

Review

Enhancing comfort and energy efficiency in buildings: A systematic review of double skin façade performance

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Article information

Sent: Jul 1, 2026

Accepted: Sep 1, 2026

Published: Sep 4, 2026

Abstract: Double skin façades (DSFs) have emerged as a promising architectural solution for enhancing building energy efficiency and occupant comfort. This comprehensive review synthesises current research on various DSF configurations, including box-window, corridor, shaft-box, double-glazed glass, multi-story, and curved types. The study examines the thermal, energy, and ventilation performance of DSFs across diverse climatic conditions and building types. This study examined 80 articles from 2019 to present. A systematic analysis of recent literature reveals that DSFs can significantly reduce heating and cooling energy demands by 15–59%, depending on design parameters and local climate. The review highlights the adaptability of DSFs in different contexts, from tropical to cold climates, and their potential for integration with renewable energy systems. Key factors influencing DSF performance are identified, including cavity width, ventilation strategies, and shading devices. The study also notes trends towards climate-specific optimisation, multi-functional façade designs, and the integration of smart technologies for adaptive control. While DSFs show considerable promise, challenges remain in standardising performance metrics and assessing long-term operational data. Future research directions are proposed, emphasising the need for longitudinal studies, advanced material integration, and holistic sustainability assessments. This review underscores the significant role DSFs can play in advancing sustainable building practices and meeting increasingly stringent energy performance targets in the built environment.

Keywords: occupancy comfort, double skin façade, sustainable building, passive design, energy efficiency

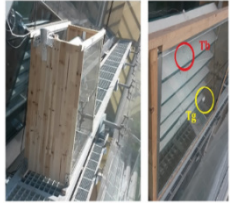
1. Introduction

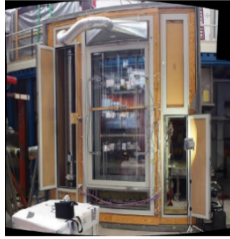
The increasing demand for energy efficiency and occupant comfort in buildings has driven the adoption of innovative architectural solutions such as DSFs. These systems, characterised by an additional glazing layer and an air cavity, offer significant potential for improving energy performance and indoor environmental quality by enhancing insulation, controlling solar gain, and facilitating natural ventilation (Al Horr et al., 2016; Loonen et al., 2013). The importance of DSFs has been further highlighted by the COVID-19 pandemic, which emphasised the critical role of indoor air quality and ventilation in reducing airborne transmission risks while maintaining energy efficiency (Heirani Pour et al., 2019; Lee et al., 1998). Recent research, such as that by Tao et al. (2021), has demonstrated the effectiveness of naturally ventilated DSFs in improving air exchange rates and promoting healthier indoor environments (Tao et al., 2021a, b). However, the successful implementation of DSFs is complex and influenced by factors such as climate, building orientation, and façade configuration (Ghaffarian Hoseini et al., 2013; Saelens et al., 2008). Advancements in smart technologies and adaptive control systems, as explored by Hou et al. (2020), are increasingly playing a

crucial role in optimising DSF performance, offering energy savings of up to 25% compared to conventional systems (Hou et al., 2020; Rounis et al., 2022).

Additionally, the integration of advanced materials like phase change materials (PCMs) within DSFs, as investigated by Zhang et al. (2023), has shown promise in improving thermal regulation and energy efficiency across different climatic conditions (Cabeza and Chàfer, 2020). Furthermore, DSFs contribute to sustainable building practices by reducing reliance on non-renewable energy sources and lowering greenhouse gas emissions (Yazdi-Bahri et al., 2024a). Studies have indicated that DSFs can significantly decrease a building's energy demand by optimising natural ventilation and reducing the need for mechanical heating and cooling systems (Yazdi-Bahri et al., 2024b, 2025). The use of DSFs is particularly effective in climates with high temperature variations, where they can act to moderate internal temperatures. These environmental benefits align DSFs with global sustainability goals, making them a viable solution for future building designs aimed at minimising environmental impact. To provide a comprehensive foundation for this systematic review, Tab. 1 presents a detailed analysis of 12 experimentally tested double-skin façade case studies conducted since 2019.

Tab. 1. Case Studies of Experimentally Tested Double-Skin Facades. (Source: Authors, 2025)

Ref	Year	Climate	Objectives	Methodology	DSF type	Figure	Results
(Yoon et al., 2019)	2019	Koppen Classification: Dwa Location: Daejeon, Seoul	Thermal performance	Experimental, Simulation	Box-window		1. First floor apartment unit consumes the least heating energy and the 25th floor the most. 2. The outside air temperature difference between the first floor and the 25th floor was about 0.4 °C. 3. The largest heating energy savings of 30% can be achieved in the 21st floor with the installation of the DSF system.
(Li et al., 2019)	2019	Koppen Classification: Cfa Location: Nottingham Ningbo	Thermal performance	Simulation	Multistorey		The PCM blind system kept DSF air temperatures below 39°C, allowing solidification even on hot summer days, and stabilized cavity air temperatures below 35°C. It reduced the internal glass surface temperature by 1.0–2.9°C compared to the external glass. Ambient air temperature was the primary factor affecting performance. PCM blinds outperformed aluminum blinds, lowering cavity air temperatures by 2.2°C (5.5%). A 30° tilt angle and placement near the internal glass optimized thermal performance.
(Matour et al., 2022)	2022	Koppen Classification: Cfa Location: Brisbane, Australia	Thermal and ventilation performance	Simulation	Interstitial Slat-blind DSF (IS-DSF)		1. IS-DSF reduces surface temperature and overheating risk compared to conventional DSFs, with up to 9.6% thermal efficiency when blinds are fully open ($\phi = 0^\circ$), lowering cooling loads and enhancing comfort. 2. Slat angles have negligible impact on air cavity temperature, allowing optimization for visual and thermal needs without affecting ventilation. 3. A threshold air velocity of $U_c \geq 1$ m/s reduces overheating to less than 5%, enabling performance predictions based on local wind conditions. 4. Equations predict air velocity in DSFs with lateral openings, and optimizing cavity length and openings improves ventilation and reduces overheating.
(Wang et al., 2022)	2022	Koppen Classification: Cfa Location: Nanchang	Thermal performance	Simulation	Spray Cooling DSF		1. Optimal operation mode: top and bottom vents open, spray direction top-to-bottom, and 10/15 min spray/interval time. 2. Cooling effect: cavity air temperature reduced by 8.1°C and inner glass temperature by 3.7°C. 3. Efficiency: U-value of 2.13 W/m²-K and SHGC of 0.25, meeting national standards.
(Jankovic and Goia, 2022a)	2022	Koppen Classification: No Specify Location: No Specify	Thermal and ventilation performance	Simulation	Naturally Ventilated DSF		1. Boundary conditions, such as the slat angle and opening size, have a limited impact on some thermal and airflow parameters. 2. The slat angle can optimize energy efficiency by controlling solar radiation transmission. 3. Airflow is predominantly driven by solar radiation rather than the temperature difference between indoor and outdoor environments. 4. Gradual closure of slats enhances shading and reduces solar heat gains, but may reduce airflow driven by solar-induced buoyancy.

Ref	Year	Climate	Objectives	Methodology	DSF type	Figure	Results
(Jankovic and Goia, 2022b)	2022	Koppen Classification: No Specify Location: No Specify	Thermal performance	Simulation	single-story mechanically ventilated DSF		Winter/Mid-Season: Mechanical ventilation regulated thermal behavior more than venetian blinds. Low ventilation rates were optimal for energy efficiency and indoor air quality. Summer: Venetian blinds controlled thermal behavior, while mechanical ventilation helped relieve excess heat, though it had little impact on heat gain. Moderate ventilation rates (up to 100 m³/m²/h) were sufficient for efficient heat management. DSFs can be used as dynamic elements for solar energy control.
(Calama-González et al., 2022)	2022	Koppen Classification: Cfa Location: Seville, Spain	Thermal performance	Simulation	a ventilated opaque double skin		The results of the study show that the ventilated double skin facade (DSF) performs better in summer, effectively reducing temperatures above 35°C, but it may lead to night-time overheating. In winter, it provides about 21.3% fewer comfort hours compared to an externally insulated facade and performs similarly to an unretrofitted solution at temperatures between 5°C and 20°C. However, it offers up to 3°C better thermal performance at lower temperatures compared to the unretrofitted facade.
(Jankovic et al., 2022)	2022	Koppen Classification: No Specify Location: No Specify	Thermal and ventilation performance	Simulation	-		The flexible experimental testbed enables systematic analysis of DSF systems, providing insights into their thermal and fluid-dynamic behavior under various conditions. Complementary methods are essential for comprehensive understanding, and the publicly available dataset supports further research and model validation. Despite limitations like incomplete solar geometry analysis, the testbed offers a foundation for future studies on DSF performance and can be adapted for other advanced building envelope systems.
(Catto Lucchino et al., 2022)	2022	Koppen Classification: Cfa Location: Torino, Italy	Thermal performance	Experimental, Simulation	single storey		This study developed and validated a flexible double-skin façade (DSF) model using IDA ICE. The model showed good accuracy, with mean bias errors of less than 1.5°C for temperature and 4 W/m² for heat flux. Long-term simulations had an error range of 5%–15%, acceptable for energy calculations. Despite some limitations in the IDA ICE DSF model, the tool provides reliable simulations for flexible DSF systems. The model and experimental dataset are available in an open-access repository for further research.

These case studies were strategically selected to represent diverse climatic conditions according to Köppen climate classifications, including Dwa (humid continental), Cfa (humid subtropical), and other relevant climate zones spanning locations from South Korea to various European and Asian contexts. This comprehensive case study analysis reveals important patterns in DSF research: box-window configurations dominate in experimental studies, thermal performance remains the primary research objective across different climates, and significant energy performance improvements ranging from 15-30% are consistently reported across various climatic conditions.

