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Optimization of the Performance of Double-Skin Façades Across Six Climates: Effects of Orientation, Blinds, and Overhangs on Energy Efficiency and Carbon Emissions

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Abstract

The building sector accounts for nearly 40% of global energy consumption and over one-third of energy-related carbon emissions. Therefore, it is vital to adopt low-carbon design strategies. Double-Skin Façades (DSFs) offer significant potential to improve energy efficiency through the dynamic control of heat and daylight. This study evaluates the combined effects of building orientation, fixed shading devices, and adjustable blinds on the performance of DSFs across six cities representing diverse climate types: Phoenix, Stockholm, Kuala Lumpur, London, Cape Town, and Tokyo. Using a model developed in DesignBuilder, 852 scenarios were simulated with 5-min time steps over a full year. The results show that optimal orientation depends on the climate and that cooling load may be reduced up to 59%, with CO_2 emission savings up to 11.7% compared to a base south-facing configuration. External blinds outperformed internal blinds in reducing the cooling demand, reaching reductions of up to 27.7% in hot climates, though often increasing the heating load in cold climates. Combining overhangs and external blinds provided additional cooling savings in some cases but was generally less effective than external blinds alone. The findings highlight the importance of climate-specific DSF designs, with orientation and external blinds being the most effective strategies for reducing operational energy use and emissions.

Keywords: double-skin façade (DSF); building energy efficiency; shading devices; sustainable buildings; façade optimization

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1. Introduction

Global awareness of climate change has led to significant international agreements. In particular, the outcomes from COP 29 aim for a 43% reduction in global greenhouse gas emissions by 2030 in comparison to 2019 levels [1]. The building sector plays a crucial role, accounting for nearly 40% of global energy consumption [2,3]. According to the United Nations Environment Program (UNEP), emissions from building operations reached a record high in 2019, representing around 38% of energy-related CO_2 emissions. In order to comply with the targets of COP 29, the building sector must implement low-carbon technologies and efficient practices to achieve a 50% reduction in direct emissions by 2030 and reach net-zero emissions by 2050. Furthermore, COP 29 stresses the need to triple renewable energy capacity and double energy efficiency improvements to effectively combat climate change [1]. Buildings are major drivers of energy use and emissions,

and while Nearly Zero-Energy Buildings (NZEBs) can reduce these impacts, their wider adoption is limited by cost and regulatory barriers [4]. Double-Skin Façades (DSFs) have emerged as useful strategies for developing energy-efficient buildings with high indoor environmental quality. These systems consist of two skins or façades with an intermediate cavity in which air can flow, facilitating the dynamic control of heat and daylight [5].

However, despite numerous investigations, most existing studies evaluate DSFs under limited climatic conditions or examine isolated parameters such as shading geometry, blind position, or airflow path. A more comprehensive, climate-adaptive assessment is still lacking. Accordingly, the present study aims to quantify the combined effects of building orientation, fixed shading devices, and adjustable blind placement on the energy performance and CO_2 emissions of DSFs across six representative Köppen climate zones. Through annual simulations, this work seeks to determine optimal façade configurations for various climates and to support global carbon-mitigation goals through façade-level design optimization.

1.1. Literature Review

Recent reviews on dynamic façade (DF) systems have emphasized their transformative role in achieving sustainable building performance, highlighting energy-saving potentials of up to 50% and CO_2 emission reductions approaching 40% compared with conventional static envelopes [6]. In this sense, DSFs can reduce the heating, cooling and lighting energy demand of a building. Moreover, integrating passive control technologies into the DSF, such as shading devices and blinds, optimizes their performance, allowing to minimize energy consumption and carbon emissions [7]. An optimal DSF design for an office building in Tehran, Iran, was identified through dynamic simulations of several configurations, shading options, and ventislation strategies. It was found that a box model with external louver shading maximized thermal comfort, while reaching a reduction in energy consumption from 7.9% to 14.8%. Although operational carbon emissions could decrease by 14–17%, embodied carbon could increase by 23.3–47% [8]. Complementary to this broader trend, machine-learning-based studies on DSFs have begun addressing the challenge of maintaining optimal indoor temperature and airflow control [9]. One such study applied a random-forest optimization algorithm to determine the best window-opening angles in DSFs based on meteorological parameters such as outdoor temperature, radiation, and dew point. The model achieved an accuracy exceeding 93%, demonstrating the potential of AI-driven control systems to improve DSF energy efficiency, comfort, and emission reduction. The influence of cavity segmentation on energy consumption and natural ventilation in Double-Skin Façades for high-rise buildings in hot-dry climates was investigated by Rezaie et al. [10] Using DesignBuilder simulations combined with a hybrid HGS–GB (Hunger Game Search–Gradient Boosting) algorithm, it was demonstrated that segmentation patterns exert a significant impact on DSF performance, with prediction accuracies (R^2) exceeding 0.99. The study indicated that machine-learning-based optimization can effectively enhance the thermal efficiency of DSF.

A recent study in China explored the performance of a multi-sectional DSF system integrating Venetian blinds, ventilation valves, and a light shelf, designed to adapt dynamically to varying climatic conditions. Using validated EnergyPlus v9.1 and Radiance simulation models supported by experimental data, the research evaluated three façade configurations across five Chinese climate zones. Results showed that the advanced DSF system achieved the highest energy efficiency, reducing annual energy use intensity by up to 17.1%, while also significantly improving indoor daylight quality and maintaining acceptable thermal comfort [11]. The performance of mechanically ventilated DSFs in temperate climates has been examined through experimentally validated simulations [12]. In the Irish climate, two

seasonal control modes were assessed: a ventilation-prioritized strategy providing daytime airflow and nighttime insulation, and a heating-prioritized mode supplying daytime heat while insulating at night. Applying these adaptive strategies month by month reduced total energy use by about 36% compared with a conventional double-glazed façade.

