) and Internet of Things (IoT) technologies have introduced real-time thermal comfort monitoring and adaptive HVAC control systems. These systems optimize indoor climates dynamically while ensuring energy-efficient building operation (Valinejadshoubi et al. 2020). The evolution of thermal comfort indices and the refinement of predictive models demonstrate the ongoing effort to optimize human comfort while improving energy efficiency in diverse built environments.

Apart from the models used to evaluate indoor thermal comfort, various studies have examined the influence of design parameters on thermal comfort conditions. For instance, Martinelli & Matzarakis (2017) investigated the impact of height-to-width (H/W) proportions in courtyard typology on thermal comfort in the Italian climate zone. Their research analyzed the annual and seasonal effects of H/W ratios on the Physiologically Equivalent Temperature (PET) index. Conducted in a humid subtropical region, the study concluded that higher H/W proportions of 4:5 to 5:5 are more suitable for warmer climates, whereas lower to medium H/W proportions of 3:5 to 4:5 are better suited for colder climates (Martinelli & Matzarakis 2017). Beyond the height-to-width (H/W) proportion, courtyard orientation and ventilation play a crucial role in regulating airflow and heat exchange in different climatic conditions. Research has shown that well-designed courtyards can enhance evaporative cooling and reduce peak temperatures (Muhaisen & Gadi 2006). These findings provide guidance on optimizing courtyard designs for climate-responsive architecture.

The building envelope plays a fundamental role in reducing a building's energy consumption (Salah & Tuna Kayılı 2021). Additionally, thermal and visual comfort conditions are significantly influenced by the physical properties of the building envelope (Hosseini, Mohammadi, Rosemann, et al. 2019). Within this context, several studies have investigated the impact of envelope design parameters on thermal comfort.

Beccali et al. (2018) conducted a comparative study on the use of traditional stone walls versus adobe wall materials and their effect on indoor thermal comfort across different zones within the same building. The study concluded that, regardless of the evaluation model used, traditional wall materials enhance comfort conditions in Naturally Ventilated Buildings (NVB) within hot-humid climate zones (Beccali et al. 2018). In a similar study, Felix & Elsamahy (2017) examined the effect of different outer-wall construction materials on thermal comfort across three distinct climate zones. Their findings suggested that integrating a skeleton system (concrete-steel) with natural materials such as clay and stone in outer walls ensures improved indoor thermal and climatic comfort across various climate conditions (Felix & Elsamahy 2017). Recent advancements in passive cooling techniques have explored the integration of phase-change materials (PCMs) and ventilated facades into building envelopes, demonstrating significant energy savings while maintaining stable indoor temperatures (Ascione et al. 2014).

Similarly, Mirrahimi et al. (2016) reviewed the impact of building envelope design on thermal comfort and energy efficiency in high-rise residential buildings in Malaysia's hot-humid climate. The study synthesized findings from multiple research efforts conducted in the same region, identifying key parameters that significantly influence energy consumption and indoor thermal comfort conditions. These parameters include:

- Building form (width, length, height),
- External wall materials,
- Glazing type and properties,
- Window-to-wall ratio (WWR),
- External shading devices and their impact on thermal performance.

The study concluded that optimal thermal comfort levels in Malaysian residential buildings range between 25°C and 31°C. Additionally, it emphasized that the building envelope is the most critical design parameter for achieving and maintaining thermal comfort (Mirrahimi et al. 2016).

The role of high-performance glazing and adaptive shading technologies has gained attention in improving daylighting efficiency while minimizing overheating risks. Dynamic shading systems, such as automated blinds and electrochromic glass, have been shown to enhance indoor comfort by adjusting solar gain based on real-time climatic conditions (Tzempelikos & Athienitis 2007). These findings further highlight the necessity of strategic envelope design in minimizing energy dependency while maximizing occupant comfort. The integration of adaptive building envelope solutions is crucial in addressing climate-specific challenges in hot and humid, arid, and Mediterranean regions. Studies have demonstrated that a systematic approach to envelope design -combining material selection, shading strategies, and passive cooling techniques- can significantly enhance building resilience and energy efficiency worldwide (Prieto et al. 2018).

Façade techniques have been introduced as innovative methods for enhancing building envelopes, improving building performance and indoor thermal comfort. Within this framework, Yang et al. (2019) investigated the effect of Double-Skin Façades (DSF) on the thermal comfort of building occupants. Their study employed numerical simulation of a Building Integrated Photovoltaic/Thermal Double-Skin Façade (BIPV/T-DSF) to assess its performance in various climate zones in Australia. The results indicated that naturally ventilated BIPV/T-DSFs maintained relatively better indoor temperatures in hot climates, whereas non-ventilated BIPV/T-DSFs provided more stable indoor temperatures ranging between 20°C and 26°C in colder climates. Additionally, the study analyzed cool temperate climates, concluding that natural ventilation within BIPV/T-DSFs helped maintain indoor temperatures between 22°C and 27°C during office hours without the need for mechanical systems, even during peak summer conditions.

Ventilation strategies play a crucial role in the performance of DSFs. Studies have demonstrated that hybrid ventilation—combining natural and mechanical airflow—offers optimal temperature regulation by balancing passive cooling with controlled heat extraction (Ghaffarianhoseini et al. 2016). This highlights the need for climate-specific DSF ventilation configurations to maximize energy efficiency and occupant comfort. The research also explored key design parameters, such as the opening ratio of louvers and fan airflow rate, and concluded that these factors significantly influence indoor thermal comfort (Yang et al. 2019).

Beyond thermal benefits, DSFs also enhance daylight utilization, reducing the need for artificial lighting and improving occupant well-being. However, careful design is required to mitigate glare and excessive solar radiation, particularly in sun-exposed façades (Tzempelikos & Athienitis 2007). Furthermore, in addition to thermal comfort improvements, BIPV/T-DSFs contribute significantly to building energy efficiency by reducing dependency on mechanical cooling systems and generating renewable energy through integrated photovoltaics (Jelle et al. 2012). This dual functionality makes BIPV/T-DSFs a promising solution for sustainable building design, particularly in regions with high solar exposure.

Adaptive building envelopes, particularly those incorporating dynamic shading devices and kinetic façades, have been recognized as effective strategies for achieving thermal and visual comfort. Kinetic components, constructed as vertical elements within a building's skin, function as microclimate modifiers by adjusting to external conditions (Iyendo et al. 2016; Hosseini, Mohammadi, Rosemann, et al. 2019).

Several research studies have investigated the impact of kinetic façades on building performance. For instance, kinetic interactive façades have been shown to enhance occupant-space interaction by controlling the amount of natural daylight, improving visual comfort (Hosseini, Mohammadi, & Guerra-Santin 2019). Meanwhile, kinetic responsive façades are designed primarily to achieve thermal comfort, as they help minimize direct solar heat gain during summer (Salah & Kayılı 2022). Beyond enhancing occupant comfort, kinetic façades contribute to energy savings by regulating solar gain and ventilation based on real-time environmental conditions.

Additionally, kinetic façades improve daylight distribution while reducing glare, which is particularly beneficial in office environments. Research has shown that dynamic façade systems can enhance workplace productivity by preventing excessive brightness contrasts and optimizing natural lighting conditions (Shen et al. 2015). These façade types demonstrate the potential for smart adaptation in energy-efficient buildings.

However, new studies focusing on both cold and hot climates using parametric simulation techniques are required to refine kinetic façade performance further (Hosseini, Mohammadi, Rosemann, et al. 2019). Kinetic façade performance is highly dependent on regional climate conditions, necessitating customized design approaches. Studies have indicated that kinetic shading elements should be tailored to local solar exposure, humidity, and seasonal temperature variations to maximize efficiency and occupant comfort (Berkouk et al. 2022).

The advancements in computational simulation tools have enabled architects to model and predict kinetic façade behavior dynamically, offering new opportunities to optimize energy efficiency across diverse climatic conditions (Hosseini, Mohammadi, Rosemann, et al. 2019; Kim et al. 2015).

Recent studies have increasingly highlighted the significant influence of façade design variables on indoor thermal comfort across different climates. Dynamic shading systems, advanced glazing technologies, and optimized window-to-wall ratios (WWR) have been shown to substantially affect indoor temperature stability and comfort conditions. For instance, Xiao et al. (2025) demonstrated that adaptive shading geometries can reduce operative temperatures by up to 4°C in Mediterranean climates through real-time modulation of solar exposure. Similarly, Teixeira et al. (2025) reported that spectrally selective glazing improves thermal comfort while maintaining high daylight quality in office environments. In cold and mixed climates, façade insulation and solar heat gain characteristics become dominant; Teixeira et al. (2024) showed that high-insulation glazing can reduce discomfort hours by more than 30% during summer–winter transitions. These contemporary findings underscore the need for climate-dependent façade optimization, aligning closely with the objectives of the present study.

The study of human thermal comfort has evolved from basic thermal balance equations to systematic models that are evaluated through internationally recognized standards and guidelines. Within this context, Fanger's models of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) have been widely adopted for assessing indoor comfort conditions. These models quantify human thermal perception and dissatisfaction levels based on environmental parameters, forming the foundation for many thermal comfort standards (Fanger 1970).

Technological advancements, such as parametric simulation, have significantly facilitated the evaluation and prediction of indoor thermal comfort at any given location and time of the year. With the availability of advanced computational tools, researchers can now conduct detailed performance assessments of various building envelope configurations before implementation.

Despite the growing body of research on kinetic façades and double-skin façade (DSF) systems, most existing studies remain limited to single-climate contexts or focus on isolated façade strategies without systematic cross-climatic comparison. Kinetic façade studies often evaluate performance within a specific climatic condition, emphasizing control logic or geometric variation, while DSF investigations frequently assess either ventilated or non-ventilated configurations within narrow regional settings. As a result, designers still lack comparative evidence that clarifies how different façade systems perform relative to each other when subjected to distinct climatic regimes under consistent modelling assumptions.