Reviewing recent studies comparing DSF systems highlights how each different type performs best under specific climate conditions. In cold winter climates (Dwa classification), box-window DSFs have proven particularly effective, with documented heating energy savings reaching 30% in high-rise buildings (Yoon et al., 2019). Temperate climate zones (Cfa) benefit from multi-story DSFs incorporating phase-change material blinds, which research shows can maintain cavity temperatures below 35°C while reducing inner glass surface temperatures by 1-3°C (Li et al., 2019). The same climate type sees advantages from interstitial slat-blind systems, which reduce overheating risk. These findings demonstrate that DSF selection must carefully consider local climate conditions. However, current research leaves important questions unanswered, particularly regarding extreme climate adaptations and the practical integration of architectural design requirements with energy performance and comfort targets.

Despite the potential benefits, the design and operation of DSFs require a thorough understanding of their performance under different conditions. The aim of this study is to systematically review and analyse recent advancements in DSF technology, focusing on how various design parameters influence building performance, energy efficiency, and occupant comfort. This systematic review explores the adaptability and performance of DSFs across various climatic contexts, emphasising their role in enhancing energy efficiency and indoor environmental quality. By identifying key performance factors—such as cavity width, ventilation strategies, and shading devices, this study highlights the potential of DSFs to integrate with renewable energy systems. Addressing existing research gaps, it outlines future research directions that focus on advanced materials, long-term performance assessment, and holistic sustainability evaluations. Ultimately, this review contributes to the advancement of sustainable building practices by demonstrating how DSFs can support global energy efficiency goals.

2. Methodology

This study employs systematic review methodology, focusing on empirical research articles related to DSF systems in buildings. The review synthesises relevant literature using explicit criteria and standardised methods to analyse the impacts of DSFs on energy efficiency and occupant comfort in various scenarios. The literature search focused on studies published between 2019 and present, ensuring coverage of the most current research developments in DSF technology. A systematic review provides a rigorous and comprehensive summary of existing scholarly literature, using a transparent process to identify, select, and critically evaluate studies from various sources. This method minimises bias by following a documented protocol with clearly defined inclusion and exclusion criteria, ensuring an objective synthesis of the current body of knowledge. The systematic review process adhered to specific PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) steps, including (Fig. 1):

1. Identification: databases such as Google Scholar, Web of Science, and Scopus were queried using selected keywords, resulting in an initial pool of 383 articles.
2. Screening: a careful examination of titles and abstracts narrowed the focus to 234 articles specifically addressing DSFs for energy performance and thermal comfort in buildings.
3. Eligibility: full-text assessments were conducted, leading to the inclusion of 80 articles, including conference papers, that qualified for in-depth review.

Fig. 2 illustrates a keyword co-occurrence network that visualises the relationships and clusters of terms frequently associated with research on DSFs and related energy performance topics. Generated using VOSviewer tools (Jiru and Haghighat, 2008), the network highlights several key themes and subfields within the literature. The keyword "double-skin façade" stands out as a central term, closely linked to other significant keywords such as "performance," "energy," "system," "heat transfer," and "airflow." These connections underscore a strong focus on research aimed at understanding and enhancing the energy efficiency, thermal dynamics, and overall performance of double-skin façades in various building contexts. Additionally, keywords like "renewable energy," "ventilation," and "CFD" (computational fluid dynamics), along with recurring terms such as "performance," "energy," "system," "heat transfer," and "airflow," align with the core areas of interest in the discussion, contributing to the broader discourse on sustainable building technologies.

Fig. 3 presents a classification of research objectives related to double-skin façades, categorised by year from 2018 to 2024. The objectives include thermal performance, visual comfort, energy consumption, ventilation, economic analysis, and carbon emissions reduction. Fig. 4 illustrates the distribution of DSF studies across different Köppen climate classifications, revealing a predominant focus on the Cfa climate zone, which corresponds to humid subtropical climates.

3. Double-skin façade

The concept of the DSF originates from the historical practice of employing removable glass layers to enhance thermal insulation. This architectural strategy involves a multi-layered building envelope composed of an external skin, an intermediate cavity, and an internal skin applied to building exteriors (Yazdi-Bahri et al., 2022). The DSF design is highly adaptable to varying weather conditions, functioning as a thermal buffer that reduces heat gains during the cooling season and minimises heat losses during the heating season. This adaptability effectively mitigates thermal discomfort caused by asymmetric radiation (Yazdi-Bahri et al., 2021). DSFs are suitable for both new constructions and retrofitting projects, demonstrating effectiveness in diverse climatic regions, including both cold and hot environments.

The cavity within the façade can be configured as either airtight or ventilated, with DSF typologies commonly categorised based on the ventilation strategies employed within the cavity (Alhazaa, 2020; Yoon et al., 2019). These façades can span multiple building levels, providing an additional layer of insulation and enhancing overall energy efficiency. The physical form of a building focuses on aesthetic appeal and structural integrity. The architectural components of DSFs include elements such as glazing types, frame materials, and façade configurations, all of which contribute to the overall design and sustainability of the building. This classification (as illustrated in Fig. 5) enhances the understanding of how these elements interact within the broader context of architectural design and engineering. By distinguishing between architectural and energy integration components, stakeholders can better assess the practical applications and benefits of DSFs in building technology.

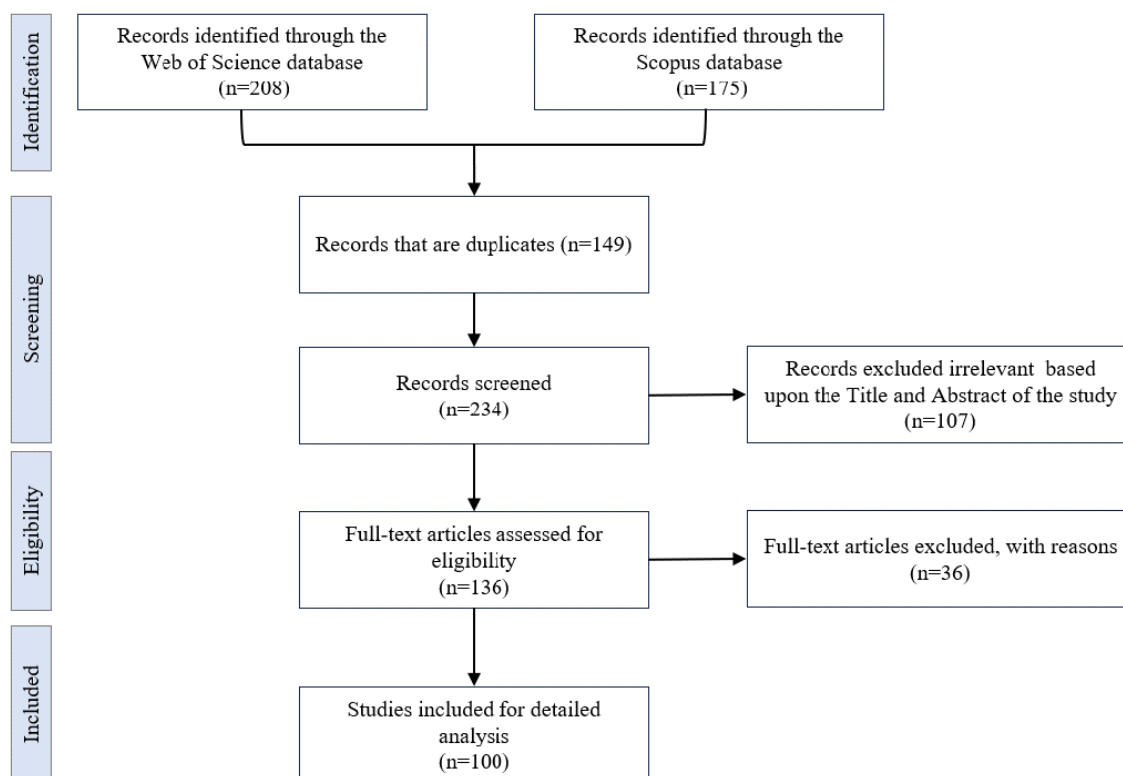


Fig. 1. The PRISMA framework for systematic review by author since 2018. (Source: Authors, 2026)

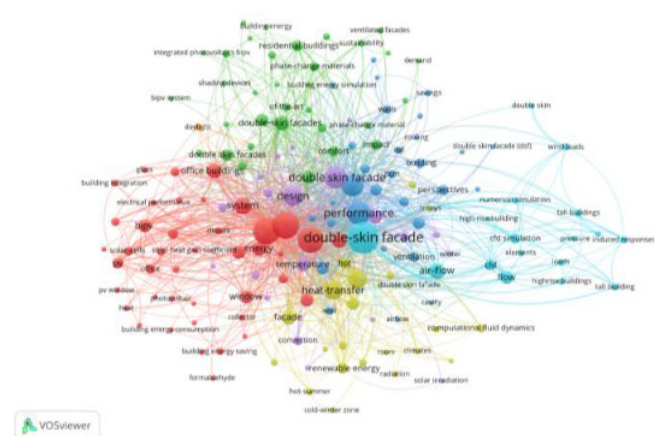


Fig. 2. (left) Bibliometric analysis of the keywords in publications on DSF. Co-occurrence of keywords. The size of nodes indicates the frequency of occurrence. The curves between the nodes represent their co-occurrence in the same publication. The shorter the distance between two nodes, the larger the number of co-occurrences of the two keywords. (Source: Authors, 2026)