Alberto et al. [13] used DesignBuilder/EnergyPlus simulations for Southern European climates and found airflow path to be the key DSF parameter, with multi-storey designs cutting HVAC demand approximately by 30%, and orientation causing up to 40% variation in energy use. The performance of DSF systems, particularly regarding thermal management and daylighting, has been explored with the integration of both interior and exterior blinds. Blinds are a critical passive control element in improving the thermal and energy performance of DSFs. Slat blinds are widely adopted in office buildings for their ability to reduce cooling and heating loads while minimizing visual discomfort [14]. Yoon et al. [15] evaluated the retrofitting of a DSF to replace thermally inefficient balcony windows in a 25-storey residential building in Seoul. Through a calibrated simulation model, heating energy savings of up to 30% were observed on the 21st storey, with the lowest consumption recorded on the first storey and the highest on the top floor, a pattern attributed to height-dependent variations in temperature, wind speed, and pressure. A buffer-type DSF with slat blinds was modeled by Kim et al. [7] using EnergyPlus, aiming to increase energy efficiency by optimizing light penetration and thermal comfort through the strategic use of blinds. The impact of blinds and natural ventilation on heating, cooling, and lighting loads was evaluated, finding potentially significant energy savings up to 40% for heating, 2% for cooling, and 52% for lighting energy consumption. Fixed shading devices (SDs) play a vital role in improving energy efficiency, particularly in hot climates. Overhangs are a commonly utilized passive design method for reducing solar heat gains, particularly through glazed surfaces, and are essential for enhancing building energy performance. Overhangs decrease direct solar radiation entering a structure in warmer months by offering exterior shade, therefore lowering cooling loads [16]. A comprehensive evaluation of 1485 scenarios involving various fixed external SDs such as overhangs, louvers, and egg-crate variations was conducted, focusing on parameters like orientation, glazing type, and window-to-wall ratio. Optimal configurations can reduce cooling energy consumption by 37% to 49% with high-performance glazing and by 73% to 78% with low-performance glazing, while total annual energy consumption decreased by approximately 33% to 70%, underscoring the significance of effective SD design in office buildings [17].

A study in Istanbul optimized a DSF-integrated high-rise office façade using air-driven conduits, achieving a 66% Energy Use Intensity reduction while meeting ASHRAE ventilation standards. The results highlight the potential of airflow-focused design for energy-efficient, naturally ventilated buildings [18]. In South Korea, validated simulations showed that combining the DSF with integrated solar PV panels can reduce cooling, heating, and lighting energy use by up to 44%, with a payback period of around 15 years. Despite this, the DSF retrofit offered strong potential for energy savings, CO_2 reduction, and increased property value [19]. Control strategies for naturally ventilated DSF vary widely in performance and cost. A review article compared five approaches found that hybrid systems achieved the highest annual energy saving by 47.9%, followed by passive (36.7%), automatic (32.1%), active (32%), and manual systems (27.3%) [20]. The orientation of a building has a profound effect on its energy performance, particularly in buildings with DSFs. Solar exposure, wind patterns, and thermal behavior vary significantly with the direction a façade faces, impacting both cooling and heating loads across different seasons [14]. Contrary to the conventional belief that south-facing orientations yield the best results, studies show that optimal orientation may vary based on climatic conditions. For example, in Montreal, west-facing DSFs have demonstrated superior performance in

energy production during summer design days, as the hourly distribution of solar radiation skews towards the afternoon. This finding highlights the importance of considering local solar irradiation patterns when determining DSF orientation to further enhance energy efficiency [21].

A case study in Spain analyzed energy consumption and savings from shading solutions in two climate zones: Bilbao and Seville. The study evaluated various orientations and perforation rates of shading devices, using DesignBuilder to calculate solar radiation gains based on characterized monthly climate data for both zones. Results indicated that cooling needs to be increased with solar radiation: Seville exhibited significantly higher cooling demands, with peak values between 2300 and 10,000 kWh/year compared to Bilbao's 750 to 3700 kWh/year. Conversely, south-facing façades required less heating energy, especially in Seville, with peak heating values of 0 to 1500 kWh/year, while Bilbao ranged from 1200 to 3500 kWh/year. This underscores the importance of shading solutions in enhancing energy efficiency across different climatic conditions [22]. A recent study conducted in Mardin's hot-arid climate analyzed an office façade with a dynamic triangular-cell shading system using Grasshopper and ClimateStudio, showing that adaptive shading notably enhanced daylight performance and glare control [23]. In a study conducted in Dhaka's tropical climate, various west-facing façade configurations, including louvres, fins, overhangs, and egg-crate systems, were evaluated using Grasshopper and ClimateStudio simulations. Results indicated that egg-crate shading provided the most balanced performance in terms of daylight and thermal comfort, with optimized configurations achieving over 12% higher daylight autonomy compared to conventional designs [24].

A study in Wuhan proposed a Double Plant-Skin Façade (DPSF) to address summer performance limitations of conventional DSFs. By incorporating a living wall and external ventilation, the DPSF lowered indoor temperatures by up to 3.7 °C and reduced cooling energy demand by about 16%, primarily through enhanced heat exchange and evaporative cooling [25]. Recent years have seen a clear research shift toward adaptive, lightweight, and smart façade systems that merge responsive controls with advanced materials. Spanodimitriou et al. [26] reviewed flexible and lightweight façade technologies and showed that such systems substantially reduce embodied energy and retrofit cost while improving thermal adaptability across diverse climates. Building on this, Bahdad et al. [27] proposed a parametric optimization framework for dynamic louver shading integrated within DSF-Insulated Glazed Units (DSF-IGUs). Using multi-objective genetic algorithms, they balanced daylight autonomy, thermal comfort, and energy performance under tropical conditions, achieving an average 25–28% reduction in energy-use intensity while maintaining optimal daylight uniformity. Furthermore, Lionar et al. [28] reported a study on smart responsive façades employing shape-memory alloys and low-emissivity coatings controlled through AI-based multi-objective optimization. These adaptive envelopes automatically adjusted optical and thermal properties, leading to 30–35% HVAC-energy savings without compromising visual comfort.

1.2. Research Gap and Objectives

Although numerous studies have examined DSFs with shading devices or blinds, most have focused on these elements separately and within limited climatic contexts. The combined influence of building orientation, fixed shading devices, and blind placement particularly across diverse Köppen climate zones remains underexplored. Existing research often targets one or two locations, limiting the applicability of findings to broader design practice. Moreover, while south-facing orientations are commonly assumed to be optimal, recent evidence suggests that climate-specific factors may lead to different orientation requirements. To address this need, the present study systematically investigates the

combined influence of building orientation, fixed shading devices, and adjustable blind placement on the energy performance and CO_2 emissions of DSFs across various climates. The analysis covers six cities representing distinct climate types, ranging from hot desert to cold continental and tropical rainforest climates using year-round simulations. The objectives are to:

1. Quantify the impact of these parameters on cooling and heating loads as well as operational CO_2 emissions.
2. Compare performance outcomes across diverse climates.
3. Identify optimal, climate-specific DSF configurations that maximize energy efficiency and emissions reduction.

By providing such comparative insights, this work aims to refine façade design strategies for sustainable building practice and contribute to achieving global carbon mitigation targets.