Moreover, existing literature rarely addresses how early-stage façade decisions—such as the selection between kinetic shading and DSF systems—should adapt when a building typology is transferred across multiple climatic zones. This gap is particularly relevant for countries like Türkiye, where a single national context encompasses Mediterranean, temperate, cold semi-arid, and severe cold climates. Türkiye therefore provides a unique natural laboratory for testing the climate-dependency of façade strategies within a unified regulatory, cultural, and construction framework.

Accordingly, this study addresses the unresolved gap in comparative façade performance assessment by conducting a parametric evaluation of kinetic louvers and non-ventilated double-skin façades across four distinct climatic zones in Türkiye. The novelty of the study lies in its cross-climatic, scenario-based comparison conducted under identical geometric, operational, and occupant assumptions, enabling a consistent evaluation of façade adaptability rather than isolated performance outcomes. The study contributes to early-stage façade decision-making by providing climate-specific insights into the effectiveness of dynamic shading, glazing selection, and window-to-wall ratio optimization, thereby supporting designers and policymakers in selecting façade strategies that are responsive to regional climatic conditions.

To achieve this, a test office model will be developed and analyzed across Türkiye's climatic zones, using parametric simulation tools to assess façade performance under real-world environmental conditions. The results of this study will serve as a foundation for implementing climate-adaptive façade designs, ensuring optimal energy efficiency, enhanced thermal comfort, and reduced environmental impact.

2. Case Study

2.1 *Test Model*

This study employs a test model of an office building designed to be adaptable across various climatic zones. The base model represents a section of an office building, consisting of three main functional floors, as illustrated in Figure 1. The interior functional layout of these three zones has been designated as "Office 1," "Office 2," and "Office 3", each representing distinct workspace configurations within the study framework.

This structured approach allows for a comprehensive evaluation of thermal comfort and energy performance across different climatic conditions, facilitating a comparative analysis of façade strategies and environmental adaptability.

The base model used in this study consists of three main office rooms. The south-facing façade has a window-to-wall ratio (WWR) of 0.9. The glazing type used is "Single Clear Glass", with a U-value of 5.9 W/m²K and a Solar Heat Gain Coefficient (SHGC) of 0.5. Each office zone measures 6.00 × 6.00 × 4.00 meters, covering a total area of 36 m² per unit.

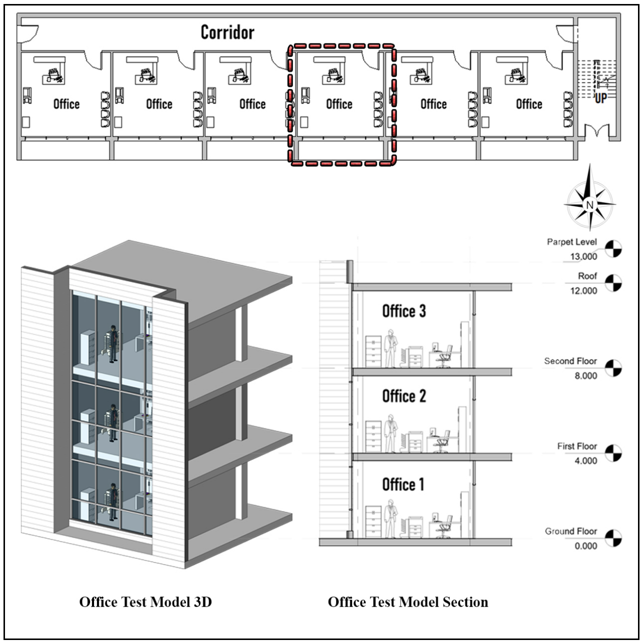


Figure 1 Plan, 3D View, section of the test model

According to TS 825, Türkiye is classified into four main climatic zones. To conduct the study, one representative city was selected from each zone. As illustrated in Figure 2, the selected cities are:

- Antalya (Zone 1) – Warm-Humid Climate,
- Istanbul (Zone 2) – Moderate Climate,
- Ankara (Zone 3) – Cold Climate,
- Erzurum (Zone 4) – Severe Cold Climate.

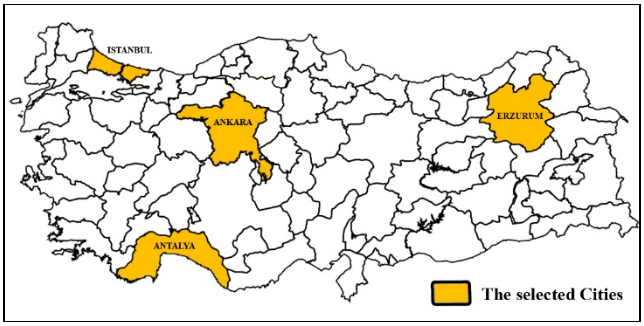


Figure 2 Selected cities from different climatic zones of Türkiye (adjusted from TS 825 2008)

The construction materials used for external and internal walls, floors, and the roof are selected based on ASHRAE standards to ensure compatibility with Turkish Standard TS 825, which defines minimum thermal insulation requirements and maximum U-values for building components in each climatic zone (TS 825, 2008) .

2.2 *Method*

This study employs the Predicted Mean Vote (PMV) method to evaluate indoor thermal comfort by measuring the Percent of Comfortable Time (PCT) within the base model and assumed scenarios across the selected cities of Türkiye (Antalya, Istanbul, Ankara, and Erzurum). The PMV-based Percent of Comfortable Time (PCT) metric was selected to ensure consistency across mechanically conditioned office scenarios and to allow direct comparison between façade configurations under controlled indoor setpoints. While adaptive comfort models are well-suited for naturally ventilated buildings, their applicability becomes limited in spaces where HVAC systems and fixed operative temperature ranges are maintained, as assumed in this study. Nevertheless, it is acknowledged that PMV may overestimate discomfort in scenarios involving dynamic façades, as it does not explicitly account for occupants' psychological adaptation or short-term behavioral responses to kinetic shading. This limitation is addressed by interpreting PCT values comparatively rather than as absolute comfort thresholds.

The study investigates various façade scenarios, including:

- Kinetic Louvers
- Double-Skin Façades (DSF)
- Changes in Window Glazing Type
- Variations in Window-to-Wall Ratio (WWR) on the South Façade.

To analyse indoor thermal comfort levels in Office 1, Office 2, and Office 3 zones, a 3D model was initially created using Revit Architecture, which was then exported to the Rhino software environment. By utilizing Grasshopper (a parametric modelling tool) combined with Ladybug and Honeybee plugins, the study generated 3D analytical zones (Honeybee Zones - Hb Zones) while location-based climate data files for the four cities were incorporated using Ladybug's Energy Plus Weather Data Component. Accordingly, the weather data for each city were obtained from the Typical Meteorological Year (TMY) EPW files used by Ladybug Tools. These datasets are constructed from long-term climate records from 2007 to 2023 to represent statistically typical weather conditions.

The Energy Plus simulation engine was utilized within the Grasshopper environment to gather key thermal comfort parameters, including:

- Air Temperature.
- Airspeed.
- Indoor Humidity.
- Clothing Level.
- Metabolic Rate.

These parameters were directly connected to the PMV calculation component within Ladybug and Grasshopper, allowing the study to determine the average Percent of Comfortable Time (PCT) for each office zone in different climatic regions. Figure 3 illustrates the workflow of the study.

To ensure consistency and comparability across the four climatic zones, additional modelling assumptions were defined according to ASHRAE 55 and EnergyPlus recommendations. The PMV-based thermal comfort calculations incorporated standard occupant characteristics, including a clothing insulation level (CLO) of 0.8 clo, representing typical summer office attire in Türkiye where long-sleeved shirts and full-length trousers are commonly worn. A metabolic rate (MET) of 1.1 met was used to reflect light desk-based activities. These values are widely used in comfort studies and reflect realistic occupant conditions in office environments.

Additinally, for fair comparison across all climatic zones, identical indoor operative temperature setpoints were applied. A cooling setpoint of 24°C and a heating setpoint of 20°C were selected, consistent with widely adopted HVAC design practices for office buildings. Although the analysis focuses primarily on summer conditions, defining both setpoints maintains stable energy balance and ensures proper transitions between thermal comfort modes during the simulation.

The EnergyPlus simulation timestep was set to 10 minutes (6 timesteps per hour) to capture rapid changes in solar radiation and façade response under dynamic shading scenarios. This resolution provides a balance between computational efficiency and the accuracy required for kinetic façade modelling.

This study aims to investigate indoor thermal comfort conditions in office buildings by exploring various façade strategies for building envelopes. To achieve this, a series of scenarios were developed and analyzed sequentially to evaluate their performance and determine the most effective strategies for each climatic zone in Türkiye. The assumed façade scenarios are categorized into two main systems as kinetic façade system and double-skin façade system.