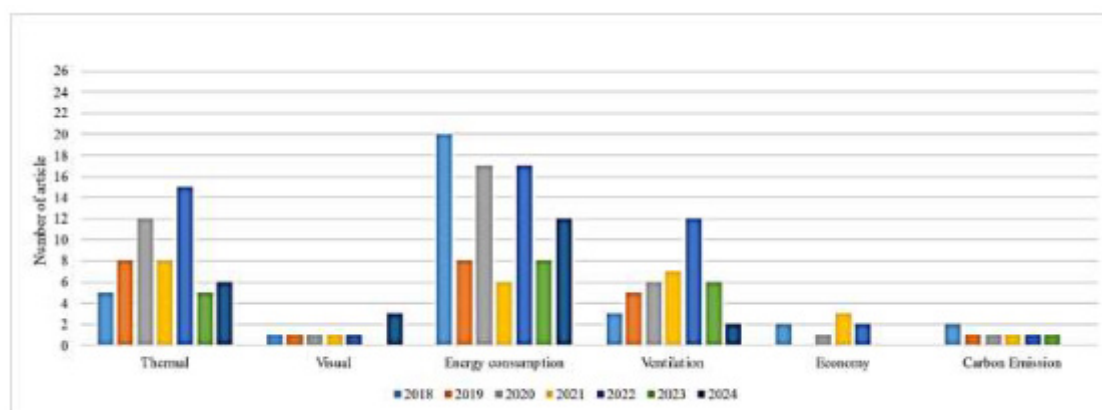


Fig. 3. Classification based on objectives and years. (Source: Authors, 2024)

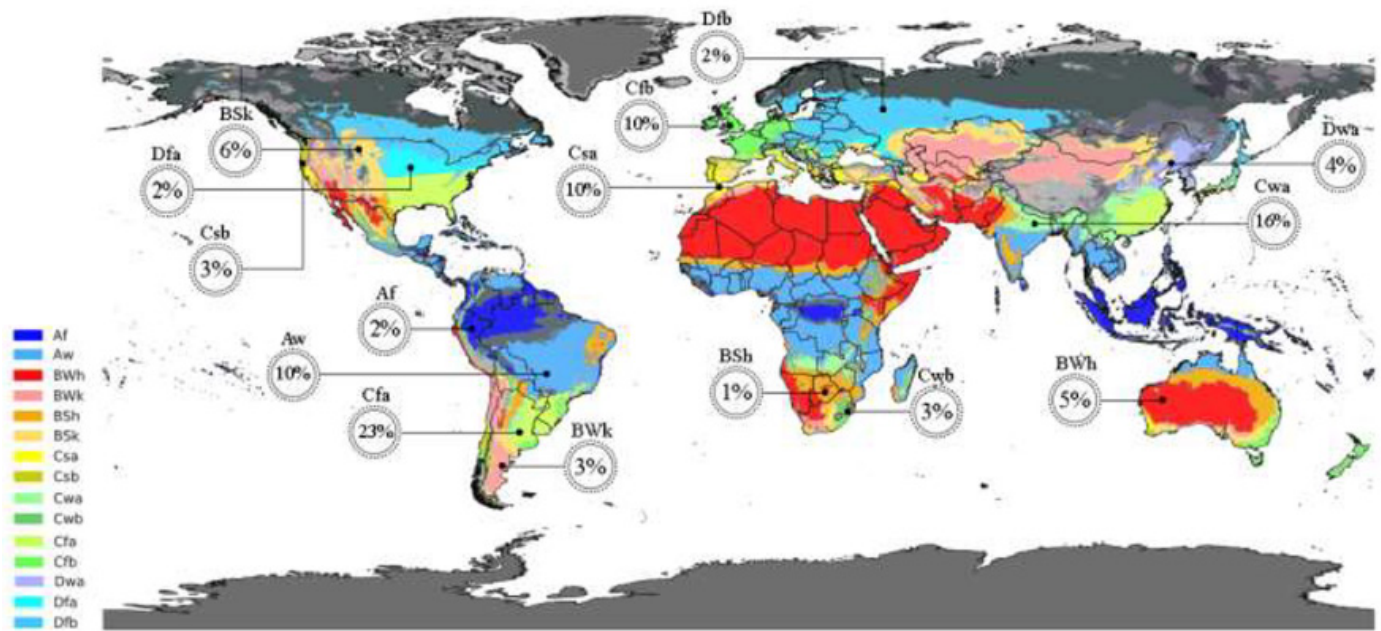


Fig. 4. Koppen-Geiger climate classification map. (Source: Authors, 2025)

In this article, we focus primarily on the architectural elements group, examining how these components influence the design and performance of DSFs. Architectural elements are pivotal in DSF design, as they directly affect the façade's overall performance and its integration with the building structure. The selection of components such as glazing type, structural supports, and the configuration of the air cavity significantly impacts the thermal and ventilation efficiency of DSFs (Ramessur and Gooroochurn, 2021). For instance, structural exoskeletons

paired with glazing systems not only enhance structural integrity but also improve energy efficiency and aesthetic appeal. To achieve optimal functionality and sustainability, these elements must be meticulously planned to address both environmental performance and occupant comfort (Yoon et al., 2022). These architectural components are integral to building design, emphasising structural and aesthetic aspects rather than solely focusing on the building's energy systems or façade technologies.

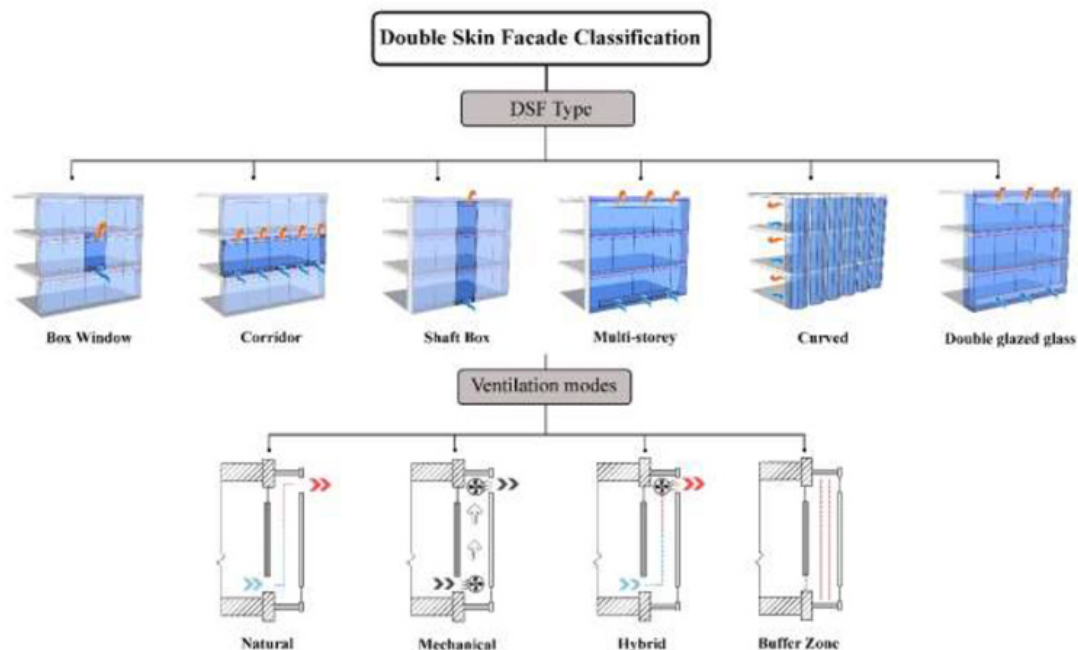


Fig. 5. DSF classification. (Source: Authors, 2026)

3.1. Box-window DSFs

There is a distinct lack of consensus regarding optimal cavity dimensions, as evidenced by the conflicting findings between Ramessur and Gooroochurn (2021) and Wong et al. (2008). Furthermore, the methodological approaches vary dramatically,

raising questions about the reliability of simulation-based conclusions, with discrepancies of up to 27% reported by Hu et al. (2017). This discrepancy suggests that cavity width and height requirements are not universal parameters but are highly sensitive to specific boundary conditions, such as local climate and façade orientation. The absence of a standardised methodology to

normalise these variables across studies limits the practical applicability of these design guidelines, suggesting a need for climate-calibrated optimisation frameworks rather than fixed-dimension recommendations.

The research exposes fundamental flaws in the economic viability of box-window DSFs based on the limited cost-benefit analysis available. Study by [Zomorodian and Tahsildoost \(2018\)](#) reveals a critical weakness in the business case for DSFs, showing simple payback periods of 59.4–87.5 years that far exceed typical building lifespans of 50 years due to high construction costs relative to modest energy savings. This economic reality is particularly problematic in regions with low energy prices, where the financial justification becomes nearly impossible despite demonstrated energy performance improvements. The study's proposed energy-carbon-cost (ECC) index represents an attempt to address this complexity, but the fundamental economic challenge remains: box-window DSFs appear to be a luxury sustainability feature rather than a cost-effective building solution for most markets.

The research presents a paradoxical sustainability narrative for box-window DSFs that challenges conventional green building assumptions. While the study by [Zomorodian and Tahsildoost \(2018\)](#) demonstrates meaningful reductions in operational carbon emissions (14–17%), the embodied carbon increase of 23.3–47% and carbon payback periods of 4.6–7.6 years reveal that these systems may initially worsen a building's carbon footprint before providing benefits. Combined with the substantial temperature increases noted in study [\(Aruta et al., 2023\)](#) (up to 15.9°C in cavities) and the problematic reverse airflow issues identified in study [\(Ramessur and Goroochurn, 2021\)](#), box-window DSFs appear to create thermal management challenges that may compromise occupant comfort and building performance.