2. Materials and Methods

Firstly, the climate conditions and locations studied will be presented. Then, the development of the building model, as well as the scenarios studied, will be explained, finishing this section with the validation of the model against literature data.

2.1. Climate Conditions and Study Locations

As the performance of DSFs varies significantly depending on climate conditions [29], six locations with different climate types were selected to represent a wide range of environmental conditions and thus of heating and cooling loads, and CO_2 emissions: Phoenix, Stokholm, Kuala Lumpur, London, Cape Town and Tokyo. The climate classifications are based on the Köppen Climate Classification system [30], a widely accepted method for categorizing global climates based on temperature and precipitation patterns. Table 1 summarizes the key geographical and climate characteristics of each location including latitude, elevation, atmospheric pressure, and dry bulb temperature ranges. Phoenix, USA, characterized by a hot desert climate (BWh), was selected for its extremely hot summers and mild winters, dominated by solar radiation and cooling demand. Stockholm, Sweden, with a cold humid continental climate (Dfb), was selected to provide insight into the performance of DSFs in cold climates with significant heating demand during long winters. Kuala Lumpur, Malaysia, possesses a tropical rainforest climate (Af) with high temperature and humidity all year round, an interesting case for cooling and dehumidification in a consistently hot and humid environment. London, UK, with a temperate oceanic climate (Cfb), offers the possibility of analyzing balanced heating and cooling loads in a moderate climate with frequent rainfall. Cape Town, South Africa, with a Mediterranean climate (Csb) characterized by warm and dry summers, and mild and wet winters, allows the analysis of the performance of DSFs across seasonal variations. Finally, Tokyo, Japan, with a humid subtropical climate (Cfa) with hot and humid summers, and mild winters, may give insight into the effects of significant seasonal changes on energy efficiency.

Table 1. Climate Characteristics for the selected cities [31].

City	Climate Type (Köppen)	Latitude	Longitude	Elevation (m)	Atmospheric Pressure (kPa)	Dry Bulb Temperature (°C)
Phoenix, USA	Hot desert (BWh)	33.44° N	111.99° W	337	97.3	4 °C (winter) to 42 °C (summer)
Stockholm, Sweden	Cold humid continental (Dfb)	59.37° N	17.90° E	14	101.2	−5 °C (winter) to 22 °C (summer)
Kuala Lumpur, Malaysia	Tropical rainforest (Af)	3.14° N	101.69° E	22	101.1	22 °C to 33 °C year-round

Table 1. *Cont.*

City	Climate Type (Köppen)	Latitude	Longitude	Elevation (m)	Atmospheric Pressure (kPa)	Dry Bulb Temperature (°C)
London, UK	Temperate oceanic (Cfb)	51.52° N	0.10° W	43	100.8	2 °C (winter) to 22 °C (summer)
Cape Town, South Africa	Mediterranean (Csb)	33.97° S	18.60° E	42	100.8	7 °C (winter) to 28 °C (summer)
Tokyo, Japan	Humid subtropical (Cfa)	35.55° N	139.78° E	9	101.2	0 °C (winter) to 31 °C (summer)

2.2. Development of the Building Model

The building model used in this study is based on a single-storey structure with a floor area of 48 m^2 and a height of 2.7 m. This model was adapted from the BESTEST (Building Energy Simulation Test) project, developed as part of the ASHRAE Standard 140-2020–Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs [32,33]. Although the BESTEST model provides a standardized approach for evaluating energy performance, the model had to be adapted for this study. Specifically, the windows in the original BESTEST model were replaced with DSFs to align with the scope of this work. While this modification ensured the relevance of the model to façade-performance analysis, it also introduced certain differences relative to the original BESTEST baseline. Replacing the single-glazed windows with a Double-Skin Façade (DSF) altered the façade thermal inertia, solar-heat-gain characteristics, and dynamic response to external temperature fluctuations. Consequently, the absolute energy-consumption values cannot be directly compared with those of the standard BESTEST case. Nevertheless, the relative variations observed among different orientations, shading configurations, and blind placements remain valid and comparable. This adjustment therefore provides a more comprehensive framework for assessing façade-related energy performance while maintaining methodological consistency with the BESTEST reference model.

Figure 1 depicts the wall configuration, consisting of four layers: brickwork as the outer surface, XPS (extruded polystyrene with CO_2 blowing) for insulation, a concrete block layer, and gypsum plastering as the inner surface. The thermal properties and thicknesses of these materials are detailed in Table 2. The simulations were performed using DesignBuilder, which operates on the EnergyPlus engine and provides an integrated environment for modeling both thermal and daylighting performance. A zone-level Packaged Terminal Heat Pump (PTHP) was implemented to supply heating and cooling exclusively through electricity from the grid. The heating and cooling seasonal coefficients of performance (COP) were fixed at 2.00 and 2.50, respectively, based on the DesignBuilder PTHP template. The supply-air temperature was limited to 35 °C for heating and 12 °C for cooling, with humidity ratios of 0.016 g/g and 0.008 g/g, respectively. The PTHP fan was configured to cycle with the compressor, and no auxiliary fossil-fuel heating or defrost mode was modeled. This configuration ensures consistent and reproducible results when analyzing façade-driven variations in energy demand across climates. The DSF examined in this study was modeled as a double-glazed bronze–clear system from the EnergyPlus materials dataset (Dbl Bronze 6 mm/6 mm Air). The outer pane consisted of 6 mm Generic Bronze glass, the inner pane of 6 mm Generic Clear glass, and the interlayer was a 6 mm air gap. The glazing unit exhibited a U-value of 3.09 $W/m^2 \cdot K$, a solar-heat-gain coefficient (SHGC) of 0.504, direct solar transmission 0.375, and visible transmittance 0.473.

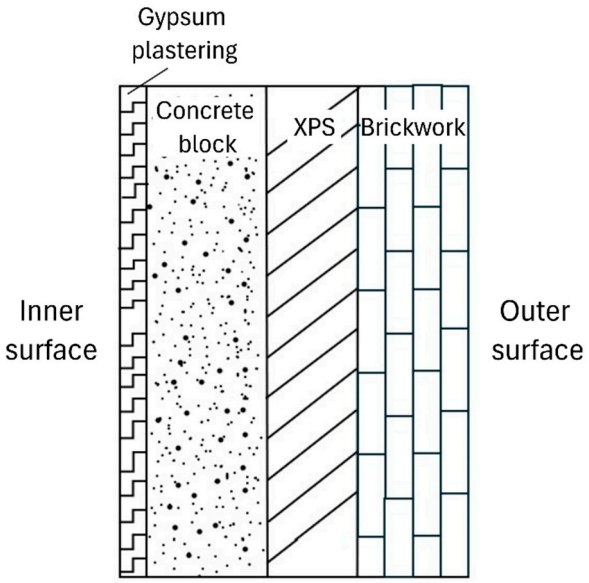


Figure 1. Wall configuration.