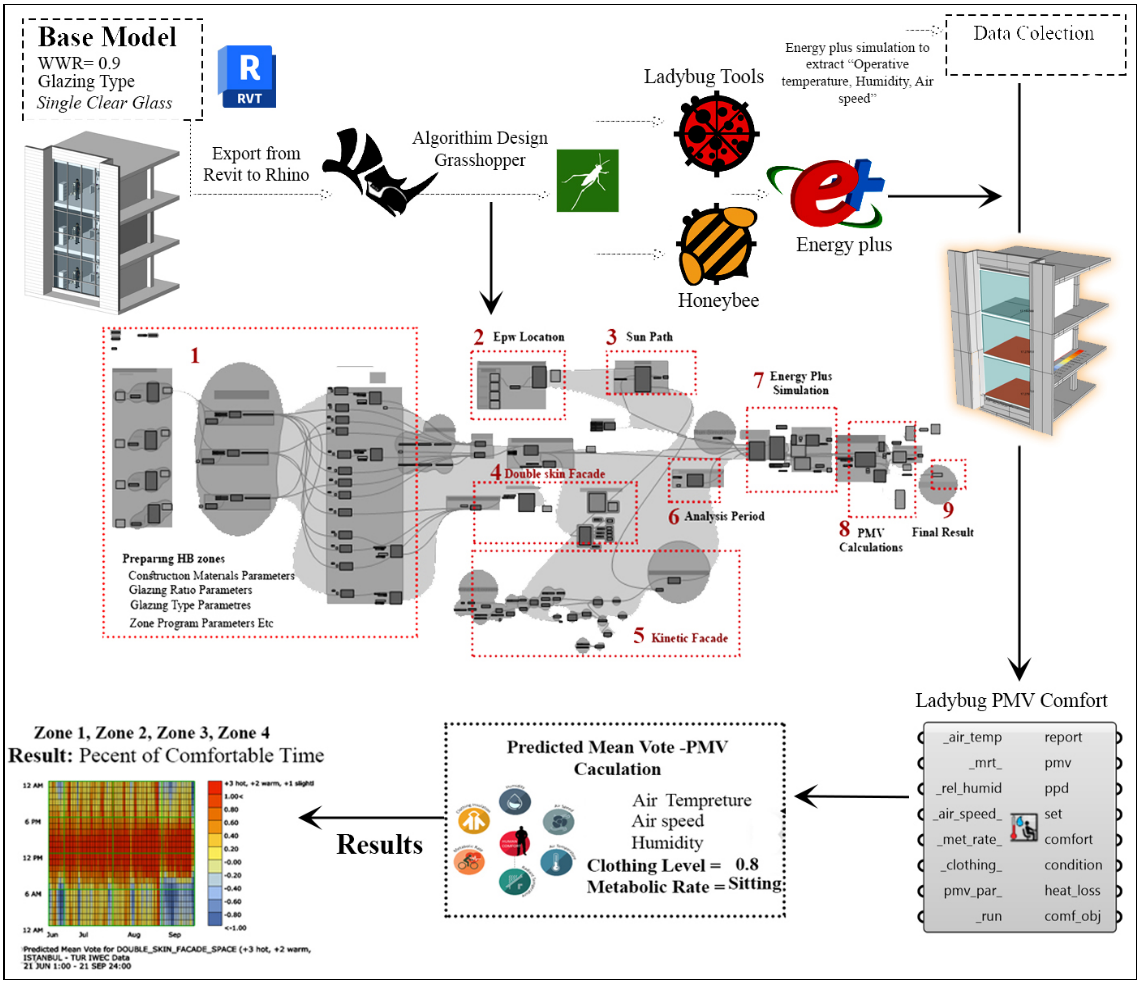


Figure 3 General study workflow

2.2.1 Kinetic Façade System Scenarios

The kinetic louver system applied in this study was modelled as a dynamic solar-responsive façade component operating through a rule-based control algorithm. Each louver panel was defined with a rotation range between 0° (fully open) and 90° (fully closed) with 15° angular increment, allowing continuous modulation of solar exposure on the south façade. The actuation mechanism was linked to real-time solar altitude and incident radiation levels using Grasshopper–Ladybug components. The louvers were programmed to update their position at 10-minute intervals, synchronized with the EnergyPlus timestep to ensure accurate interaction between façade shading and thermal loads. When direct solar irradiance on a louver exceeded 250 W/m², the system initiated a closing movement to reduce heat gain; conversely, the louvers remained open when irradiance levels fell below this threshold, permitting daylight admission and minimizing unnecessary shading. The proposed kinetic facade system scenarios are summerized as follows:

○ Scenario 1: Kinetic louvers

This scenario introduces vertical kinetic louvers on the south façade of the base model. These kinetic components are responsive to the sun's position, meaning they automatically open and close based on the solar altitude angle and incident radiation on each individual louver as described previously and illustrated in Figure 4.

○ Scenario 2: Kinetic louvers and modified glass type

In this scenario, kinetic louvers are combined with a change in window glazing type. The south-facing façade glazing is modified from "Single Clear Glass" (U-value = 5.9 W/m²K) to "Double Pane Low-E Glass" (U-value = 1.127 W/m²K) to improve thermal insulation and solar control.

○ Scenario 3: Kinetic louvers, modified glass type & adjusted WWR

This scenario further enhances the previous setup by modifying the Window-to-Wall Ratio (WWR). The WWR of 0.9 in the base model is reduced to 0.6 and 0.3, respectively, optimizing solar heat gain control and daylight utilization, as shown in Figure 4.

2.2.2 Double-Skin Façade System Scenarios

The Double-Skin Façade (DSF) system employed in this study was modelled as a non-ventilated façade, consisting of an exterior glazing layer separated from the primary façade by a 1-meter air cavity. The cavity was defined as a sealed thermal zone in EnergyPlus using the Honeybee "air-gap" configuration, allowing the simulation to represent conduction and radiative heat transfer across the enclosed air layer. As no ventilation openings were introduced, the DSF operates without stack-effect or buoyancy-driven airflow, consistent with closed-cavity DSF systems commonly used in temperate and cold climates.

EnergyPlus computes the cavity temperature dynamically based on absorbed solar radiation, longwave exchanges between glazing layers, and limited conductive coupling to the indoor façade. Although the absence of ventilation restricts convective cooling, the model captures the characteristic heat-buildup behaviour of non-ventilated DSFs, providing a consistent and realistic basis for performance comparison across climatic zones. The proposed Double-Skin Facade system scenarios are summerized as follows:

- Scenario 4: Second glazed layer

This scenario involves adding a second glass layer on the south façade of the base model, creating a double-skin façade (DSF) with a cavity width of 1 meter. The outer glazing type remains Single Clear Glass, similar to the base model, forming a non-ventilated DSF system.

- Scenario 5: Second glazed layer & modified glass type

In this scenario, the double-skin façade is combined with upgraded window glazing. The south-facing façade glass is changed from "Single Clear Glass" (U-value = 5.9 W/m²K) to "Double Pane Low-E Glass" (U-value = 1.127 W/m²K), enhancing thermal performance and reducing heat loss.

- Scenario 6: Second glazed layer, modified glass type & adjusted WWR

This scenario integrates the double-skin façade system with both modified glazing type and adjusted WWR. The WWR is reduced from 0.9 (base model) to 0.6 and 0.3, as shown in Figure 4, to further regulate indoor temperature and solar exposure.

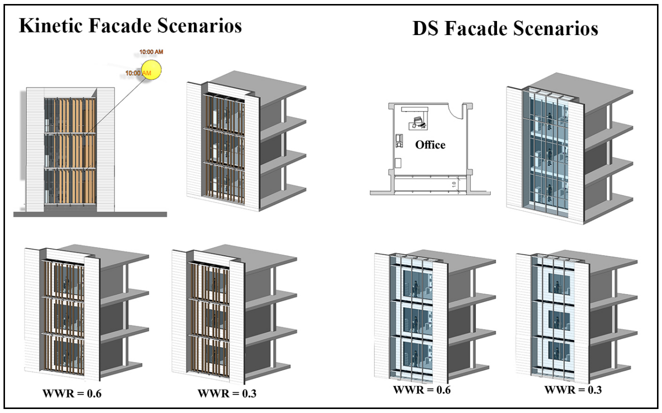


Figure 4 The suggested scenarios

2.2.3 Simulation and Analysis Process

After constructing the base model, it was exported to Rhino for simulation. A parametric algorithm was developed in Grasshopper, beginning with the identification of analytical zones (Hb Zones) and the import of climate data for the selected cities (Antalya, Istanbul, Ankara, and Erzurum).

- Preparation of Hb Zones

The Hb Zones were configured by assigning construction materials for walls, floors, and roofs based on ASHRAE and TS 825 standards to ensure compliance with minimum insulation requirements for each climatic zone as shown in Tables 1 and 2. Zone programs were defined, including functional classifications, occupancy schedules, and internal heat gains to accurately represent real-world conditions. Adjacent surfaces were specified to account for heat transfer between spaces, improving the accuracy of thermal performance assessments. Temperature control setpoints for heating and cooling systems were established to ensure that simulations reflect realistic indoor thermal conditions.

- Integration of Climate Data & Façade Systems

Weather data files from Ladybug's Energy plus database were incorporated for each city. The analysis period was set from June 21 to September 21 (summer period) to evaluate peak cooling demands. Kinetic façade scripts were developed and connected to the sun path and shading control parameters within the Energy plus simulation environment. Double-skin façade scripts were integrated as Hb Zones, with modified ventilation settings (non-ventilated), ensuring compatibility with energy modelling frameworks.

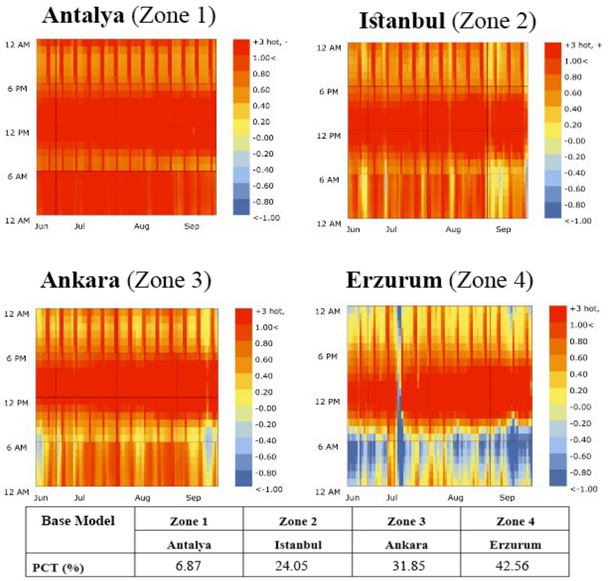
- Simulation Outputs and Data Visualization

The simulation was executed to generate "Comfort Metrics" within the Grasshopper script environment. The resulting thermal comfort data were extracted, analysed, and visualized for each scenario to determine the most effective strategy for each climatic zone.

3. Results

3.1 Base Model Results

The results of the base model indicate that the average Percent of Comfortable Time (PCT) during the summer analysis period varies significantly across the selected climatic zones in Türkiye. The findings reveal that Antalya (Zone 1) has the lowest PCT at 6.87%, followed by Istanbul (Zone 2) at 24.05%, Ankara (Zone 3) at 31.58%, and Erzurum (Zone 4) at 42.56%, as illustrated in Figure 5. These variations highlight the impact of regional climate conditions on thermal comfort levels in the base model.