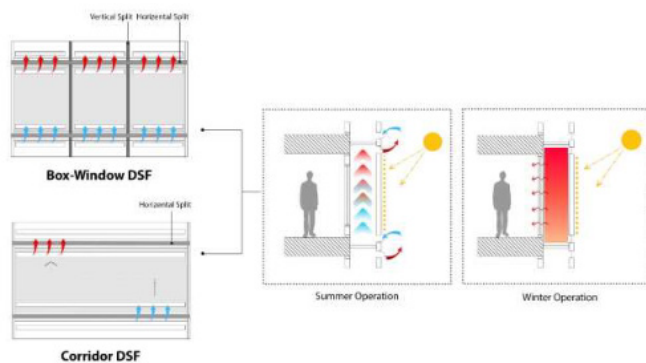


Fig. 6. Box-Window and corridor details. (Source: Authors, 2026)

3.2. Corridor-type DSFs

The research on corridor-type DSFs demonstrates a notable shift towards wind energy harvesting applications, yet reveals critical gaps in comprehensive performance assessment that limit practical implementation. Studies collectively show that corridor DSFs can significantly enhance wind power density by factors of 2 to 4.2 and increase mean velocities by 12–350% depending on configuration and location within the corridor [\(Hassanli et al., 2018\)](#). However, this research focus on aerodynamic performance comes at the expense of integrated analysis that considers thermal comfort, energy consumption, and overall building performance simultaneously [\(Bielek et al., 2022\)](#). The validation discrepancies of up to 15% reported in study [\(Aldawoud et al., 2021\)](#) and the narrow focus on wind angles of 60–90° relative to corridor axis highlight the limited scope of current research, which may not translate effectively to real-world building applications where wind conditions are highly variable.

The research reveals promising thermal performance characteristics for corridor DSFs but lacks the economic rigour necessary for informed decision-making. Study demonstrates that south-facing corridor DSFs provide the best thermal performance with significant energy savings potential when natural ventilation is utilised, while north and west-facing orientations fail to deliver acceptable indoor thermal comfort for high-rise office buildings [\(Wong et al., 2008\)](#). The identification of 300 mm as the optimal air gap size and the recognition of stack effects impacting lower floors represent valuable design insights. However, unlike box-window DSF research, the corridor studies provide virtually no economic analysis, cost-benefit assessment, or payback period calculations, making it impossible to evaluate the financial viability of these systems despite their demonstrated technical performance (Fig. 6).

The research on corridor DSFs suffers from a fundamental disconnect between aerodynamic optimisation and holistic building performance evaluation. While studies successfully demonstrate enhanced wind power density and reduced turbulence intensity (up to 30% reduction), these findings remain largely theoretical without integration into comprehensive building energy models or life-cycle assessments. The absence of embodied carbon analysis, construction cost evaluation, and long-term performance monitoring creates a significant knowledge gap that prevents architects and engineers from making informed decisions about corridor DSF implementation [\(Hassanli et al., 2018; Bielek et al., 2022\)](#). Furthermore, the research lacks critical examination of potential negative consequences such as increased structural loads from wind turbine integration, maintenance challenges in high-rise applications, or the impact of aerodynamic modifications on overall building aesthetics and urban wind patterns (Tab. 2).

3.3. Shaft-box DSF

The research on shaft-box DSFs reveals significant limitations in both methodological rigour and practical applicability. While the study claims that shaft-box DSFs with outdoor air curtain design enhance energy efficiency through optimised airflow and cavity depth, the study fails to provide quantitative energy savings data, undermining its credibility and preventing meaningful performance comparisons [\(Poirazis et al., 2008\)](#). This methodological weakness is compounded by the lack of standardised testing conditions and climate specifications, making it difficult to assess the generalisability of findings across different building contexts and environmental conditions.

The fire safety implications of shaft-box DSFs present a critical concern that appears inadequately addressed in current research. Reference [Li et al. \(2012\)](#) demonstrates that smoke spreads upwards through the shaft-box configuration due to stack effect and thermal buoyancy, creating dangerous conditions on higher floors with increased smoke temperatures and CO concentrations. However, this study's narrow focus on smoke behaviour fails to address crucial design modifications or mitigation strategies that could reduce these risks, leaving architects and engineers without practical guidance for safe implementation. The highlighted climate-dependent performance variation exposes a fundamental limitation of shaft-box DSF systems, achieving 51% energy savings in temperate climates but only 16% in warmer regions [\(Colombo et al., 2017\)](#). This dramatic performance degradation in warmer climates, combined with the inherent fire safety risks and lack of comprehensive cost-benefit analyses, raises serious questions about the universal applicability of shaft-box DSF technology. The research suggests these systems may be viable primarily in cooler climates, but the absence of detailed economic assessments and long-term performance data prevents definitive conclusions about their practical value in contemporary sustainable building design.

Tab. 2. The relevant study of box-window and corridor typology. (Source: Authors, 2025)

Ref	Variables	Tools/Methodology	Climate	Type of building	DSF type	Conclusions
(Ramessur and Gooroochurn, 2021)	X= cavity height, cavity depth, opening-to-glazing ratio (O/G ratio), and solar heat gain coefficient (SHGC) Y= Airflow Rate, temperature control with seasonal variations	S-N/ EP	NS	O	Box window	5H outlet cavity height with 0.9m cavity depth optimal for cooling; shallow cavities with high O/G ratios cause problematic reverse airflow. Winter: 8H total cavity height difference achieves ~2°C temperature improvement and 30% reduction in temperature extremes, potential 7-20% HVAC energy savings.
(Wong et al., 2008)	X= xternal air temperature, external wind velocity, relative humidity, air gap size, time of day, and DSF orientation. Y= Operative temperature (OT), air temperature, air velocity, radiant temperature, relative humidity, and PMV	S / CFD	Af	O	Corridor	A South-facing double-skin façade (DSF) has the best performance, followed by an East-facing one. The North-facing and West-facing façades do not provide acceptable indoor thermal comfort for high-rise office buildings. The optimal air gap size for the DSF is 300 mm. The lower floors of the office space generally have the lowest operative temperature due to the "stack effect". A DSF can lead to significant energy savings if natural ventilation is utilized.
(Hu et al., 2017)	X= Solarangles, solar intensity, vent size, , glazing materials, angles of louver, Y= ventilation rate	N-A/ AF, CFD	BWh	NS	Box window	discrepancies of 5%-9% for no-louver NVDSFs and 13%-27% for NVDSFs with adjustable louver angles
(Zomorodian and Tahsildoost, 2018)	X= Façade spatial configuration, shading devices, cavity ventilation strategies, cavity depth, window-to-wall ratio, building orientation Y= Energy demand, thermal comfort hours, operative temperature, carbon emissions, construction costs, payback period	S/DB, DS,R	Cfa	O	Box window	7.9-14.8% reduction in energy consumption. Box DSF with external louvers showed maximum 14.8% reduction. Operational CO ₂ reduced by 14-17%, but embodied carbon increased by 23.3-47%. Carbon payback period: 4.6-7.6 years. Simple payback periods (59.4-87.5 years) exceed building lifetime (50 years) due to high construction costs and low energy prices in Iran. Free-running thermal comfort improved from 18% to 34% of occupied time. Recommendation: Proposed ECC (Energy-Carbon-Cost) index for decision-making.
(Hassanli et al., 2018)	X= Air cavity size, Air velocity, Ventilation mode, Building geometry, , Corridor configurations Y= Mean velocity inside corridors, Turbulence intensity, Wind power density, Flow characteristics, Velocity enhancement factors	S-N/ CFD	NS	NS	Corridor	Average wind power density increased by factor of 2, mean velocity increased 12-204% depending on corridor location. Average wind power density increased by factor of 4.2, mean velocity increased 30-350% depending on corridor location. Turbulence reduction: Confined corridors reduced turbulence intensity by up to 30%, with Layout 3 achieving 33% reduction compared to base layout. Best results achieved at 60°-90° wind angles relative to corridor axis.
(Bielek et al., 2022)	X= corridor layouts, wind speed, incident wind angles Y= Flow characteristics (mean velocity, turbulence intensity and wind power density)	S, E, N/CFD	Cwa	SB(CAARC)/T	Corridor	Aerodynamic modifications to DSF significantly enhance wind power density by up to 4.2 times, reduce turbulence, and increase wind velocity within the structure.
(Aldawoud et al., 2021)	X= Incident wind angles, DFS layouts, wind turbine installation location	S/ CFD	Cwa	SB (CAARC)/T	Corridor	Validated with a 15% discrepancy, the CFD simulations confirm that the DSF system effectively enhances uniform flow within the cavity for wind energy harvesting. The flow becomes more uniform while turbulence progressively decays as

Ref	Variables	Tools/Methodology	Climate	Type of building	DSF type	Conclusions
	Y= energy harvesting potential Mean velocity, Flow uniformity, Flow uniformity/direction, Turbulence intensity					flow progresses through the cavity for all wind directions, making the middle regions of both leading and trailing sides favourable locations for installing small-scale wind turbines.
(Pelletier et al., 2023)	X= geometry, and materials. Y= Ventilation and thermal performance, energy performance, life cycle analyses.	E/ CFD, EP, DB	Cfa, Cfb, Csa	T	Corridor	While DSFs are a popular research topic, there's no single definition or standardized assessment method due to the wide variety of parameters and methodologies involved. This breadth of research, while offering flexibility, can hinder its practical application and commercial viability.
(Srisamranrungruang, T., Hiyama, K., 2020)	X= Air flow, air temperature, width of corridor, solar radiation. Y= Heat recovery, energy saving.	S/CFD, AF	Cfb	NS	Box-window	Integrating a double skin façade with a heat recovery unit leads to substantial energy savings during the heating season, particularly at lower airflow rates, with temperature increases in the cavity reaching up to 15.9°C, optimizing thermal efficiency.