Table 2. Building construction materials.

Component	Material	Thickness (m)	Conductivity (W/m·K)	Specific Heat (J/(kg·K))	Density (kg/m^3)	Thermal Resistance (m^2·K/W)
External wall (outer to inner)	Brickwork	0.1	0.84	800	1700	0.18
	XPS Extruded Polystyrene	0.0795	0.034	1400	35	
	Concrete Block	0.1	0.51	1000	1400	
	Gypsum Plastering	0.013	0.4	1000	1000	
Roof (outer to inner)	Asphalt	0.01	0.7	1000	2100	
	MW Glass Wool	0.1445	0.04	840	12	
	Air gap					
	Plasterboard	0.013	0.25	896	2800	

2.3. Studied Scenarios

Apart from studying the influence of the location and climate conditions, the effects of building orientation, the use of fixed shading devices and adjustable blinds were examined:

- The orientation of the DSF was modified from 0 to 360°, in 5° increments, with the aim of understanding the effect of building orientation in energy demand.
- Two configurations of window shading devices (inside and outside the DSF) were considered, as shown in Figure 2. The blinds were set to operate dynamically in response to solar radiation, activating when sunlight intensity exceeded a defined threshold to prevent overheating and reduce cooling demand [34]. The slat blind configuration was defined using the Window Shading—Slat Data object from the EnergyPlus dataset integrated in DesignBuilder. The slats were modelled as flat, equally spaced elements with width = 0.025 m, separation = 0.01875 m, thickness = 0.001 m, and blind-to-glass distance = 0.015 m. The solar reflectance of both sides of the slats was 0.8, and solar transmittance was 0.0, representing opaque metallic Venetian blinds. The default slat angle was set to 45°, corresponding to the midpoint between vertical (0°) and horizontal (90°) orientations, as defined by the DesignBuilder geometry standard. The blinds were controlled dynamically in response to vertical solar irradiance: activation occurred when incident radiation exceeded 180 W/m^2, and retraction occurred when it fell below 140 W/m^2, following the built-in DesignBuilder hysteresis algorithm.

- Finally, the interaction between blinds and overhangs was studied by introducing an overhang, as shown in Figure 3. A fixed horizontal overhang of 1 m length was installed directly above the glazing lintel, with a tilt angle of 90°, corresponding to a fully horizontal configuration. This geometry aligns with the low-position configuration described by Krarti [16], where dynamic overhangs operate between 90° and 135°, with 90° representing the fully extended shading position that effectively blocks high-angle solar radiation during summer while allowing low-angle solar gains in winter. The purpose was to enhance thermal and energy performance by controlling the amount of solar radiation that reaches the façade, with the aim of decreasing cooling demand in hot and temperate regions and increasing comfort by minimizing glare.

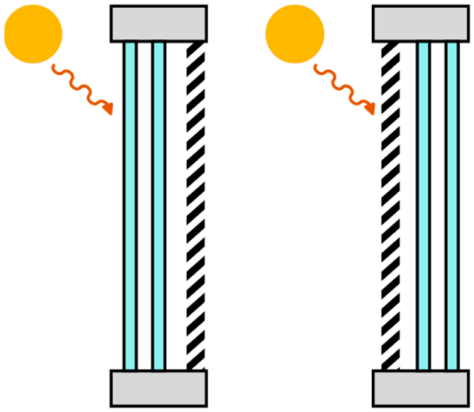


Figure 2. Positioning of shading devices: inside and outside the zone (DSF) [35]. (**left**) Inside (**right**) Outside.

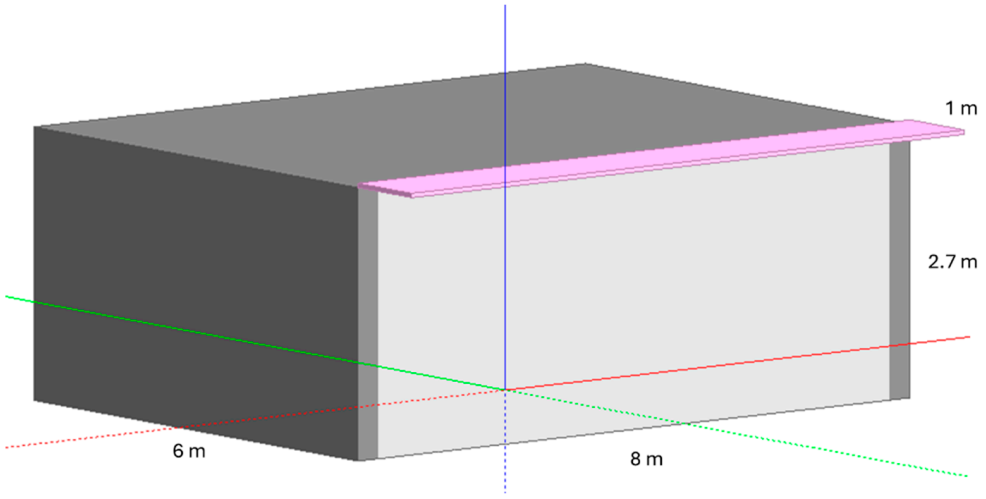


Figure 3. Building model with an overhang.

These configurations resulted in a total of 852 different simulation scenarios. This number was obtained by combining six climatic locations, seventy-one façade orientations (evaluated every 5° from 0° to 355°), and two blind-control types (internal and external), resulting in 852 configurations. The fixed overhang projection was applied uniformly to all cases and therefore did not add an additional variable. All other building parameters (wall assembly, glazing, HVAC system, and control settings) were kept constant to isolate the effects of orientation and blind position.

The energy demand of each configuration, including heating and cooling loads, was analyzed; along with the corresponding operational CO_2 emissions. Simulations were

conducted using a 5-min time step, ensuring high temporal resolution for dynamic façade responses and control operations. Each case was evaluated over a full calendar year (1 January–31 December) to account for seasonal variations in solar radiation, thermal behavior, and the performance of shading devices integrated into the DSF. Figure 4 shows a graphical summary of the methodology followed throughout this work.