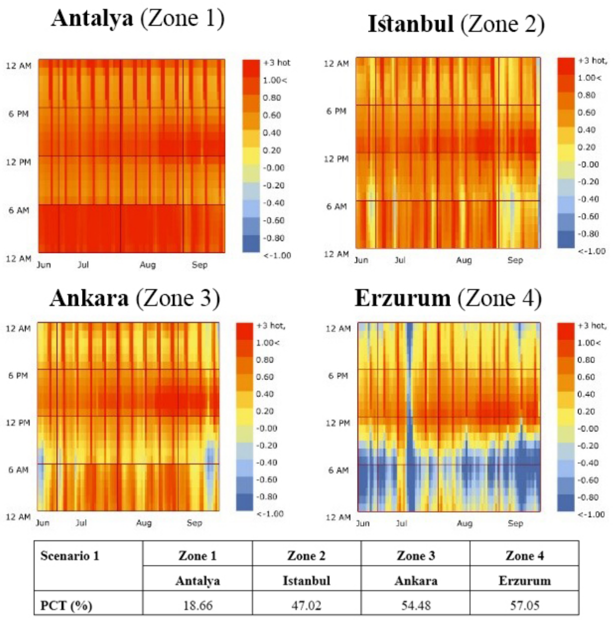


Base Model	Zone 1	Zone 2	Zone 3	Zone 4
	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	6.87	24.05	31.85	42.56

Figure 5 Base model results of PMV-PCT

3.2 Kinetic Façade Scenarios Results

The results indicate that applying kinetic louvers on the south façade of the base model (Scenario 1) significantly improves thermal comfort across all climatic zones. The average Percent of Comfortable Time (PCT) during the summer analysis period increased to 18.66% in Antalya (Zone 1), 47.02% in Istanbul (Zone 2), 54.48% in Ankara (Zone 3), and 57.05% in Erzurum (Zone 4), as illustrated in Figure 6.



Scenario 1	Zone 1	Zone 2	Zone 3	Zone 4
	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	18.66	47.02	54.48	57.05

Figure 6 Results of PMV-PCT of scenario 1

Table 1 Construction materials properties of Antalya (Zone 1) & Istanbul (Zone 2)

Antalya (Zone 1)					
Components		**Layers**	**Thickness (cm)**	**U- Value W/m²K**	**TS825 U-value W/m²K**
Walls	Exterior	Stucco	2.54	0.647805	0.7
		Heavyweight Concrete	20.32		
		Mass Wall Insulation R- 11.70 IP	10.09		
		Gypsum	1.27		
		Total thickness	34.22		
	Interior	Gypsum Board	1.9	0.454477	
		Wall air space	8.0		
		Gypsum board	1.9		
		Total thickness	11.80		
Floors		Porcelain Tile	1.27	0.157874	0.7
		Floor Insulation R-35.07 IP	30.25		
		Gypsum	1.27		
		Total thickness	32.79		
Roof		Roof Membrane	0.95	0.326303	0.45
		IEAD Roof Insulation R- 19.72 IP	17.01		
		MAT- CC0.5 HW Concrete	15.16		
		Total thickness	33.12		

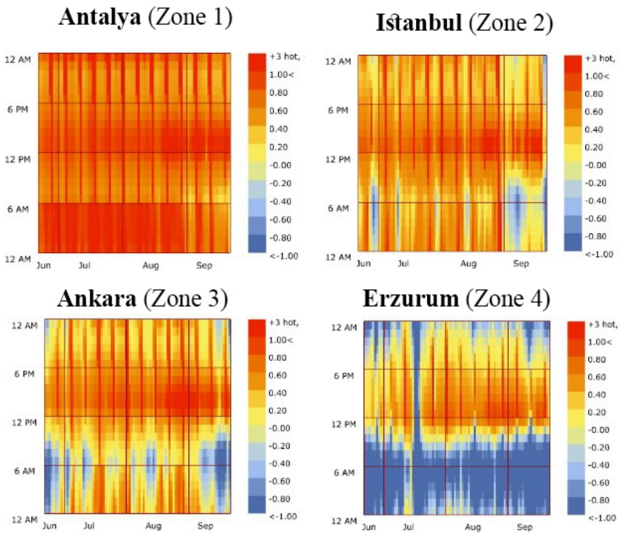
Istanbul (Zone 2)					
Components		**Layers**	**Thickness (cm)**	**U- Value W/m²K**	**TS825 U-value W/m²K**
Walls	Exterior	Stucco	2.54	0.513649	0.6
		Heavyweight Concrete	20.32		
		Mass Wall Insulation R- 7.23 IP	6.23		
		Gypsum	1.27		
		Total thickness	30.36		
	Interior	Gypsum Board	1.9	0.454477	
		Wall air space	8.0		
		Gypsum board	1.9		
		Total thickness	11.80		
Floors		Porcelain Tile	1.27	0.199447	0.6
		Floor Insulation	23.79		
		Gypsum	1.27		
		Total thickness	26.33		
Roof		Roof Membrane	0.95	0.326303	0.4
		IEAD Roof Insulation R- 19.72 IP	17.01		
		MAT- CC0.5 HW Concrete	15.16		
		Total thickness	33.12		

Table 2 Construction materials properties of Ankara (Zone 3) & Erzurum (Zone 4)

Ankara (Zone 3)					
Components		**Layers**	**Thickness (cm)**	**U- Value W/m²K**	**TS825 U-value W/m²K**
Walls	Exterior	Stucco	2.54	0.416211	0.5
		Heavyweight Concrete	20.32		
		Mass Wall Insulation R- 8.72 IP	7.52		
		Gypsum	1.27		
		Total thickness	31.65		
	Interior	Gypsum Board	1.9	0.454477	
		Wall air space	8.0		
		Gypsum board	1.9		
		Total thickness	11.8		
Floors		Porcelain Tile	1.27	0.199447	0.45
		Floor Insulation	23.79		
		Gypsum	1.27		
		Total thickness	26.33		
Roof		Roof Membrane	0.95	0.283158	0.30
		IEAD Roof Insulation R- 14.76 IP	12.73		
		MAT- CC0.5 HW Concrete	15.16		
		Total thickness	28.84		
Erzurum (Zone 4)					
Components		**Layers**	**Thickness (cm)**	**U- Value W/m²K**	**TS825 U-value W/m²K**
Walls	Exterior	Stucco	2.54	0.302714	0.4
		Heavyweight Concrete	20.32		
		Mass Wall Insulation R- 10.11IP	8.72		
		Gypsum	1.27		
		Total thickness	32.85		
	Interior	Gypsum Board	1.9	0.454477	
		Wall air space	8.0		

		Gypsum board	1.9		
		Total thickness	11.8		
Floors		Porcelain Tile	1.27	0.157874	0.4
		Floor Insulation R-35.07 IP	30.25		
		Gypsum	1.27		
		Total thickness	32.79		
Roof		Roof Membrane	0.95	0.186304	0.25
		Roof Insulation	26.01		
		MAT- CC0.5 HW Concrete	15.16		
		Total thickness	42.12		

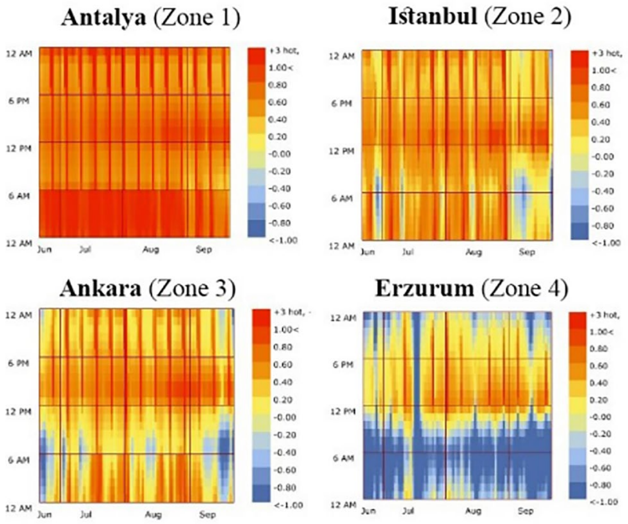
For Scenario 2, which combines kinetic louvers with a glazing upgrade to double-pane Low-E glass, the results further demonstrate an increase in PCT values. The findings show that thermal comfort improves to 22.37% in Antalya (Zone 1), 62.81% in Istanbul (Zone 2), 61.49% in Ankara (Zone 3), and 48.74% in Erzurum (Zone 4), as shown in Figure 7. These results highlight the effectiveness of integrating kinetic shading devices with high-performance glazing to enhance indoor thermal conditions.



Scenario 2	Zone 1	Zone 2	Zone 3	Zone 4
	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	22.37	62.81	61.49	48.74

Figure 7 Results of PMV-PCT of scenario 2

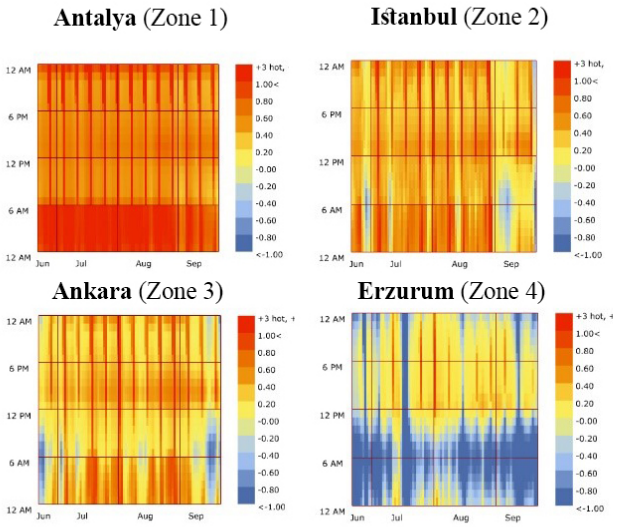
For Scenario 3, which integrates kinetic louvers, modified glass type, and a reduced WWR of 0.6, the results indicate a notable improvement in indoor thermal comfort across all climate zones. The average Percent of Comfortable Time (PCT) during the summer analysis period increased to 26.57% in Antalya (Zone 1), 71.39% in Istanbul (Zone 2), 70.25% in Ankara (Zone 3), and 55.57% in Erzurum (Zone 4), as presented in Figure 8.