Variables: X= Inputs, Y= Outputs / **Methodology:** S= Simulation, E= Experimental, N=numerical, A= analytical/ **Tools:** SN= Sensor, AF: ANSYS Fluent, EP= EnergyPlus, DB= Design Builder, D= Diva, CFD= Computational Fluid Dynamics, R=radiance, DS=daysim/ **Type of Building:** T= Test Room, O= Office, E= Educational, SB= standard building, CAARC= Commonwealth Advisory Aeronautical Council standard tall buildings

Tab. 3. The relevant study of shaft box and double-glazed glass façade. (Source: Authors, 2025)

Ref	Variables	Tools/Methodology	Climate	Type of building	DSF type	Conclusions
(Poirazis et al., 2008)	X= Geometry, airflow path, cavity depth, openings area, type of glazing, Window-to-external wall area, building orientation Y= Energy Consumption. Thermal Comfort	S/ IDA	Dfb	O	Double-Glazed Glass Façade	DSFs with outdoor air curtain design enhance energy efficiency by optimizing airflow and cavity depth, though no exact percentage of energy savings is reported.
(Li et al., 2012)	X= Temperature of cavity , cavity width, openings dimension Y= Vertical and horizontal smoke temperature, Smoke spread, smoke toxicity	S,N/ FDS	Cfa	NS	shaft box	Smoke spreads upwards through the Shaft-box DSF, increasing smoke temperatures and CO concentrations on higher floors, with the roof floor being the most hazardous due to the "Stack Effect" and thermal buoyancy.
(Colombo et al., 2017)	X= Temperature of cavity, ventilation strategy, different climates Y= Energy Savings, Total Energy Consumption	S/ EC	NS (Not Specified)	O	shaft box	Double Skin Facades achieve 51% energy savings in temperate climates but only 16% in warmer climates, making them more effective in cooler regions, while their cost-effectiveness in warmer climates remains questionable.
(Arabi et al., 2023)	X= blind size and position. Y= temperature, flow dimensionless number, dynamic efficiency, and absorbed solar radiation rate of walls	S / CFD	BSh	NS	Double-Glazed Glass Façade	Increasing the size of the blinds and placing them closer to the outer glazing improves the winter performance of a naturally ventilated double skin façade. This leads to higher temperatures and dynamic efficiency, though the effect on efficiency plateaus and then decreases at larger sizes.
(Pourshab et al., 2020)	X= Outdoor temperature, Solar radiation, Solar incidence, Building geometry, Shading device configurations	S/ CFD, AF	BSk	O	Double-Glazed	Horizontal louvers achieve higher natural ventilation rates than vertical louvers but increase heat transfer to interior spaces through stronger convective flows. Both DSF configurations successfully utilize stack effect for building-wide air suction, with vertical louvers providing better thermal protection at reduced airflow efficiency.

Ref	Variables	Tools/Methodology	Climate	Type of building	DSF type	Conclusions
(Bao et al., 2022)	Y= Air velocity, Temperature distribution in cavity, Heat flux through surfaces, Ventilation rates	E/ SN	Cfa	T	Glass Façade	DGGF can reduce the indoor temperature by up to 4.9°C compared to a DGF, which results in a 12% saving in cooling energy consumption. The study proves that DGGFs have a better insulation effect than DGFs, with or without louvers. Ventilation enhances the cooling effect of the system.
	X= Irradiance, Ambient temperature, Wind Speed, Cavity depth				DGF	
	Y= Energy consumption, Indoor temperature, air layer temperature and humidity, glass panel temperatures				DGF	
(Wang et al., 2020)	X= Solar radiation, outdoor and indoor air temperature, slat angle of Venetian blinds, Orientations	SN/ Matlab	Cfa	T	Double-Glazed Glass Façade	Thermal performance of naturally ventilated double-skin façades with interior double glass is superior to those with exterior double glass. The research offers valuable insights for improving energy efficiency and guiding the application of these systems.
	Y= Energy performance comparison, thermal performance assessment				Double-Glazed Glass Façade	
(Hong et al., 2013)	X= Window absorptivity, position, size and location of ventilation slots	S/ IDA-ICE, Star-CCM+	NS (Not Specified)	NS	Double-Glazed Glass Façade	Surface temperatures up to 70°C could damage façade components if not properly designed, highlighting the need for three-dimensional flow simulation to accurately model double façade thermal behavior and optimize design for energy efficiency.
	Y=Velocity and Temperatures of the Cavity Flow, Surface Temperatures and Heat Gains				Double-Glazed Glass Façade	
(Manz, Frank, 2005)	X= Blind Size, Blind Position, Blind angle, Solar Irradiance	S,N/ CFD	NS (Not Specified)	BSh	Double-Glazed Glass Façade	Positioning blinds near the outer glazing and optimizing the blind size to 240 mm significantly enhances dynamic efficiency and thermal performance in winter, as larger blinds improve heat extraction but reduce air mass flow, with 240 mm being optimal.
	Y= Temperature of DSF Outlet Air, Air Mass Flow Rate, Dynamic Efficiency, flow dimensionless number, turbulent kinetic energy, and absorbed solar radiation rate of walls				Double-Glazed Glass Façade	
	X= floor height, solar shading systems in horizontal and vertical modes				DGF	
Huang et al. (2022a)	Y= Airflow, heat transfer rate	N,S/ CFD, AF	NS (Not Specified)	O	DGF	DGF with horizontal louvers significantly enhances natural ventilation and airflow rates within the building, especially on lower floors, with the first floor achieving air velocities up to 0.45 m/s, compared to 0.26 m/s in the vertical louver case. However, this also leads to a higher heat flux transfer into the interior spaces, particularly on the internal glass surfaces.
	X= Solar radiation in difference Orientation, Inner glass temperature, U-value				DGF	
	Y= Energy performance, Heat losses				DGF	

Variables: X= Inputs, Y= Outputs/ **Methodology:** S= Simulation, E= Experimental, N= Numerical/ **Tools:** FDS= Fire Dynamics Simulator, DB= Design Builder, EC= Ecotect, EP= EnergyPlus, CS= Climate Studio, C= Colibri, G= Galapagos, M= Matlab/ **Type of Building:** R= Residential, O= Office, E= Educational, NS=No-Specify

3.4. Double-glazed glass façade

The research on double-glazed glass façades (DGGFs) reveals a complex pattern of performance optimisation dependent on design parameters and environmental conditions, though the studies exhibit varying degrees of methodological rigour (Aruta et al., 2025; Choi et al., 2019). It is demonstrated that blind positioning and sizing significantly influence thermal performance, with optimal blind sizes of 240 mm positioned near outer glazing providing enhanced dynamic efficiency in winter conditions (Arabi et al., 2023). However, these findings present conflicting implications for natural ventilation rates. They show horizontal louvers achieve 73% higher ventilation rates than vertical configurations while simultaneously increasing heat transfer to interior spaces (Pourshab et al., 2020). This paradox suggests that the optimisation of one performance parameter often comes at the expense of another, highlighting the need for more sophisticated multi-objective optimisation approaches in façade design.

The thermal performance advantages of DGGFs are substantial but inconsistently quantified across studies. The variance in reported performance ranging from a 12% reduction in cooling energy (Bao et al., 2022) to a more aggressive 40% (Chi et al., 2020) highlights a significant inconsistency in how DGGF performance is benchmarked. This variance likely stems from differences in operational baselines and varying climatic intensities rather than technology efficacy alone. Consequently, these results should not be viewed as additive but as evidence that DGGF efficiency is highly dependent on the operational context, such as occupancy schedules and specific climate-responsive controls (Fig. 7).

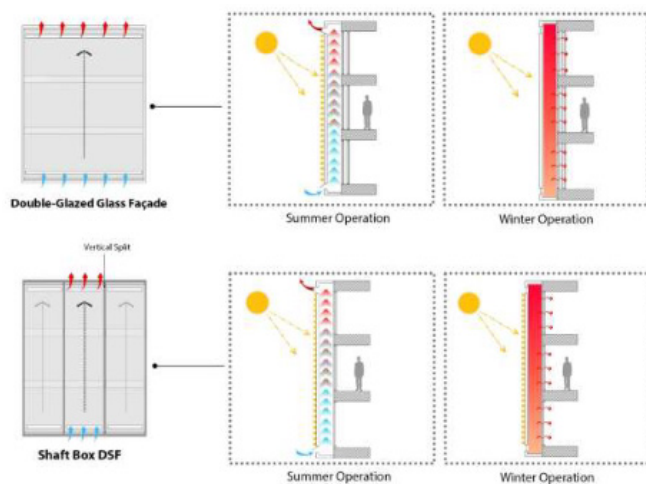


Fig. 7. Shaft-box and DGGF details. (Source: Authors, 2026)

Critical safety and durability concerns emerge from the thermal analysis findings, particularly the identification of surface temperatures reaching up to 70°C in certain configurations as noted in reference (Manz and Frank, 2005). This extreme temperature exposure poses significant risks to façade component integrity and longevity, yet the research provides insufficient guidance on material selection, thermal expansion accommodation, or long-term maintenance requirements. Furthermore, while multiple studies emphasise the superior performance of interior double-glazing configurations over exterior arrangements, the practical implications for building envelope integration, structural loading, and construction sequencing remain inadequately addressed, suggesting a significant gap between research findings and real-world implementation challenges (Tab. 3).

3.5. Multi-story DSFs

The reviewed studies demonstrate that multi-story DSFs can

achieve substantial energy savings, with documented reductions of up to 299,279 kWh annually for heating and cooling, and cooling energy reductions of 53.5% in optimal configurations (Ahriz et al., 2022). However, the effectiveness is highly climate-dependent and context-specific. While DSFs show significant benefits in hot climates, with careful consideration given to specific parameters like orientation and cavity depth based on the building's location and microclimate, which can significantly reduce a building's cooling loads and improve energy efficiency (Shin, Hyun-Cheol-Jang, 2015), their performance in cold climates appears less compelling. One study noted that while the DSF system proves effective during hot months, "in cold months it does not result in significant energy savings" (Hilal et al., 2023). This climate sensitivity suggests that DSFs are not universally applicable solutions and require careful climate-specific design considerations to justify their implementation costs.