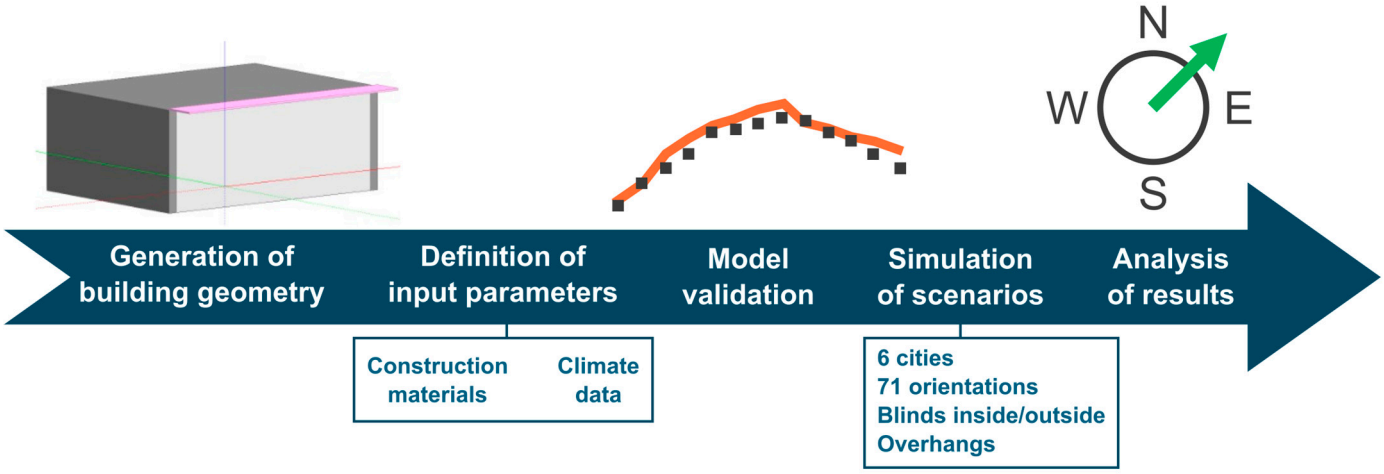


Figure 4. Methodology followed in this study for building simulation.

The emission factors used to calculate CO_2 emissions were obtained from the internal database of DesignBuilder; applying national datasets when available and generic factors obtained from IPCC and IEA when local datasets were not available. The emission factors used are collected in Table 3.

Table 3. Carbon dioxide emission factors used in the simulations.

City	CO_2 Emission Factor (kg CO_2/kWh)	Data Source (DesignBuilder v7.3)
Phoenix	0.476	USA Department of Energy
Stockholm	0.606	Generic database
Kuala Lumpur	0.606	Generic database
London	0.519	UK National Calculation Method
Cape Town	0.606	Generic database
Tokyo	0.606	Generic database

2.4. Validation of the Model

To validate the introduction of blinds into the model, a building located in Tianjin, China, was simulated, using the experimental and numerical results from Liu et al. [36] for contrast. The evolution of indoor air temperature of the building with blinds during summer solstice is presented in Figure 5, where it may be observed that the present work follows the evolution of the experimental results with great accuracy, even higher than the original numerical results at some daytimes. Statistical validation yielded RMSE = 0.40 °C, NMBE = +0.13%, and R^2 = 0.991. These indicators demonstrate an excellent level of agreement, confirming that the model reliably reproduces the experimental thermal response under the specified boundary conditions.

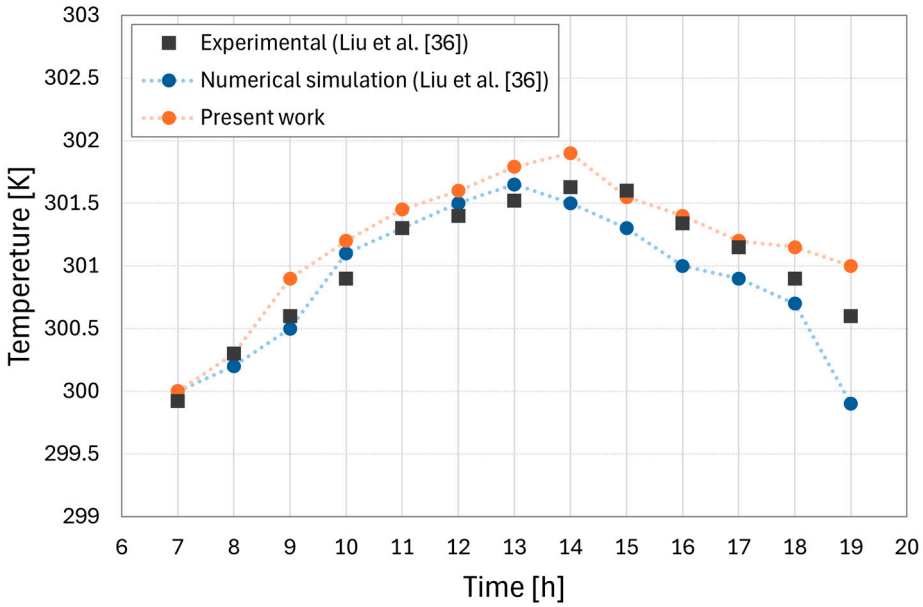


Figure 5. Comparison of Simulated Air Temperature for a Building in Tianjin during the Summer Solstice with the results from Liu et al. [36].

3. Results

This section presents the findings from the simulations conducted on the DSF system for the six locations studied, considering the orientation of the building and the use of shading devices and blind configurations. The results focus on the impacts on energy performance, cooling and heating loads, and CO_2 emissions in diverse climatic conditions.

3.1. Impact of Building Orientation

Building orientation strongly influences the annual energy performance of DSFs. Simulations revealed clear climatic contrasts among the six representative cities. Annual cooling and heating loads and CO_2 emissions by orientation for the six representative cities are presented in Figure 6. In Phoenix's hot desert climate, cooling demand dominated the energy profile, with the peak load observed when the DSF was southeast, corresponding to maximum solar exposure during afternoon hours. Heating demand was negligible, reflecting the city's mild winters. Consequently, CO_2 emissions followed a similar trend, reaching their highest levels under northwest exposure and their lowest when the DSF was oriented north. Across all climates, the orientation-dependent performance patterns reflected local solar geometry and seasonal behavior. Northern cities such as Stockholm and London displayed higher sensitivity in heating loads, with optimal orientations aligning the DSF toward the south and southeast, maximizing winter solar gains. In contrast, Kuala Lumpur and Phoenix, both characterized by year-round solar intensity, benefited from orientations minimizing direct exposure during peak hours, highlighting the dominance of cooling-driven behavior. Intermediate climates such as Cape Town and Tokyo showed more balanced profiles, where the orientation shifts modestly influenced annual loads and emissions. The results emphasize that optimal DSF orientation is climate-dependent: minimizing cooling exposure in hot climates and maximizing passive solar gains in cold ones. These findings confirm that façade orientation design plays a pivotal role in achieving energy-efficient DSF configurations across diverse latitudes.