Scenario 3	Zone 1	Zone 2	Zone 3	Zone 4
WWR=0.6	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	26.57	71.39	70.25	55.57

Figure 8 Results of PMV-PCT of scenario 3- WWR= 0.6

Further reducing WWR to 0.3 in Scenario 3 resulted in even higher PCT values, particularly in warmer climates. The PCT increased to 40.32% in Antalya (Zone 1), 79.59% in Istanbul (Zone 2), 79.23% in Ankara (Zone 3), and 56.13% in Erzurum (Zone 4), as shown in Figure 9. These results suggest that reducing the window area, when combined with kinetic shading and high-performance glazing, significantly enhances indoor comfort levels in warm and moderate climates.

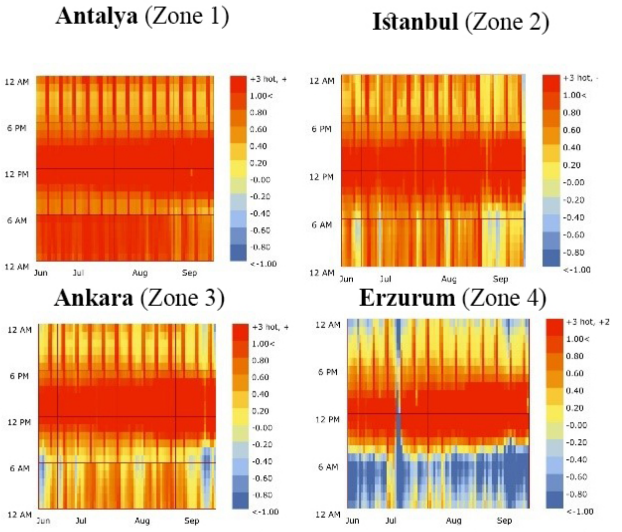


Scenario 3	Zone 1	Zone 2	Zone 3	Zone 4
WWR=0.3	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	40.32	79.59	79.23	56.13

Figure 9 Results of PMV-PCT of scenario 3- WWR= 0.3

3.2 Double-Skin Façade Scenarios Results

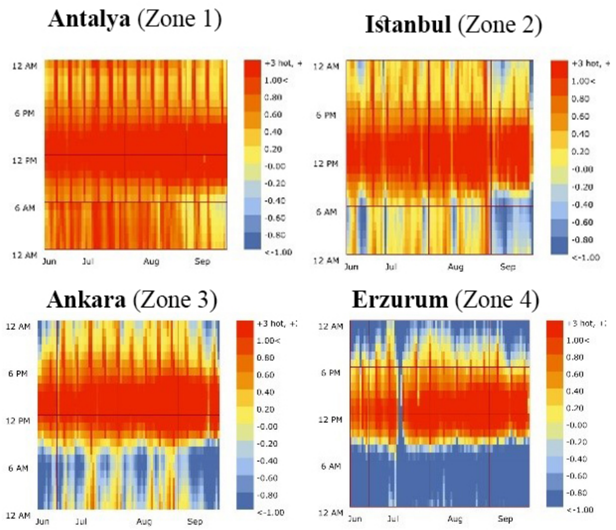
The application of a Non-Ventilated Double-Skin Façade (DSF) system to the base model (Scenario 4) resulted in an increase in PCT values compared to the base model, though it was less effective than kinetic façades. The results showed that the average PCT reached 17.17% in Antalya (Zone 1), 39.20% in Istanbul (Zone 2), 46.81% in Ankara (Zone 3), and 48.34% in Erzurum (Zone 4), as illustrated in Figure 10.



Scenario 4	Zone 1	Zone 2	Zone 3	Zone 4
	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	17.17	39.20	46.81	48.34

Figure 10 Results of PMV-PCT of scenario 4

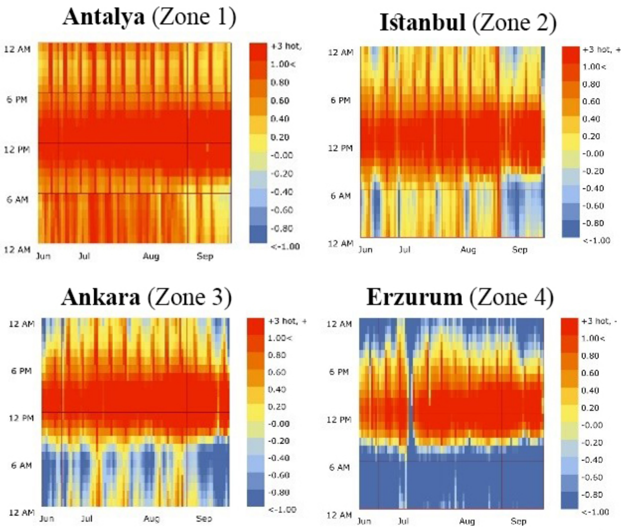
For Scenario 5, which combines the Double-Skin Façade system with a glazing upgrade to Double Pane Low-E Glass, the results demonstrate a further improvement in PCT values. The PCT increased to 23.35% in Antalya (Zone 1), 49.61% in Istanbul (Zone 2), 50.43% in Ankara (Zone 3), and 41.35% in Erzurum (Zone 4), as shown in Figure 11.



Scenario 5	Zone 1	Zone 2	Zone 3	Zone 4
	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	23.35	49.61	**50.43**	41.35

Figure 11 Results of PMV-PCT of scenario 5

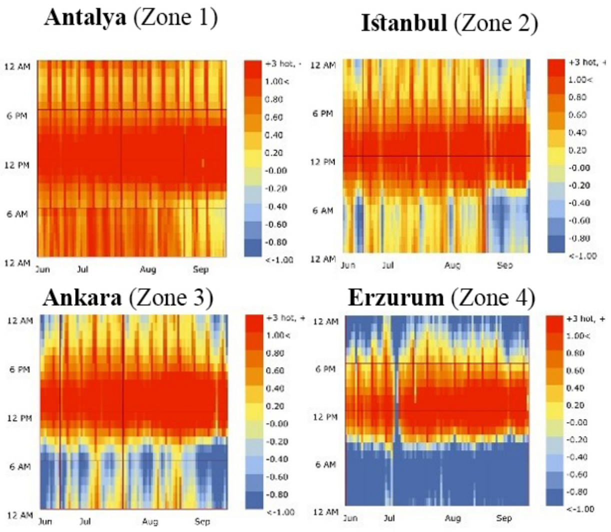
The final scenario, Scenario 6, examined the effect of modifying the WWR within the Double-Skin Façade system. With WWR = 0.6, the results showed that the PCT values reached 23.08% in Antalya (Zone 1), 48.34% in Istanbul (Zone 2), 50.14% in Ankara (Zone 3), and 42.35% in Erzurum (Zone 4), as displayed in Figure 12.



Scenario 6	Zone 1	Zone 2	Zone 3	Zone 4
WWR=0.6	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	23.08	48.34	50.14	42.35

Figure 12 Results of PMV-PCT of scenario 6- WWR=0.6

When the WWR was further reduced to 0.3 in Scenario 6, PCT values slightly decreased in most climate zones except Erzurum (Zone 4). The final PCT values were 22.70% in Antalya (Zone 1), 47.67% in Istanbul (Zone 2), 50.19% in Ankara (Zone 3), and 43.92% in Erzurum (Zone 4), as illustrated in Figure 13. This suggests that while reducing WWR improves indoor comfort in some cases, extremely low WWR values may not always yield the best thermal comfort performance, particularly in cooler climates.


Antalya (Zone 1)
Istanbul (Zone 2)
Ankara (Zone 3)
Erzurum (Zone 4)

Scenario 6	Zone 1	Zone 2	Zone 3	Zone 4
WWR=0.3	Antalya	Istanbul	Ankara	Erzurum
PCT (%)	22.70	47.67	50.19	43.92

Figure 13 Results of PMV-PCT of scenario 6-WWR= 0.3

4. Discussion & Analysis

Building envelopes play a crucial role in determining indoor thermal comfort conditions in office buildings. The results indicate that certain façade strategies perform better in specific climatic zones, highlighting the importance of climate-responsive design. Additionally, design parameters such as glazing type, window-to-wall ratio (WWR), and shading strategies significantly impact overall building thermal performance. In this section, the results are analyzed separately for each climatic zone to determine the most effective strategies based on the findings.

While several façade configurations achieved high Percent of Comfortable Time (PCT) values—particularly in Istanbul and Ankara—these results should be interpreted with caution. The reported PCT levels are sensitive to assumptions related to occupant behavior, including clothing insulation, metabolic rate, and the use of fixed HVAC setpoints. In real office environments, variations in user behavior, control strategies, or operational schedules may lead to lower realized comfort levels. Therefore, the high PCT values reported in this study should be understood as indicators of relative performance potential under controlled conditions rather than guaranteed comfort outcomes in occupied buildings.

It should be noted that the DSF evaluated in this study represents a non-ventilated configuration, selected to ensure cross-climatic comparability rather than to reflect the full performance potential of DSF systems.

4.1 Antalya (Zone 1 – Hot-Summer Mediterranean Climate)

The best-performing scenario for Antalya was Scenario 3 with WWR = 0.3, where the Percent of Comfortable Time (PCT) reached 40.32%. Compared to the base model (6.87%), this scenario resulted in a significant increase of 33.45%. The improvements were achieved by integrating kinetic louvers on the south façade, upgrading to double-pane Low-E glass, and reducing WWR to 0.3. These modifications effectively minimized solar heat gain, enhanced thermal insulation, and improved indoor temperature regulation.

The second-best scenario was Scenario 3 with WWR = 0.6, where the PCT increased to 26.57%, representing an improvement of 19.70% compared to the base model. This setup included kinetic louvers with double-pane Low-E glass but maintained a higher WWR (0.6). The results suggest that, while increasing the glazing area allows more daylight penetration, it can also increase solar heat gain, requiring an optimal balance between WWR and shading strategies.