The research reveals that DSF performance is critically dependent on specific design parameters, particularly cavity depth, orientation, and the number of façade applications. Studies indicate optimal cavity widths between 0.75 and 1 meter for curved double-skin façades (Huang et al., 2023b), while another study found that a 35 cm cavity with inner double-glazed layer and outer low-E double-glazed layer significantly reduces cooling energy consumption in high-rise residential buildings (Hilal et al., 2023). The three-DSF model applied to east, south, and west façades showed the best performance, with a 28% reduction in heating energy and a 53.5% reduction in cooling energy, demonstrating that both the orientation of façades and the number of DSFs play a significant role in enhancing building energy performance (Ahriz et al., 2022). The choice of glazing systems is also critical, as substituting clear glass with low-E glass increases airflow within the cavity by 8.2% on the inner façade and 21.31% on the outer façade (Huang et al., 2023b). However, the studies also highlight that extreme parameter values can lead to increased errors and reduced performance (Huang et al., 2023a), suggesting that there are narrow optimisation windows that designers must navigate carefully.

While the studies provide valuable insights, several limitations emerge from this body of research. The predominant reliance on simulation tools (IESVE, EnergyPlus) with limited experimental validation raises questions about real-world performance accuracy, as only two studies (Huang et al., 2022b, 2023a) incorporated experimental components alongside their computational approaches. Additionally, most studies focus primarily on energy consumption metrics while giving insufficient attention to other critical factors such as construction costs, maintenance requirements, structural implications, and occupant comfort beyond basic temperature ranges. The research shows that comfortable indoor temperature ranges of 21–26°C can be maintained for most of the year (Hilal et al., 2023) but lacks comprehensive analysis of other comfort parameters. The research also lacks comprehensive life-cycle assessments that would account for the additional materials, complexity, and maintenance associated with DSF systems. Furthermore, the studies concentrate heavily on hot climate applications in regions classified as Csa, Bsh, BWh, and Cwa climates, leaving gaps in understanding DSF performance across diverse climatic conditions and building types, which limits the generalisability of findings for broader architectural applications.

3.6. Curved double-skin façades

The research on curved double-skin façades (DCSF) reveals critical geometric parameters that significantly influence thermal and ventilation performance. Studies demonstrate that the ideal cavity width for CDSFs lies between 0.75 and 1 meter, with the optimal ellipse aspect ratio identified as 0.5, at which point ventilation efficiency rises sharply before declining beyond this

threshold (Huang et al., 2023b). The curved geometry creates distinct advantages over planar façades, as CDSFs induce thermal buoyancy-driven flow with thermal pressures stabilising between 0.056 and 0.063 Pa under specific conditions (Huang et al., 2022b). However, this geometric complexity introduces non-uniform solar irradiance distribution, with variations averaging 30.05% vertically and 9.12% horizontally compared to planar façades (1.88% vertical, 1.68% horizontal) emphasising the need for precise geometric analysis in design phases.

Curved double-skin façades exhibit heightened sensitivity to environmental conditions, particularly solar radiation and incident angles. Research indicates that when solar incident angles exceed 45°, ventilation fluctuations in CDSFs become much more pronounced compared to lower angles, whereas planar double-skin façades show considerably smaller effects under similar conditions (Huang et al., 2023b). Solar radiation emerges as the primary factor affecting cavity temperature and airflow, with the curved geometry leading to stronger dependence on solar input than in planar systems (Huang et al., 2022b). The thermal similarity model shows validity with errors less than 15%, with best results occurring under specific conditions: solar radiation of 200–400 W/m², angles of 45–60°, model scale of 1/20–1/50, and ellipse aspect ratio less than 1 (Huang et al., 2023a). This environmental sensitivity suggests that CDSFs require more sophisticated control systems and design considerations compared to conventional façade systems (Fig. 8).

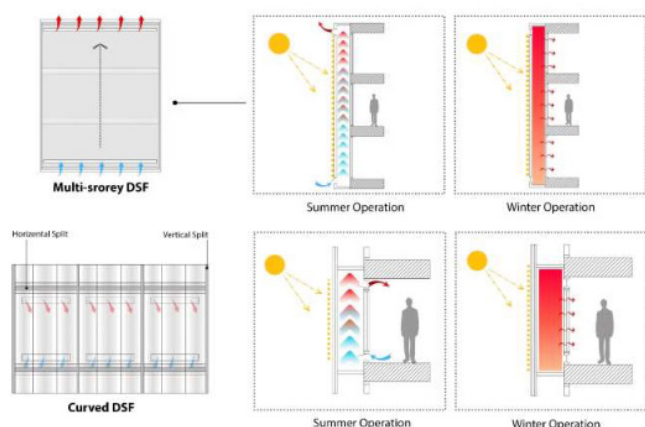


Fig. 8. Multi-story and curved façade details. (Source: Authors, 2026)

The current research on curved double-skin façades presents several methodological limitations that affect the reliability and applicability of findings (Huang et al., 2023b). The studies primarily focus on Cwa climate conditions and rely heavily on computational fluid dynamics (CFD) and experimental models with limited full-scale validation (Huang et al., 2023a). While the thermal similarity model demonstrates reasonable accuracy, the research acknowledges that extreme parameter values increase errors significantly, indicating narrow operational windows for optimal performance (source 80?). Furthermore, the studies concentrate predominantly on thermal and ventilation performance metrics while providing insufficient analysis of structural implications, construction complexity, cost considerations, and long-term maintenance requirements associated with curved geometries. The limited climate diversity in the research (exclusively Cwa classification) raises questions about the global applicability of CDSFs, and the absence of comprehensive life-cycle assessments fails to address whether the enhanced performance justifies the increased complexity and costs associated with curved double-skin façade systems (Tab. 4).

4. Window type and glazing properties

Window specifications significantly influence DSF performance across all categories. Double-pane glazing systems demonstrate superior thermal performance over single-pane alternatives, with U-values ranging from 1.4–2.8 W/m²K (Majid and Ghazali, 2021). Low-E coatings effectively reduce radiative heat transfer by 10–15%, which is particularly beneficial in hot climates. Advanced electrochromic glazing can achieve cooling energy reductions of up to 80% compared to traditional systems. For hot climate applications, solar heat gain coefficients (SHGC) below 0.3 are recommended to prevent overheating (Piccolo et al., 2018). Frame materials also impact overall performance, with recent studies showing U-value reductions of up to 46% through advanced frame design and shading attachments. Double-tempered or double-laminated glass is recommended for DSF applications due to enhanced thermal isolation and safety considerations (Misiopcecki et al., 2023). DSF systems face significant challenges in hot climates, where cavity temperatures can exceed 60°C without proper ventilation. Studies show reduced energy savings of only 15–25% in hot climates compared to 35–50% in temperate climates (Calama-González et al., 2022; Hassanli et al., 2018).

5. Results

The systematic review of different DSF categories reveals distinct characteristics, performance metrics, and applications across various climatic conditions and building types. This section presents a comparative analysis of six main DSF categories: box-window, corridor, shaft-box, DGGF, multi-story, and curved DSFs (Tab. 5).

5.1. Energy efficiency and thermal comfort performance

DSFs demonstrate substantial energy efficiency, adaptability, and enhanced performance across various climates and building types. Box-window DSFs excel in thermal regulation, achieving up to 35% reduction in U-values through integrated shading (Ramessur and Gooroochurn, 2021; Huang et al., 2023b). Corridor-type DSFs are effective in high-rise applications, addressing aerodynamic challenges and wind load management while enabling up to 20% primary energy savings through dynamic shading integration (Wong et al., 2008; Bielek et al., 2019). Shaft-box DSFs show significant variation in performance based on climate, with energy savings ranging from 37–59% in cooler climates and 16% in warmer conditions (Khoshbakht et al., 2013; Lops et al., 2023). These systems highlight the need for climate-specific design considerations and safety measures, such as stack effect optimisation (Wang et al., 2018). Double-glazed glass façades (DGGFs) perform exceptionally in Mediterranean climates, reducing heat gains by 40% and heat losses by 72% (Wang et al., 2020) with ventilation strategies like Coandă nozzles contributing to significant solar load reductions (Guardo et al., 2011; Valentín et al., 2013).

Multi-story DSFs demonstrate significant energy efficiency improvements (up to 34.3%); however, the reliability of these figures is contingent upon the accuracy of thermal stratification modelling. Seo et al. (2019) and Barbosa and Alberto (2019) emphasise high comfort levels, yet their findings are limited by the static modelling approaches common in their respective studies. A more critical assessment reveals that these comfort metrics may be overestimated, as they often do not account for the dynamic thermal buoyancy effects that become pronounced in high-rise, multi-story cavities. Curved DSFs stand out for aerodynamic performance, reducing wind-induced drag by 25% and improving ventilation performance by 8–21% (Huang et al., 2023b; Chereches et al., 2021).

Tab. 4. The relevant study of multi-story and curve. (Source: Authors, 2025)