In Stockholm's cold humid continental climate, heating dominated the energy profile, far exceeding cooling demand. Maximum heating load occurred when the DSF was oriented north-northwest, where limited solar exposure required higher indoor heating. Minimum heating demand appeared at DSF south, benefiting from direct solar gains during

winter. Cooling loads remained negligible, and CO_2 emissions followed the same trend, with the lowest annual values observed when the DSF faced south, confirming the strong seasonal dependence of façade performance in cold climates.

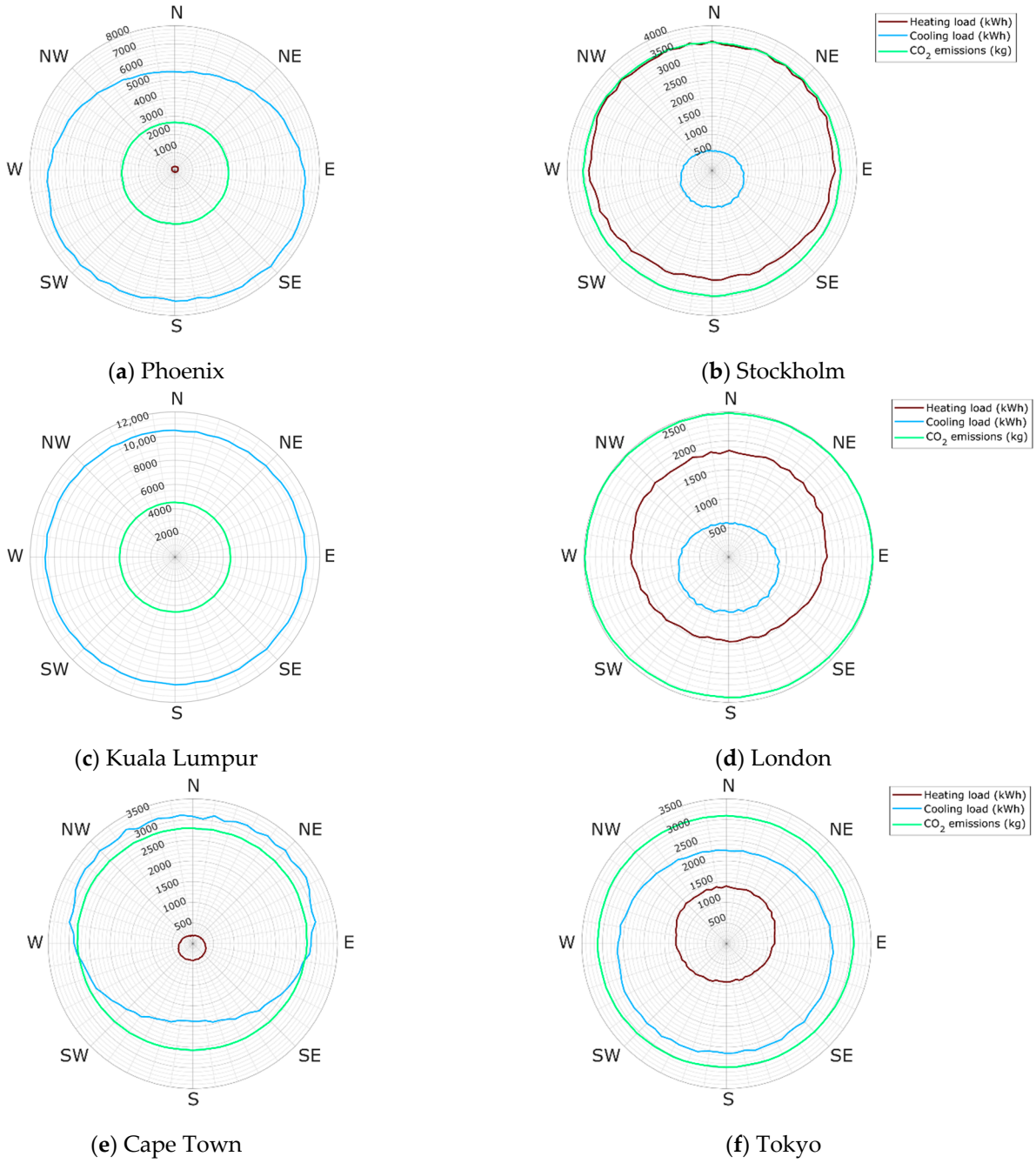


Figure 6. Annual cooling and heating loads and CO_2 emissions by orientation for the six representative cities.

In Kuala Lumpur's tropical rainforest climate, cooling demand was persistently high throughout the year due to constant solar exposure and humidity. The orientation effect was minimal—the DSF orientation of east produced the highest cooling load, while the lowest occurred at DSF north. The near-uniform CO_2 emissions across all orientations underscore the limited influence of orientation at equatorial latitudes. Consequently, design optimization in such regions should prioritize dynamic shading, high-performance glazing, and natural-ventilation strategies rather than directional façade control.

London's temperate oceanic climate exhibited a more balanced seasonal behavior. Cooling demand remained modest, while heating dominated during winter. The highest heating load occurred when the DSF faced north-northwest, decreasing steadily as the DSF approaches the south, where passive solar gains were maximized. CO_2 emissions varied proportionally with heating energy, reflecting the sensitivity of London's climate to façade exposure during the cold season.

Cape Town's Mediterranean climate showed a distinct inverse pattern compared to northern cities, as it lies in the Southern Hemisphere. The south facing DSF experienced the lowest cooling demand and CO_2 emissions, while the north-facing DSF recorded higher loads due to greater solar radiation exposure. This reversed behavior emphasizes the importance of façade orientation in southern latitudes—north-facing façades there correspond to the most solar-exposed surfaces, requiring enhanced shading. For such climates, solar-control strategies must account for the opposite solar path, while in tropical zones like Kuala Lumpur, omnidirectional shading remains more relevant.

3.2. Impact of Blinds

The analysis explored the impact of blinds installed both inside and outside the windows on the building energy performance, starting with the base model (DSF oriented to the south). By comparing the thermal behavior with internal and external blinds, significant differences were observed in terms of cooling loads, heating loads, and overall energy efficiency. External blinds, when deployed, provided effective shading by blocking solar radiation before it entered the façade cavity, reducing cooling loads, particularly in warm climates. In contrast, internal blinds, while still improving energy performance, were less effective at reducing direct solar heat gains, leading to higher cooling loads compared to external shading solutions. The influence of these blinds was evaluated across different orientations to determine the optimal configuration for minimizing energy consumption and CO_2 emissions. The cooling load, heating load, and CO_2 emissions for the selected cities are illustrated in Figure 7, Figure 8, and Figure 9, respectively. The exact values may be found in Appendix A.