The third-best scenario was Scenario 5, where the PCT improved to 23.35%, reflecting an increase of 16.48% from the base model. This scenario applied a Double-Skin Façade (DSF) with double-pane Low-E glass, without modifying WWR. DSFs have been widely recognized for their ability to enhance thermal insulation, reduce cooling loads, and improve indoor air stratification, making them a viable passive cooling strategy (Ghaffarianhoseini et al. 2016).

According to the Köppen climate classification, Antalya has a hot-summer Mediterranean climate, characterized by high solar radiation and warm temperatures. Yang et al. (2019) concluded that Double-Skin Façades (DSFs) contribute to stable indoor temperatures in hot climates, primarily by buffering solar radiation and reducing thermal fluctuations. However, the results of this study suggest that kinetic louvers outperform DSFs in Antalya, particularly in terms of achieving higher PCT values during the summer period.

These findings align with researches by Hosseini et al. (2019), which highlighted that kinetic shading systems dynamically adjust to solar angles, optimizing daylight control and reducing peak indoor temperatures. In contrast, non-ventilated DSFs can trap heat, leading to higher internal temperatures if not designed with effective ventilation strategies (Yang et al. 2019). Additionally, studies by Tzempelikos & Athienitis (2007) emphasize that kinetic shading systems can reduce solar heat gain by up to 60%, making them more effective in hot climates where solar exposure is a primary concern.

Moreover, Prieto et al. (2018) found that adjusting WWR in hot climates is crucial for optimizing energy performance, as excessive glazing can increase cooling demand despite improvements in glazing technology. The results from this study support this conclusion, as reducing WWR to 0.3 in Scenario 3 provided the highest PCT improvement in Antalya. This finding suggests that a lower WWR, combined with kinetic shading and Low-E glazing, is a highly effective strategy for hot Mediterranean climates.

Overall, these results indicate that dynamic shading solutions (kinetic louvers) are more adaptable and responsive to varying solar angles throughout the day, making them a superior alternative to static DSFs in Antalya's climate. Future studies could explore hybrid façade designs, incorporating both kinetic shading and ventilated DSFs, to optimize thermal comfort and natural ventilation simultaneously.

4.2 Istanbul (Zone 2 – Moderate Climate)

The best-performing scenario for Istanbul was Scenario 3 with WWR = 0.3, where the Percent of Comfortable Time (PCT) reached 79.59%. Compared to the base model (24.05%), this scenario resulted in a significant increase of 55.54%. The enhancements were due to kinetic louvers, double-pane Low-E glass, and a reduced WWR of 0.3, which effectively optimized solar control and thermal performance. These findings align with research by Prieto et al. (2018), which highlights that reducing WWR in moderate climates contributes to improved thermal comfort and energy efficiency. This improvement is mainly achieved by minimizing excessive heat gain while still allowing adequate daylight penetration.

The second-best scenario was Scenario 3 with WWR = 0.6, where the PCT increased to 71.39%, representing an improvement of 47.34% from the base model. This scenario applied kinetic louvers and double-pane Low-E glass, while maintaining a WWR of 0.6. The performance of this scenario suggests that higher WWR values can still maintain good thermal comfort if coupled with effective shading and glazing strategies, a conclusion supported by Ghaffarianhoseini et al. (2018), who found that the interaction between WWR and shading devices plays a crucial role in balancing daylight, energy performance, and occupant comfort in mixed climates.

The third-best scenario was Scenario 2, where the PCT reached 62.81%, reflecting a 38.76% increase over the base model. This scenario involved kinetic louvers and a glass upgrade from single clear glass to double-pane Low-E glass, but maintained a high WWR of 0.9. The results indicate that Scenario 2 is particularly suitable in cases where high levels of natural daylight and transparent façades are prioritized. This aligns with research by Tzempelikos & Athienitis (2007), which concluded that high-performance glazing, when paired with dynamic shading systems, allows for maximized daylight utilization while mitigating glare and overheating risks.

These results emphasize the importance of dynamic shading and glazing selection in moderate climates, where solar exposure varies seasonally and requires adaptive façade solutions. Research by Hosseini et al. (2019) highlights that kinetic façade offers superior adaptability by responding to real-time climatic conditions, adjusting to varying sun angles and intensities. Furthermore, study by Lu (2022) indicate that smart façades integrating kinetic shading and high-performance glazing can reduce cooling loads by up to 30% in moderate climates, improving both thermal comfort and energy efficiency.

While reducing WWR enhances thermal comfort, maintaining an optimal balance between daylight access and energy efficiency is critical. The findings suggest that Scenario 3 with WWR = 0.3 offers the highest improvement in thermal comfort, but Scenario 2 remains an attractive option where increased daylight penetration is prioritized. Future studies could further explore hybrid façade systems integrating ventilated DSFs with kinetic shading devices to assess their impact on year-round thermal comfort and energy consumption in mixed climates.

4.3 Ankara (Zone 3 – Cold Semi-Arid Climate)

The best-performing scenario for Ankara was Scenario 3 with WWR = 0.3, where the Percent of Comfortable Time (PCT) reached 79.23%. Compared to the base model (31.85%), this scenario resulted in a significant increase of 47.65%. The improvements were achieved by integrating kinetic louvers on the south façade, upgrading to double-pane Low-E glass, and reducing WWR to 0.3, which effectively enhanced solar control and thermal insulation. These findings align with research by Tzempelikos & Athienitis (2007), which emphasized that dynamic shading devices significantly reduce direct solar heat gain while maintaining adequate daylighting in mixed and cold climates.

The second-best scenario was Scenario 3 with WWR = 0.6, where the PCT increased to 70.25%, reflecting an improvement of 38.40% over the base model. This scenario maintained kinetic louvers and double-pane Low-E glass but with a higher WWR of 0.6, allowing for greater daylight penetration while still optimizing solar heat gain and energy performance. Studies by Wu (2022) found that facades incorporating dynamic shading and low-emissivity glazing can improve occupant thermal comfort while reducing heating loads by up to 25% in semi-arid climates.

The third-best scenario was Scenario 2 with WWR = 0.9, where the PCT reached 61.49%, representing an increase of 29.64% compared to the base model. This scenario applied kinetic louvers and an upgraded glazing system, replacing single clear glass with double-pane Low-E glass while maintaining a high WWR of 0.9. These results suggest that while increased glazing area allows for improved daylight utilization, excessive WWR can lead to greater thermal losses during colder months. This trend has also been observed in previous studies (Prieto et al. 2018).

The results for Ankara closely resemble those observed in Istanbul, indicating that kinetic shading and optimized glazing selection are effective strategies in moderate to cold semi-arid climates. However, additional considerations such as thermal mass and passive solar design could further enhance building performance. Research by Ghaffarianhoseini et al. (2018) suggests that incorporating thermal mass materials alongside adaptive shading systems can further improve indoor comfort by storing solar heat during the day and releasing it at night, reducing temperature fluctuations in semi-arid climates.

Moreover, studies by Lu (2022) and Wu (2022) emphasize that parametric optimization of kinetic shading devices, combined with passive heating techniques, can significantly enhance energy efficiency in buildings located in regions with high diurnal temperature variations, such as Ankara. This indicates that further integration of climate-responsive design elements, including thermal mass storage and ventilated façades, could optimize performance beyond the kinetic shading and glazing improvements tested in this study.

Future research could explore hybrid façade systems that combine kinetic shading with phase-change materials (PCMs) or ventilated double-skin façades, as suggested by Soudian & Berardi (2019).

4.4 Erzurum (Zone 4 – Cold Climate)

The best-performing scenario for Erzurum was Scenario 1 with WWR = 0.9, where the Percent of Comfortable Time (PCT) reached 57.05%. Compared to the base model (42.56%), this scenario resulted in an increase of 14.49%. The improvement was achieved by changing the glazing construction and integrating kinetic louvers, without modifying WWR.

The second-best scenario was Scenario 3 with WWR = 0.3, where the PCT increased to 56.13%, representing an improvement of 13.57% over the base model. This scenario incorporated kinetic louvers and upgraded glazing to double-pane Low-E glass, with a reduced WWR of 0.3.

The third-best scenario was Scenario 3 with WWR = 0.6, where the PCT reached 55.57%, reflecting an increase of 13.01% from the base model. Similar to the previous scenario, this case involved kinetic louvers and double-pane Low-E glass, but with a WWR of 0.6.

The results suggest that WWR has a relatively lower impact on PCT in Erzurum (Zone 4) once kinetic louvers are applied during the summer period. This is particularly beneficial when maximum daylighting is required in office spaces, ensuring sufficient natural illumination without significant variations in energy consumption to maintain indoor thermal comfort. These findings align with the conclusions of Soudian & Berardi (2019), who found that glazing selection and shading integration in cold climates should prioritize passive heat retention while maintaining daylighting efficiency.

In cold climates, glazing selection plays a crucial role in thermal performance, but its influence on PCT in Erzurum is relatively lower than in warm or temperate zones. Research by Cucumo et al. (2013) demonstrated that Low-E coatings significantly contribute to thermal comfort improvements in various climates, particularly by reducing unwanted heat gain in summer while maintaining insulation in winter. However, in extremely cold regions like Erzurum, the impact of Low-E glazing becomes marginal since heat retention is more critical than solar heat gain reduction. Prieto et al. (2018) further emphasize that glazing strategies in cold climates should focus on triple-glazed units or vacuum-insulated glazing to minimize heat loss while still permitting beneficial solar gain.

Kinetic louvers are typically employed as a solar shading strategy, but their role in cold climates differs significantly from that in warmer regions. A study by Wu (2022) found that kinetic louvers can optimize solar heat gain in cold environments when integrated with automated control systems that adjust to seasonal variations. For Erzurum, this suggests that kinetic shading should be configured not only to prevent overheating during summer but also to maximize passive solar heating during colder months, particularly in shoulder seasons (spring and autumn).