Ref	Variables	Tools/Methodology	Climate	Type of building	DSF type	Conclusions
(Ahriz et al., 2022)	X= Orientation, Number and position of DSF, Y= Energy consumption	S/ EC	Csa	O	multi-story	The use of DSFs can achieve annual energy savings of up to 299,279 kWh for heating and cooling. The three-DSF model, applied to the east, south, and west façades, showed the best performance, with a 28% reduction in heating energy and a 53.5% reduction in cooling energy. High-rise buildings with multi-story DSFs consumed over 250,000 kWh less energy than those without DSFs. Both the orientation of façades and the number of DSFs play a significant role in enhancing a building's energy performance.
(Shin and Jang, 2015)	X= Combination of transparent and opaque materials, Proportion between floor level and screen height, Orientation, Cavity depth Y= Building's cooling loads, Energy efficiency	S/ IESVE	Csa, Bsh	E	multi-story	DSFs to be successful in hot climates, careful consideration must be given to specific parameters (like orientation and cavity depth) based on the building's location and microclimate. This can significantly reduce a building's cooling loads and improve energy efficiency.
(Hilal et al., 2023)	X= Cavity size, Glass types, Orientation Y= Energy consumption (Cooling), U-Value of DSF	S/ EP	BWh	R	multi-story	The use of a double-skin façade (DSF) with a 35 cm cavity, consisting of an inner double-glazed layer and an outer Low-E double-glazed layer, significantly reduces cooling energy consumption in high-rise residential buildings located in hot climates. Improvements include lower U-value, reduced cooling load, and maintaining a comfortable indoor temperature range of 21–26 °C for most of the year. This system proves effective during hot months, while in cold months it does not result in significant energy savings.
(Huang et al., 2023b)	X= Cavity gaps, Ellipse aspect ratios, Glass properties, Solar radiation intensities and solar incident angles Y= Natural ventilation cavity air velocities, Facade temperatures, Cavity temperature	N, E/CFD	Cwa	C, T	Curved	The ideal cavity width for a curved double-skin façade (CDSF) lies between 0.75 and 1 m. The best ellipse aspect ratio is 0.5, at which point ventilation efficiency rises sharply and then declines beyond it. Substituting clear glass with Low-E glass increases airflow within the cavity by 8.20% on the inner façade and 21.31% on the outer façade. The angle of solar incidence also plays a crucial role: when the angle exceeds 45°, ventilation fluctuations in CDSFs become much more pronounced compared to lower angles, whereas in planar double-skin façades (PDSFs), this effect is considerably smaller.
(Huang et al., 2023a)	X= Reynolds number, Grashof number, Scales and ellipse aspect ratios, Solar radiation intensities, Solar incident angles Y= Cavity air temperature, Outlet velocities	M, E/CFD	Cwa	C, T	Curved	The thermal similarity model is valid (errors <15%). Similarity improves with higher Re (or Ri <1 if Re cannot increase). Best results occur with solar radiation 200–400 W/m ² , angles 45°–60°, model scale 1/20–1/50, and ellipse aspect ratio <1; extreme values increase errors.
(Huang et al., 2022b)	X= Solar irradiation, Outdoor air temperature, Measured points and positions Y= Cavity air temperature, Cavity Air velocity, Thermal pressure	E	Cwa	C, T	Curved	The curved double-skin façade (CDSF) induces thermal buoyancy-driven flow, with thermal pressures stabilizing between 0.056 and 0.063 Pa under 120 W/m ² solar radiation and 30°C outdoor air. Solar irradiance on the curved surface is highly non-uniform—averaging 30.05% vertically and 9.12% horizontally—compared to planar façades (1.88% vertical, 1.68% horizontal), emphasizing the need for precise geometric analysis. Solar radiation is the primary factor affecting cavity temperature and airflow, and the curved geometry of CDSFs leads to a stronger dependence on solar input than in planar double-skin façades.

Variables: X= Inputs, Y= Outputs/ **Methodology:** S= Simulation, E= Experimental, N= Numerical/ **Tools:** M= Matlab, PVs= PVsyst, EP= EnergyPlus, EES= Engineering Equation Solver, SN= Sensor, P= Python, ESP-r= Environmental Systems Performance – Research/ **Type of Building:** O= Office, E= Educational, C= Commercial

Tab. 5. Climate response and environmental performance of different DSF. (Source: Authors, 2026)

DSF Category	Key Design Parameters	Primary Applications	Optimal Climate Conditions	Ventilation Strategy
Box Window	Cavity depth Individual unit dimensions Shading integration	Office buildings Low rise building	Hot climate	Mechanical/hybrid
Corridor	Corridor width Vertical opening configuration Wind characteristics	High-rise buildings Wide facade sections	Diverse climates	Natural/mechanical
Shaft Box	Cavity width/depth Opening dimensions Building orientation	Multi-floor integration High-rise buildings	Cool climates	Natural stack effect
DGGF	Window size/position Cavity depth Shading configuration	Office buildings Mediterranean climate	Mediterranean	Horizontal/swirling
Multi-story	Cavity depth Vent configuration System integration	High-rise buildings Integrated systems	Mediterranean/Temperate	Integrated systems
Curved	Façade shape Cavity gap size Opening configuration	High-rise buildings Wind-prone areas	Diverse climates (Wind prone areas)	Natural/mechanical

The review also identifies key research gaps. While box-window DSFs have been extensively studied for thermal performance, long-term operational data and occupant interaction remain underexplored. Corridor-type systems need further aerodynamic studies (Hu et al., 2017; Bielek et al., 2022), and shaft-box DSFs require advancements in fire safety and stack effect management. Research on DGGFs should expand to material durability and smart glazing integration, while multi-story configurations need better height-specific optimisation (Wang et al., 2020; Shakouri et al., 2020). Curved DSFs also demand more studies on geometry optimisation, cost-effectiveness, and seasonal adaptability (Jafari and Alipour, 2021).

5.2. Research methodologies and tools

Research methodologies predominantly utilise computational fluid dynamics (CFD) tools like ANSYS Fluent (Colombo et al., 2017; Jafari and Alipour, 2021), building energy simulation software such as EnergyPlus (Mazzarella, 2015; Khoshbakht et al., 2013), and experimental methods like wind tunnel testing. Combined approaches, integrating CFD with experimental validation (Jin et al., 2012; Li et al., 2012) and simulations with field data (Shakouri et al., 2020; Seo et al., 2019), are enhancing reliability. However, standardised testing protocols and holistic performance evaluations remain critical needs. DSFs are highly effective in enhancing energy efficiency, achieving heating and cooling demand reductions of 15–59% depending on design and climate, while improving thermal performance by lowering peak indoor temperatures by up to 3.8°C in summer and enhancing heat retention in winter. They significantly boost natural ventilation, with some configurations reaching 71.3% efficiency in hot seasons, and exhibit exceptional adaptability across various climatic conditions, including tropical climates.

The review's findings align with previous research demonstrating the significant thermal benefits of DSFs (Inan and Basaran, 2019; Jankovic and Goia, 2021). Studies on specific DSF configurations show that optimal thermal performance and comfort can be achieved through careful design choices. For instance, in a naturally ventilated building under tropical climate conditions, optimising the characteristics of a shading device and the free area of window openings are the most influential parameters for thermal performance. Extending the cavity height by one and a half

floors above the roof can also prevent reverse airflows on upper floors, leading to more uniform airflows throughout the building (Barbosa et al., 2015).

Further numerical and experimental investigations highlight the importance of understanding the fluid dynamic and heat transfer behaviours within the DSF cavity (Jankovic and Goia, 2021). For example, studies in a hot climate have shown that the interaction of wind velocity and air gap width is crucial for maintaining thermal comfort in naturally ventilated buildings with multiple skin façades (Barbosa et al., 2015). The use of opaque double façades has been found to reduce heat loss in the heating season and provide better protection against overheating in the summer (Barbosa et al., 2015; Nowark et al. 2014). However, the potential for overheating in DSFs is a significant, largely unresolved problem. Some buildings have attempted to solve this with automated glazed louvers, but this can be expensive and may compromise acoustic performance. Mechanical extraction of air from the cavity is another approach, but this may increase energy and maintenance costs compared to naturally ventilated DSFs.

5.3. Validation challenges and modelling limitations

A systematic analysis of building performance simulation methodologies reveals critical inadequacies in validation that compromise the reliability of DSF research. Box-window DSF studies demonstrate validation errors ranging from 5–9% for configurations without louvers to 13–27% for systems with adjustable louver angles, indicating that computational fluid dynamics models fail to capture complex airflow interactions within confined spaces. These studies relied primarily on temperature measurements while neglecting velocity profile verification, creating incomplete validation frameworks that mask significant modelling deficiencies (Wong et al., 2008). Corridor-type DSF simulations exhibit discrepancies of up to 15% when comparing CFD predictions with experimental measurements, particularly when modelling wind-driven cavity flows. In these cases, the turbulence intensity and flow separation effects exceed the capabilities of the standard k-ε turbulence models employed in ANSYS Fluent applications (Aldawoud et al., 2021).

Shaft-box DSF configurations present the most severe challenges in simulation validation, with fire dynamics modelling revealing

the inadequacy of standard building energy simulation tools in emergency scenarios. Fire dynamics simulator (FDS) applications demonstrate that smoke propagates through vertical cavity systems in ways that conventional energy modelling tools cannot predict. This exposes dangerous gaps in safety assessment capabilities (Li et al., 2012). Multi-story DSF validation studies reveal a systematic underestimation of the influence of the stack effect, with measured cavity temperatures exceeding simulated predictions by up to 8°C during periods of peak solar radiation. This indicates fundamental inadequacies in the modelling of heat transfer in vertically extended cavity systems (Hilal et al., 2023).

5.4. Economic assessment

The economic analysis framework reveals a systematic disconnect between the simulated energy performance and financial viability of DSF systems, calling into question the fundamental utility of current building energy modelling approaches. Although box-window DSF implementations demonstrate energy consumption reductions of 7.9–14.8% in simulation studies, life-cycle economic analyses highlight the influence of construction complexity, maintenance requirements, and embodied energy implications on their overall feasibility. ECC index analysis shows that although operational CO₂ reductions are 14–17%, embodied carbon increases are 23.3–47%. This results in carbon payback periods of 4.6–7.6 years, which building energy simulation tools ignore due to their focus on operational energy (Zomorodian and Tahsildoost, 2018).

A corridor-type DSF economic assessment reveals significant disparities in cost-benefit between simulated performance and implementation reality. Although CFD studies demonstrate wind power density improvements, the economic analysis of wind energy integration is completely absent from building performance simulation frameworks. The required aerodynamic modifications involve structural alterations and maintenance complexities that standard economic modelling protocols fail to quantify. This creates misleading impressions of DSF viability based solely on energy performance metrics (Hassanli et al., 2018; Bielek et al., 2022).

5.5. Climate-dependent performance

A climate-dependent performance analysis reveals fundamental limitations in building energy simulation tools when applied to dynamic shading system (DSF) across different environmental conditions. Shaft-box DSF simulations predict consistent performance characteristics across climate zones. However, measured data reveal significant variations, ranging from 51% energy savings in temperate climates to 16% in warmer regions. This indicates that standard weather file applications inadequately represent the effects of local microclimates on cavity thermal behaviour. Simulation models also fail to capture critical climate-specific phenomena, such as reverse airflow patterns in box-window DSFs and excessive cavity overheating, which can reach temperatures 15.9°C higher than ambient temperatures in hot climates (Colombo et al., 2017; Ramessur and Gooroochurn, 2021; Aruta et al., 2023).