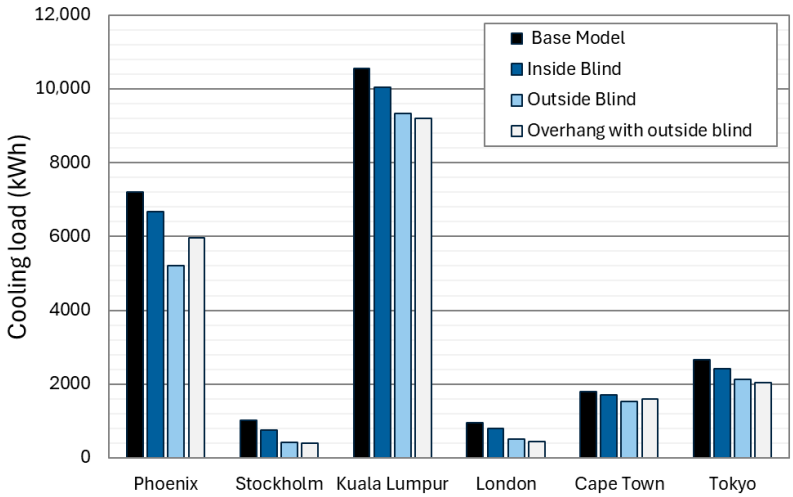


Figure 7. Effects of internal and external blinds and overhangs on cooling load.

The incorporation of blinds significantly improved the thermal and environmental performance of the DSF system across all climatic zones, though the magnitude of improvement varied by region. In every case, external blinds outperformed internal ones, confirming their superior ability to block solar radiation before it enters the façade cavity. This resulted in pronounced reductions in cooling loads, especially in warm climates such

as Phoenix, Kuala Lumpur, and Tokyo, where external shading minimized direct solar heat gain during long cooling seasons.

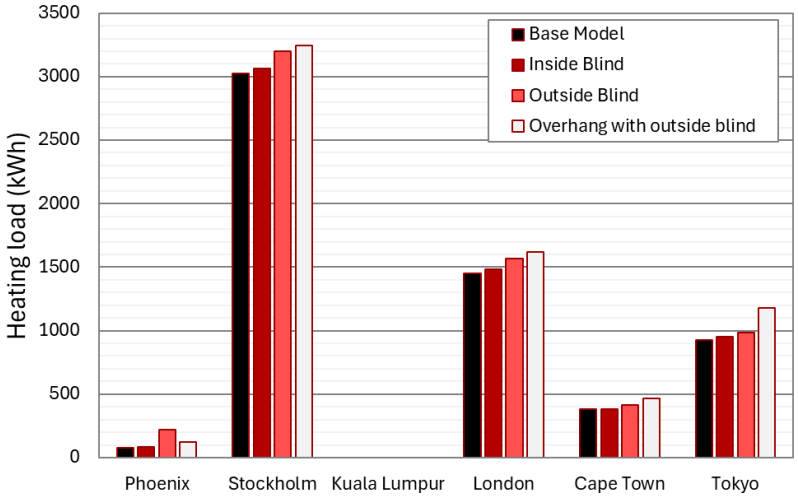


Figure 8. Effects of internal and external blinds and overhangs on heating load.

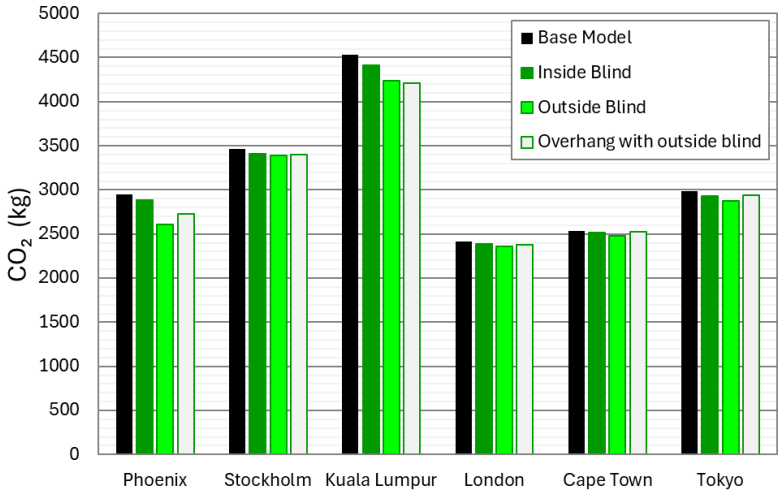


Figure 9. Effects of internal and external blinds and overhangs on CO_2 emissions.

In hot-dry regions like Phoenix, the application of external blinds achieved the highest cooling load reduction, while in humid tropical climates like Kuala Lumpur, orientation-independent solar exposure meant that shading primarily mitigated afternoon heat peaks. In temperate and mixed climates such as London and Tokyo, external blinds substantially reduced cooling demand during summer while maintaining acceptable daylight levels. In contrast, Stockholm, with its cold climate, benefited less from shading due to limited cooling needs but still recorded measurable efficiency gains during warmer months.

Heating behavior exhibited the opposite trend: across most locations, the use of blinds slightly increased winter heating load. This occurred because the blinds, while effective at blocking unwanted heat in summer, also reduced beneficial solar gains during colder months. The effect was more pronounced in Stockholm, London, and Cape Town, where passive winter solar heating plays a larger role. Conversely, in Kuala Lumpur and Phoenix, heating demand remained negligible regardless of blind configuration.

CO_2 emissions followed the same overall pattern as cooling energy: reductions were consistent in all cities, with the most notable decreases achieved through external blinds. The improvement was strongest in cooling-dominated climates, reaffirming that shading systems are especially effective where solar loads represent the dominant energy driver.

Overall, the analysis demonstrates that external blinds are the most effective passive control strategy for DSFs, offering substantial energy and carbon benefits in warm climates while only marginally affecting winter heating needs in colder ones. Future designs can further refine this balance by integrating adaptive or seasonally operable shading systems to maintain year-round efficiency.