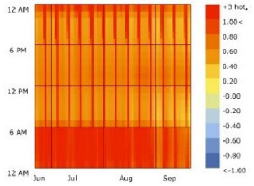
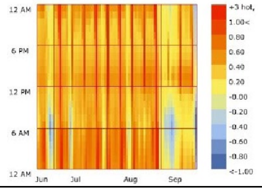
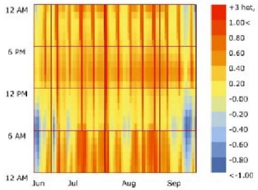
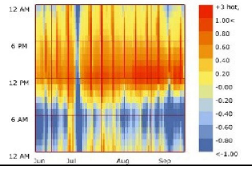
While kinetic louvers proved effective in Erzurum, the Non-ventilated double-skin façades (DSFs) present an alternative approach for improving thermal comfort and energy performance in extreme cold conditions. Research by Ghaffarianhoseini et al. (2018) suggests that ventilated DSFs are highly beneficial in cold climates, as they reduce heat loss by forming an insulating air buffer while allowing controlled solar heat gain. However, the non-ventilated DSF used in this study may have limited effectiveness in Erzurum, due to insufficient air circulation, which could trap excessive heat in summer while reducing its insulating capacity in winter (Yang et al. 2019).

It should be emphasized that the DSF evaluated in this study represents a non-ventilated configuration, selected to maintain comparability across climates rather than to reflect the full performance potential of DSF systems. A more adaptive DSF approach could be explored for Erzurum, as proposed by Alberto et al. (2017), where airflow within DSFs is dynamically controlled based on external and internal temperature conditions. This would allow for enhanced heat retention in winter while maintaining cooling benefits in summer. Future research should explore hybrid façade solutions that combine automated kinetic shading with naturally ventilated DSFs to enhance thermal comfort throughout the year.

5. Summary of Top-Performing Façade Strategies Across Türkiye's Climatic Zones

To consolidate the findings presented for each climatic zone, a comparative summary was developed to highlight how the different façade strategies performed across Türkiye. While the previous subsections presented detailed results for each city individually, the following table provides an integrated overview that clarifies which configurations achieved the highest PCT values under each regional climate condition. This summary enables a clearer understanding of the climate-dependent behavior of façade systems. Table 5 summarizes the top-Performing Façade Strategies Across Türkiye's Climatic Zones.

Table 5 Top-Performing façade strategies across Türkiye's climatic zones

Climate Zone / Representative City	Best Performing Strategy (PCT %)	PCT Improvement Percentage (%)	Key Façade Components	Why it Performs Best	Result's Graphical Representation
Zone 1 – Hot-Summer Mediterranean / **Antalya**	Scenario 3 (40.32%)	33.45%	Kinetic louvers + Low-E glazing + Reduced WWR to 30%	Strong reduction of solar heat gain under intense radiation	
Zone 2 – Temperate Climate / **Istanbul**	Scenario 3 (79.59%)	55.54%	Kinetic louvers + Low-E glazing + Reduced WWR to 30%	Balanced daylight–cooling load control; shading highly effective	
Zone 3 – Cold Semi-Arid Climate / **Ankara**	Scenario 3 (79.23%)	47.65%	Kinetic louvers + Low-E glazing + Reduced WWR to 30%	Reduces overheating while maintaining daylight in mixed climate	
Zone 4 – Severe Cold Climate / **Erzurum**	Scenario 1 (57.05%)	14.49%	Kinetic louvers + Base glazing	WWR has limited impact; shading sufficient; solar gains beneficial	

6. Limitations of the Study

The study focuses exclusively on summer thermal comfort conditions, and therefore does not account for winter performance or year-round comfort variations. In addition, the kinetic louver model applied a rule-based control algorithm without exploring alternative optimization strategies or automated control systems. The DSF was modeled as a non-ventilated configuration, which limits the ability to evaluate buoyancy-driven airflow or mechanically assisted ventilation scenarios. These limitations provide opportunities for future research to explore more advanced control strategies, alternative DSF configurations, and comprehensive annual comfort assessments.

7. Conclusion

This study evaluated the impact of kinetic louvers, glazing upgrades, and non-ventilated double-skin façades on indoor thermal comfort across Türkiye's four major climatic zones using PMV-based Percent of Comfortable Time (PCT). The results demonstrated that kinetic louvers were the most effective strategy in reducing overheating, increasing PCT from 6.87% to 18.66% in Antalya, 24.05% to 47.02% in Istanbul, 31.58% to 54.48% in Ankara, and 42.56% to 57.05% in Erzurum. When combined with Low-E double glazing and reduced WWR to 0.3, Scenario 3 achieved the highest comfort performance with PCT values of 40.32% (Zone 1), 79.59% (Zone 2), and 79.23% (Zone 3). In contrast, the coldest climate (Zone 4) showed limited sensitivity to WWR reductions, with Scenario 1 performing the best due to the beneficial contribution of solar gains.

The non-ventilated DSF provided moderate improvements, particularly in Zones 2 and 3, but remained less effective than dynamic shading in extreme hot or cold climates. These findings confirm that façade design must be climate-responsive rather than uniform, and that the integration of kinetic shading with high-performance glazing yields substantial thermal comfort benefits in warm and temperate regions.

Future research should expand the analysis to include winter performance, annual comfort evaluation, glare and daylight quality, and alternative DSF ventilation strategies. Investigating adaptive or optimization-based louver control algorithms may also provide deeper insights into the full potential of kinetic façades in complex climatic contexts.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

Alberto, A., Ramos, N. M. M., & Almeida, R. M. S. F. (2017). Parametric Study of Double-Skin Façades Performance in Mild Climate Countries. *Journal of Building Engineering*, 12: 87–98. DOI: https://doi.org/10.1016/j.jobe.2017.05.013

Al horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of Indoor Environmental Quality on Occupant Well-Being and Comfort: A Review of The Literature. *International Journal of Sustainable Built Environment*. 5(1): 1–11. DOI: https://doi.org/10.1016/j.ijsbe.2016.03.006

Ascione, F., Bianco, N., De Masi, R. F., de'Rossi, F., & Vanoli, G. P. (2014). Energy Refurbishment of Existing Buildings Through the Use of Phase Change Materials: Energy Savings and Indoor Comfort in the Cooling Season. *Applied Energy*. 113: 990-1007. DOI: https://doi.org/10.1016/j.apenergy.2013.08.045

Beccali, M., Strazzeri, V., Germanà, M. L., Melluso, V., & Galatioto, A. (2018). Vernacular and Bioclimatic Architecture and Indoor Thermal Comfort Implications in Hot-humid Climates: An Overview. *Renewable and Sustainable Energy Reviews*. 82(2): 1726–1736. DOI: https://doi.org/10.1016/j.rser.2017.06.062

Berkouk, D., Bouzir, T. A. K., Mazouz, S., & Boucherit, S. (2022). Studying The Influence of Shading Devices on Indoor Thermal Comfort in Desert and Mediterranean Climates. *IOP Conference Series: Earth and Environmental Science, 992*(1): 012004. DOI: https://doi.org/10.1088/1755-1315/992/1/012004

Cao, B., Luo, M., Li, M., & Zhu, Y. (2016). Too Cold or Too Warm? A Winter Thermal Comfort Study in Different Climate Zones in China. *Energy and Buildings*. 133: 469–477. DOI: https://doi.org/10.1016/j.enbuild.2016.09.050

U. S. G. B. Council (2021, April). LEED v4. 1 Interior Design and Construction. https://www.usgbc.org/leed/v4. Accessed 12 February 2025.

Cucumo, M., Ferraro, V., Kaliakatsos, D., & Marinelli, V. (2013). Simulation of the Thermal Behavior of Buildings Equipped with Low-Emissivity Glazed Components: A Performance Analysis. *International Journal of Heat and Technology*. 31(2): 111–118. https://www.iieta.org/journals/ijht/paper/10.18280/ijht.310215

Daemei, A. B., Eghbali, S. R., & Khotbehsara, E. M. (2019). Bioclimatic Design Strategies: A Guideline to Enhance Human Thermal Comfort in Cfa Climate Zones. *Journal of Building Engineering*, 25(2019): 100758. DOI: https://doi.org/10.1016/j.jobe.2019.100758

De Dear, R., & Brager, G. S. (1998). Developing An Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions*, 104. https://escholarship.org/content/qt4qq2p9c6/qt4qq2p9c6.pdf .

Elzeyadi, I. M. K. (2002). Designing for Indoor Comfort: A Systemic Model for Assessing Occupant Comfort in Sustainable Office Buildings. In Proceedings of the 26th National Passive Solar Conference, Nevada, USA, 1–13.

Enescu, D. (2017). A Review of Thermal Comfort Models and Indicators for Indoor Environments. *Renewable and Sustainable Energy Reviews*. 79(2017): 1353–1379. DOI: https://doi.org/10.1016/j.rser.2017.05.175

Fanger, P. O. (1970). Thermal Comfort: Analysis and Applications in Environmental Engineering. New York: McGraw-Hill.

Felix, M., & Elsamahy, E. (2017). The Efficiency of Using Different Outer Wall Construction Materials to Achieve Thermal Comfort in Various Climatic Zones. *Energy Procedia*, 115: 321–331. DOI: https://doi.org/10.1016/j.egypro.2017.05.029

Ghaffarianhoseini, A., Ghaffarianhoseini, A., Berardi, U., Tookey, J., Li, D. H. W., & Kariminia, S. (2016). Exploring The Advantages and Challenges of Double-Skin Facades (DSFs). *Renewable and Sustainable Energy Reviews.* 60: 1052-1065. DOI: https://doi.org/10.1016/j.rser.2016.01.130

Givoni, B. (1998). Climate Considerations in Building and Urban Design. New York: John Wiley & Sons.