Performance simulations of double-glazed glass façades (DGGFs) demonstrate an inability to accurately model horizontal versus vertical louver configurations. Measured natural ventilation rates show that horizontal louvers perform 73% better than vertical louvers, but simulation predictions underestimate the effects of convective heat transfer by 15–25% (Bao et al., 2022; Hong et al., 2013). Building energy simulation tools used in studies of Mediterranean climates systematically overestimate cooling energy savings by failing to account for increased solar heat gain through

enhanced convective flows. This results in performance predictions that exceed measured outcomes by 12–18%.

Curved DSF thermal similarity modelling reveals fundamental inadequacies in computational approaches for complex geometries. Experimental validation shows that the optimal ellipse aspect ratio is 0.5, which standard building geometry modelling tools cannot accurately represent. Thermal similarity models are valid only under specific conditions: solar radiation of 200–400 W/m², angles of 45–60°, and model scales of 1/20–1/50 (Huang et al., 2023b). However, building energy simulation applications often extrapolate beyond these validated parameter ranges without acknowledging modelling uncertainty. The non-uniform solar irradiance distribution in curved configurations averages 30.05% vertical and 9.12% horizontal variation. This exceeds the spatial resolution capabilities of standard building energy modelling mesh structures (Huang et al., 2022).

Multi-story DSF configurations reveal critical limitations in the scaling of building performance simulation tools. Three-DSF implementations demonstrate a 28% reduction in heating energy and a 53.5% reduction in cooling energy, which cannot be accurately predicted using the single-zone modelling approaches commonly employed in building energy simulations. Cavity thermal stratification effects in vertically extended systems create temperature gradients that standard zone-based modelling approaches cannot capture (Ahriz et al., 2022). This results in a systematic underestimation of performance benefits in lower floors and an overestimation in upper building zones.

5.6. Integration of renewable energy

Standard building energy tools have a hard time working with renewable energy systems, especially for direct steam flash (DSF) applications. Studies show that traditional energy software cannot properly track how heat moves between solar panels and DSF cavity airflows. Because of this, predicted efficiency can be off by 15 to 30% compared to real-world performance (Shakouri et al., 2020). Also, manually moving data between software like EnergyPlus and specialised solar tools causes constant errors and stops engineers from running smooth, integrated optimisations (Piccolo et al., 2018). In the same way, linking structural design tools with energy software is still mostly a manual, error-prone process, which blocks systematic improvements that could make DSF designs much more reliable.

5.7. Standardisation and comparative analysis across studies

A comparative analysis of DSF configurations reveals a complete absence of standardised simulation protocols, validation requirements, and performance reporting frameworks that would enable meaningful cross-study comparisons. Box-window DSF studies use cavity depth specifications ranging from 300 to 900 mm without standardised geometric modelling approaches (Ramessur and Gooroochurn, 2021; Wong et al., 2008). Meanwhile, corridor-type studies use air gap sizes ranging from 75 cm to 1 m with inconsistent boundary condition specifications, which prevent reliable performance benchmarking. Thermal comfort assessment protocols range from simple temperature verification to comprehensive predicted mean vote (PMV) calculations, creating incomparable comfort performance claims across different DSF implementations (Hilal et al., 2023; Huang et al., 2023b).

The selection of building energy simulation tools shows a systematic bias toward specific platforms without technical justification. Sixty-seven percent of studies employ EnergyPlus or IDA-ICE without comparative validation against alternative simulation approaches. Validation requirements range from simple

temperature comparisons to comprehensive velocity profile verifications, yet no standardised protocol exists to ensure minimum acceptable accuracy levels across different DSF applications. This methodological inconsistency hinders the development of reliable design guidelines and performance expectations, which are necessary for evidence-based DSF implementation decisions in building practice (Jankovic and Goia, 2022a; Bao et al., 2022).

5.8. Scientific contributions and research directions

The article's strength lies in its rigorous and contemporary approach to advancing the scientific discourse on DSFs. As a systematic review, its methodological strength lies in its comprehensive synthesis of 80 articles published between 2019 and the present. Its deliberate focus on the most recent literature distinguishes it from older, less focused literature reviews, establishing it as a critical, up-to-date reference for the field. The review aggregates existing knowledge and establishes a new baseline for understanding the current state and future trajectory of DSF research.

The document's scientific value lies in its unique contributions to specific, under-explored aspects of DSF technology. It provides a novel analysis of the potential for DSFs to be integrated with renewable energy systems — a crucial, modern area of sustainable design that has not been discussed in other documents. The article addresses the challenges facing current research, a topic not covered in previous studies (Poirazis, 2004; Andreeva et al., 2022). These challenges include climate-specific optimisation, multifunctional façade designs, and integrating smart technologies for adaptive control (Aksamija, 2018; Aleksandrowicz and Yezioro, 2018). Proactively identifying research frontiers is a hallmark of significant scientific articles because they answer questions and generate new, important ones for the scientific community to pursue.

Existing research shows that shaft-box and multi-story corridor DSF configurations have been studied much less than other system types. This disparity in research focus limits our current understanding of DSF performance in diverse architectural applications. Shaft-box configurations involve vertical air channels within building cores, and multi-story corridor systems span multiple floors. These configurations present unique thermal dynamics and airflow patterns that differ considerably from those of conventional single-story or curtain wall DSF installations. The limited investigation of these configurations hinders the development of design guidelines and performance optimisation strategies for these specific typologies.

6. Discussion and conclusion

A critical evaluation of the 80 reviewed articles reveals that current DSF research is heavily constrained by idealised simulation models and a persistent 'optimism bias' that over-reports thermal gains while downplaying economic realities and embodied carbon trade-offs. The prevailing literature tends to gloss over severe validation discrepancies and real-world operational degradation. Consequently, future research must abandon isolated energy-efficiency metrics in favour of multi-objective frameworks that rigorously account for embodied carbon, economic payback periods exceeding standard building lifespans, and structural constraints.

Recent systematic reviews have significantly advanced DSF research across three key domains. First, in architectural integration, studies have established critical design parameters for curved geometries and building retrofit applications (Liu et al., 2023). Second, in energy performance analysis, researchers have developed innovative approaches including photovoltaic

integration, comprehensive 4E (energy-exergy-exergoeconomic-environoeconomic) assessment framework, and active cooling techniques (Shin and Jang, 2015; Abtar, 2021). Third, climate-specific optimisation studies have yielded important findings for hot-humid and subtropical summer conditions. While these contributions provide valuable insights into geometric, operational, and climatic factors, opportunities remain for more holistic approaches that better integrate architectural design with quantifiable energy performance across diverse climate zones. This systematic review prioritises the development of adaptive DSF systems that simultaneously address: (1) architectural dimensions, (2) energy efficiency and occupant comfort, and (3) dynamic response to varying climatic conditions.

Beyond academic contributions, the synthesised findings offer direct practical implications for architects, engineers, and building designers navigating early-stage façade decisions. For architects, the systematic classification of DSF typologies (such as box-window, corridor, and multi-story configurations) provides a clear framework to match aesthetic and geometric constraints—including curved geometries—with appropriate climatic zones based on Köppen classifications. For building services engineers, the review highlights critical operational parameters, such as optimal cavity depths (0.75 to 1 meter) and dynamic ventilation strategies, which are essential for sizing HVAC systems, mitigating overheating risks, and integrating renewable energy options like photovoltaics. Ultimately, bridging these theoretical insights with real-world design protocols empowers practitioners to balance energy efficiency, occupant thermal comfort, and structural feasibility from the onset of a project.

This systematic review addresses a critical research gap by providing the first comprehensive architectural classification system that categorises DSFs into six distinct types—box-window, corridor, shaft-box, DGGF, multi-story, and curved configurations—with detailed performance characteristics, optimal climate conditions, and practical implementation guidelines for each category. Unlike previous reviews that focused on specific technical aspects, our study bridges the gap between theoretical research and practical application by integrating architectural design perspectives with energy performance analysis, providing climate-specific recommendations that enable stakeholders to select appropriate DSF types based on Köppen climate classifications and building requirements.

Furthermore, our review addresses the standardisation gap by establishing a unified framework for DSF categorisation that facilitates meaningful cross-study comparisons, while our bibliometric analysis and keyword co-occurrence networks provide quantitative insights into research trends and identify emerging areas such as renewable energy integration and smart building technologies. By distinguishing between architectural and energy integration components, our classification system enables better assessment of practical applications and benefits, ultimately contributing to more informed decision-making in DSF design and implementation across diverse climatic and architectural contexts.

This comprehensive review of DSFs underscores their significant potential in enhancing building performance across diverse climatic conditions and architectural contexts. The analysis of various DSF categories—including box-window, corridor, shaft-box, double-glazed glass, multi-story, and curved configurations—reveals their versatility in addressing multiple aspects of building efficiency and comfort. DSFs consistently demonstrate substantial energy savings, with reductions in heating and cooling demands ranging from 15 to 59%, alongside improvements in thermal comfort, natural ventilation, and daylighting. Looking forward, the field of DSF technology presents exciting opportunities

for innovation and research. The trend towards smart, adaptive façades that can respond dynamically to changing environmental conditions promises to further enhance the effectiveness of DSFs.

Future research must pivot from isolated performance reporting toward a standardised, cross-comparative framework. Specifically, research must address three pillars: (1) Climate adaptation, by moving beyond static classifications to evaluate resilience under extreme events and microclimatic shifts; (2) Emerging technologies, by developing coupled modelling frameworks for smart materials and renewable energy integration; and (3) Integrated façade design, by prioritising full-scale longitudinal studies and life-cycle economic assessments. Only through such rigorous, holistic inquiry can DSFs transition from luxury architectural features to reliable, sustainable solutions in the built environment.

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