3.3. Interaction of Blinds and Overhangs

This section analyzes the combined impact of external blinds and overhangs on building energy performance, comparing their effectiveness against the base model and the external-blind-only configuration. Table 4 collects the aggregate results for the studied locations. Initial analyses indicated that the external blind consistently outperformed the internal blind in reducing solar gains and cooling loads. Therefore, further simulations assessed the potential benefits of adding an overhang to the external-blind configuration. Both configurations, the external blind alone and in combination with an overhang significantly reduced cooling load and CO_2 emissions compared to the base case. However, the external blind alone consistently demonstrated superior performance across all climates. For instance, in Phoenix, the external blind reduced cooling demand by nearly 28%, while the addition of an overhang achieved only a 17% reduction.

Table 4. Aggregate results for the studied locations.

City	Köppen Climate Classification	Predominant Energy Demand	Cooling Demand Reduction Potential	CO_2 Savings
Phoenix	Hot desert (BWh)	Cooling	27.7%	11.7%
Stockholm	Cold humid continental (Dfb)	Heating	59.1%	2%
Kuala Lumpur	Tropical rainforest (Af)	Cooling	12.6%	7.1%
London	Temperate oceanic (Cfb)	Heating	53.8%	2.6%
Cape Town	Mediterranean (Csb)	Cooling	15.8%	2.3%
Tokyo	Humid subtropical (Cfa)	Mixed	22.9%	3.7%

This difference arises from geometric and seasonal factors. Overhangs primarily block high-angle summer sun but are less effective against low solar angles during morning and afternoon hours. In contrast, external blinds dynamically limit both direct and diffuse radiation throughout the day. The overlap between the overhang and the upper glazing restricts daylight penetration but leaves the lower portion exposed, allowing residual solar heat gain. Consequently, the blind system yields greater cooling-load reductions, particularly in regions with strong horizontal solar exposure such as Phoenix or Kuala Lumpur. In cooler climates such as Stockholm or London, the overhang slightly increased heating loads during winter by obstructing low-angle sunlight that could otherwise contribute to passive heating. This seasonal trade-off explains the smaller net energy savings when both systems were combined. CO_2 emission trends followed similar patterns, declining in all climates but more markedly for the external-blind-only configuration. Overall, while overhangs complement blinds by improving peak summer shading, external blinds remain the more effective year-round strategy, offering superior adaptability to solar angle variations across diverse climates.

The results of the present study align with and extend previous optimization-based investigations on façade performance. Bahdad et al. [27] demonstrated that integrating dynamic louver shading within DSF-IGUs in tropical climates reduced cooling loads by approximately 25–28%, showing the effectiveness of adaptive control strategies. Similarly, a study conducted in Wuhan [25] introduced a Double Plant-Skin Façade that combined vegetation and external ventilation, achieving indoor temperature reductions of up to 3.7 °C and cooling-energy savings of about 16% through enhanced evaporative and convective

exchange. In comparison, the current research achieved 27.7% cooling-load reduction in Phoenix and 12.6% in Kuala Lumpur. These results indicate that optimized passive DSF configurations, when properly oriented and equipped with simple shading devices, can achieve energy savings comparable to those of more complex adaptive façades, providing a practical and robust solution for diverse climatic conditions.

4. Conclusions

This study has provided valuable insights into the energy performance and CO_2 emissions of Double-Skin Façades across different climatic conditions. The results underscore the significant potential of DSFs as a sustainable solution in the quest for energy efficiency and reduced environmental impacts. Key conclusions drawn from the findings are as follows:

- Climatic contrasts and orientation sensitivity:

In cooling-dominated climates such as Phoenix and Kuala Lumpur, façade orientation strongly influenced annual performance, with south- and southwest-facing DSFs showing the highest solar exposure and thus the greatest cooling demand. Conversely, in heating-dominated regions like Stockholm and London, south-facing DSFs improved winter heat gains, minimizing heating energy. Cape Town displayed the inverse behavior due to its Southern Hemisphere location, where north-facing façades receive the most solar radiation.

- Shading systems and trade-offs:

External blinds emerged as the most effective passive control strategy, substantially reducing cooling loads and operational CO_2 emissions by blocking solar radiation before it entered the façade cavity. However, this shading also limited useful winter gains, slightly increasing heating loads in colder climates. This trade-off illustrates the need to balance solar control with passive heating potential, particularly in regions with mixed climatic conditions. Adaptive or seasonally controlled blinds can help manage this balance by dynamically modulating solar gains to maintain comfort and efficiency throughout the year.

- Scope and Future Directions:

This study focused on a simulation-based evaluation under standardized conditions, ensuring a controlled and comparable assessment across multiple climates. The adopted approach enabled clear identification of façade-driven effects on energy performance and CO_2 emissions. Although the methodology used in this work was validated with experimental data, more experiments could help reduce the uncertainty of the predictions. The building geometrical simplifications, although validated as an ASHRAE standard, on the other hand, allowed for the comparison of multiple configurations of strategies to study their impact on the energy performance of the building. Future research could build upon the results by integrating advanced control algorithms, adaptive shading systems, and experimental validation under real operational environments. Extending the investigation to include occupant comfort assessments and life-cycle carbon analysis would further enhance our understanding of DSF performance and long-term sustainability potential. Overall, the findings demonstrate that Double-Skin Façades, when designed and oriented strategically, can make a substantial contribution to global energy-efficiency and decarbonization targets. Continued exploration of adaptive and climate-responsive DSF systems will further strengthen their role in shaping the next generation of low-carbon, resilient buildings.

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Appendix A. Results for Cooling and Heating Loads and CO_2 Emissions for Different DSF Configurations in Selected Cities

Table A1. Cooling Load (kWh) for different DSF configurations in selected cities.

City	Base Model	Inside Blind	Outside Blind	Overhang with Outside Blind
Phoenix	7209	6678	5209	5975
Stockholm	1021	751	417	398
Kuala Lumpur	10,546	10,050	9343	9209
London	947	803	505	437
Cape Town	1804	1706	1518	1603
Tokyo	2649	2406	2127	2041

Table A2. Heating Load (kWh) for different DSF configurations in selected cities.

City	Base Model	Inside Blind	Outside Blind	Overhang with Outside Blind
Phoenix	77	81	218	122
Stockholm	3025	3066	3202	3245
Kuala Lumpur	0	0	0	0
London	1454	1484	1568	1620
Cape Town	382	385	413	466
Tokyo	927	954	984	1180

Table A3. CO_2 Emissions (kg) for different DSF configurations in selected cities.

City	Base Model	Inside Blind	Outside Blind	Overhang with Outside Blind
Phoenix	2949	2881	2604	2726
Stockholm	3464	3413	3393	3404
Kuala Lumpur	4536	4408	4237	4212
London	2419	2389	2356	2376
Cape Town	2536	2513	2478	2526
Tokyo	2985	2928	2872	2940

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