Hosseini, S. M., Mohammadi, M., & Guerra-Santin, O. (2019). Interactive Kinetic Façade: Improving Visual Comfort Based on Dynamic Daylight and Occupant's Positions By 2D And 3D Shape Changes. *Building and Environment*. 165: 106396. DOI: https://doi.org/10.1016/j.buildenv.2019.106396

Hosseini, S. M., Mohammadi, M., Rosemann, A., Schröder, T., & Lichtenberg, J. (2019). A Morphological Approach for Kinetic Façade Design Process to Improve Visual and Thermal Comfort: Review. *Building and Environment*. 153: 186–204. DOI: https://doi.org/10.1016/j.buildenv.2019.02.040

Iyendo, T. O., Akingbaso, E. Y., Alibaba, H. Z., & Özdeniz, M. B. (2016). A Relative Study of Microclimate Responsive Design Approaches to Buildings in Cypriot Settlements. *A/Z ITU Journal of the Faculty of Architecture*. 13(1): 69–81. DOI: https://doi.org/10.5505/itujfa.2016.51423

Jelle, B. P., Breivik, C., & Røkenes, H. D. (2012). Building Integrated Photovoltaic Products: A State-Of-The-Art Review and Future Research Opportunities. *Solar Energy Materials & Solar Cells*. 100: 69-96. DOI: https://doi.org/10.1016/j.solmat.2011.12.016

Kim, H., Asl, M. R., & Yan, W. (2015). Parametric BIM-Based Energy Simulation for Buildings with Complex Kinetic Façades. In Proceedings of the 33rd eCAADe Conference, Vienna, Austria, pp. 657–664. DOI: https://www.semanticscholar.org/paper/Parametric-BIM-based-Energy-Simulation-for-with-Kim-Asl/68cd43b722dbb4eccf54b6852da5be729779e2d9

Lan, L., Wargocki, P., Wyon, D. P., & Lian, Z. (2011). Effects Of Thermal Discomfort in An Office on Perceived Air Quality, SBS Symptoms, Physiological Responses, And Human Performance. *Indoor air*, 21(5): 376-390. DOI: https://doi.org/10.1111/j.1600-0668.2011.00714.x

Lu, W. (2022). Dynamic Shading and Glazing Technologies: Improve Energy, Visual, And Thermal Performance. *Energy and Built Environment*, 5(2): 211–221. DOI: https://doi.org/10.1016/j.enbenv.2022.09.004

Manu, S., Shukla, Y., Rawal, R., Thomas, L. E., & De Dear, R. (2016). Field Studies of Thermal Comfort Across Multiple Climate Zones for The Subcontinent: India Model for Adaptive Comfort

(IMAC). *Building and Environment*, 98: 55–70. DOI: https://doi.org/10.1016/j.buildenv.2015.12.019

Manzano-Agugliaro, F., Montoya, F. G., Sabio-Ortega, A., & García-Cruz, A. (2015). Review Of Bioclimatic Architecture Strategies for Achieving Thermal Comfort. *Renewable and Sustainable Energy Reviews*. 49: 736–755. DOI: https://doi.org/10.1016/j.rser.2015.04.095

Martinelli, L., & Matzarakis, A. (2017). Influence Of Height/Width Proportions on The Thermal Comfort of Courtyard Typology for Italian Climate Zones. *Sustainable Cities and Society*. 29: 97–106. DOI: https://doi.org/10.1016/j.scs.2016.12.004

Mirrahimi, S., Mohamed, M. F., Haw, L. C., Ibrahim, N. L. N., Yusoff, W. F. M., & Aflaki, A. (2016). The Effect of Building Envelope on The Thermal Comfort and Energy Saving for High-Rise Buildings in Hot-Humid Climate. *Renewable and Sustainable Energy Reviews*. 53: 1508–1519. DOI: https://doi.org/10.1016/j.rser.2015.09.055

Muhaisen, A. S., & Gadi, M. B. (2006). Shading Performance of Polygonal Courtyard Buildings. *Building and Environment*. 41(8): 1050-1059. DOI: https://doi.org/10.1016/j.buildenv.2005.04.027.

Nicol, F., & Humphreys, M. (2010). Derivation Of the Adaptive Equations for Thermal Comfort in Free-Running Buildings in European Standard EN15251. *Building and environment*. 45(1): 11-17. DOI: https://doi.org/10.1016/j.buildenv.2008.12.013

Olgyay, V. (1963). Design with Climate: Bioclimatic Approach to Architectural Regionalism. Princeton, NJ: Princeton University Press.

Oseland, N. A. (1994). A Comparison of The Predicted and Reported Thermal Sensation Vote in Homes During Winter and Summer. *Energy and Buildings*. 21(1): 45–54. DOI: https://doi.org/10.1016/0378-7788(94)90015-9

Panopoulos, K., & Papadopoulos, A. M. (2017). Smart Facades for Non-Residential Buildings: An Assessment. *Advances in Building Energy Research*. 11(1): 26–36. DOI: https://doi.org/10.1080/17512549.2015.1119058

Prieto, A., Knaack, U., Auer, T. & Klein, T. (2018). Passive Cooling & Climate Responsive Façade Design: Exploring the Limits of Passive Cooling Strategies to Improve the Performance of Commercial Buildings in Warm Climates. *Energy and Buildings*. 175: 30–47. DOI: https://doi.org/10.1016/j.enbuild.2018.06.016.

Ren, J., Yang, J., Zhang, Y., Xiao, X., Xia, J. C., Li, X., & Wang, S. (2022). Exploring Thermal Comfort of Urban Buildings Based on Local Climate Zones. *Journal of Cleaner Production*. 340: 130744. DOI: https://doi.org/10.1016/j.jclepro.2022.130744

Salah, F., & Kayili, M. T. (2022). Responsive Kinetic Façade Strategy and Determination of The Effect on Solar Heat Gain Using Parametric BIM-Based Energy Simulation. *Journal of Green Building*. 17(1): 71–88. DOI: https://doi.org/10.3992/jgb.17.1.71

Salah, F., & Tuna Kayılı, M. (2021). Identifying Retrofitting Strategies for Access to Energy Efficient Building Design in Existing Buildings. *Periodica Polytechnica Architecture*. 52(6): 1–10. DOI: https://doi.org/10.3311/ppar.16909

Seppanen, O., Fisk, W. J., & Lei, Q. H. (2006). Room Temperature and Productivity in Office Work. www.escholarship.org/content/qt9bw3n707/qt9bw3n707.pdf,(2006). Accessed 14 March 2025.

Sheliahovich, N. (2011). Bioclimatic Architecture: Brief History and Future of The Phenomenon. Semantic Scholar. 88–91. https://elib.grsu.by/katalog/184667-423959.pdf. Accessed 5 March 2025.

Shen, H., Tzempelikos, A., Atzeri, A. M., Gasparella, A., & Cappelletti, F. (2015). Dynamic Commercial Façades Versus Traditional Construction: Energy Performance and Comparative Analysis. *Journal of Energy Engineering*, 141(4): 04014041. DOI: https://doi.org/10.1061/(ASCE)EY.1943-7897.0000225

Singh, M. K., Mahapatra, S., & Teller, J. (2015). Development Of Thermal Comfort Models for Various Climatic Zones of North-East India. *Sustainable Cities and Society*. 14: 133–145. DOI: https://doi.org/10.1016/j.scs.2014.08.011

Soudian, S., & Berardi, U. (2019). Assessing the Effect of Night Ventilation on PCM Performance in High-Rise Residential Buildings. *Energy and Buildings*. 186: 336-343. DOI: https://doi.org/10.1177/1744259119848128.

Taleghani, M., Tenpierik, M., Kurvers, S., & Van Den Dobbelsteen, A. (2013). A Review into Thermal Comfort in Buildings. *Renewable and Sustainable Energy Reviews*. 26: 201–215. DOI: https://doi.org/10.1016/j.rser.2013.05.050

Teixeira, H., Rodrigues Moret, A., Aelenei, D., & Gomes, M. G. (2025). Literature review of solar control smart building glazing: Technologies, performance, and research insights. *Building and Environment*, Article 112784. DOI: https://doi.org/10.1016/j.buildenv.2025.112784

Teixeira, H., Moret Rodrigues, A., Aelenei, D., & Gomes, M. G. (2024). Simulation-based evaluation of the impact of an electrochromic glazing on the energy use and indoor comfort of an office room. *Energies*, 17(9): 2110. DOI: https://doi.org/10.3390/en17092110

TS 825. (2008). Thermal Insulation Requirements for Buildings TS 825. Turkish Standards Institution, Ankara, ICS 91.120, 1–80.

Tzempelikos, A., & Athienitis, A. K. (2007). The Impact of Shading Design and Control on Building Cooling and Lighting Demand. *Solar Energy*. 81(3): 369-382. DOI: https://doi.org/10.1016/j.solener.2006.06.015

UNEP. (2020). Global Status Report for Buildings and Construction: Towards A Zero-Emission, Efficient, and Resilient Buildings and Construction Sector. United Nations Environment Programme. https://globalabc.org/resources/publications/2020-global-status-report-buildings-and-construction. Accessed 17 April 2025.

Valinejadshoubi, M., Moselhi, O., Bagchi, A., & Salem, A. (2020). Development of an IoT and BIM-Based Automated Alert System for Thermal Comfort Monitoring in Buildings. *Sustainable Cities and Society*. 66: 103265. DOI: https://doi.org/10.1016/j.scs.2020.102602

Wu, C. (2022). Energy performance analysis of kinetic façades by climate zones. In Advanced Materials in Smart Building Skins for Sustainability: From Nano to Macroscale. 149–165. Springer. DOI: https://doi.org/10.1007/978-3-031-09695-2_7

Xiao, X., et al. (2025). Shading effects on building energy performance: A multi-city analysis. *Results in Engineering*. Advance online publication. https://www.sciencedirect.com/science/article/pii/S2590123025029330

Yang, S., Cannavale, A., Prasad, D., Sproul, A., & Fiorito, F. (2019). Numerical Simulation Study Of BIPV/T Double-Skin Facade for Various Climate Zones in Australia: Effects on Indoor Thermal Comfort. *Building Simulation*. 12(1): 51–67. DOI: https://doi.org/10.1007/s12273-018-0489-x.