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Exploring the advantages and challenges of double-skin façades (DSFs)

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A B S T R A C T

With the global target to promote energy saving in buildings, various studies draw attention to the role of environmentally benign building envelopes. In this regard, double-skin façades (DSFs) have been proposed as a promising passive building technology to enhance the energy efficiency and improve the indoor thermal comfort at the same time. A comprehensive analysis of the current design of DSFs, and their technical aspects is presented in this paper. Construction characteristics of DSFs are also reported. The impacts of DSFs on the energy efficiency and thermal performance are discussed by looking at measured and simulated performances. Findings confirm that significant benefits result from using DSFs. Finally, research opportunities are outlined for further investigation.

Contents

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1. Introduction

Sustainable development principles in the built environment have encouraged researchers to focus on more efficient building envelopes. Façades, as a principal constituent of building envelopes, have a vital role in protecting indoor environments and controlling the interactions between outdoor and indoor spaces. Nevertheless, conventional façades can lead to poor natural ventilation, low level of daylighting, thermal discomfort, and increased energy consumption. These disadvantages are often intensified in modern façades having substantial amounts of glazing [2]. As the result of high solar thermal gains or significant thermal loss at night or in cold climate, extensive glass curtain walls cause significant energy consumption [3]. In recent years, new façade technologies have been designed and proposed for better thermal insulation, shading the solar radiation, improved thermal comfort and visual quality [4,98]. Among the emergent advanced façades, double-skin façades (DSFs) have been proposed as an efficient solution to control the interactions of indoor and outdoor environments [5–18]. As a basic definition, "*Double-skin façade is a special type of envelope, where a second "skin", usually a transparent glazing, is placed in front of a regular building façade*" [8]. DSF refers to a building façade covering one or more levels with multiple glazed skins, separated by an air gap, with the common attribute of controllable shading system and airflow within the cavity between the skins of the façade [2]. The air space between the two layers of DSFs performs as an insulating barrier against the unwanted impacts of microclimatic conditions. The ventilation of the cavity can be natural or mechanical [2]. DSF technology can result in full height glazing, particularly for tall buildings, while protecting the indoor ambient and enhancing the daylighting, thermal comfort and energy efficiency [93].

With their potential for a desired facade transparency and their capabilities for reducing thermal gains and losses, as well as their aesthetic appeal, DSFs are globally accepted [19–21]. Different attempts have been made to analyze and optimize the thermal energy performance of DSFs in different regions and climates. Globally diverse climatic conditions need to be considered in order to rationalize the use of DSFs [22]. This study provides a broad review of the environmental benefits of DSFs, as well as a confirmation of their economic feasibility. The observed challenges and obstacles are expressed together with the current implementations and future development.

2. Overview of literature on double-skin façades (DSFs)

2.1. Essence of DSFs

Glass façades are widely used for modern architectural projects, particularly commercial buildings, due to their aesthetics, lightweight and daylight potential. In spite of their universal employment, single-layer glass façades have common weaknesses that should preclude (or at least moderate) their use in certain circumstances, such as poor thermal insulation and sound reduction index [10]. Application of DSFs to overcome these problems is widely accepted as offering significant opportunities to reduce energy consumption and thus to improve the sustainability of buildings.

The first DSF integrated in a building was observed in a factory designed by Richard Steiff in Giengen, Germany in 1903 with attention to the cold weather and strong winds of the region and the target of daylighting enhancement [86]. Despite being predominantly used in European region, in recent years, DSFs are gaining more and more popularity in North America and Asia [87].

Studies about DSF performance can be categorized based on the study approaches into analytical and lumped models [24], dimensional analysis [19], network and zonal models [25], and air flow network linked with energy simulation [26]. Moreover, computational fluid dynamics (CFD) models have been applied to investigate the performance of naturally [8,27] and mechanically-ventilated façades [28].

DSFs have been characterized as multiple skins [30]. They were developed as an effective enhancement of traditional façades for colder climates [9], although their application in hot climates has often been reported [9]. In general, DSFs can be applied to both new and renovated buildings [9]. According to [25], "*The ventilated cavity functions as a thermal buffer, which reduces problems such as undesired heat gain during the cooling season, heat loss during the heating season and thermal discomfort due to asymmetric thermal radiation*".

This study targets to explore the diversified benefits of DSFs [32] including 'energy consumption reduction', 'ventilation, airflow and thermal comfort enhancement', 'daylighting and glare control', 'sound insulation, noise reduction and acoustic enhancement' and 'visual and aesthetic quality enhancement' as summarized in Table 1. Moreover, the study also investigates the possible disadvantages of DSFs such as high investment cost, excessive heat gain due to high U-value, risk of overheating in hot sunny days, and asymmetric thermal radiation and consequent thermal discomfort [33].

Table 1
Identified environmental and economic benefits of DSFs.

No	Main identified benefits		Key references
1	Environmental benefits	Energy consumption reduction	[16,21,29,31,86]
		Ventilation, airflow and thermal comfort enhancement	[1,10,16]
		Daylighting and glare control	[2,10,31,86]
		Sound insulation, noise reduction and acoustic enhancement	[31,34,86]
		Visual and aesthetic quality enhancement	[9,16,21,32]
2	Economic benefits	Reduced long-term cost	[2,16,86]

Table 2 highlights the key findings of recent studies with focus on the evaluation and optimization of the overall sustainable performance of DSFs.

2.2. Classification of DSFs

DSFs cover several levels of a building with multiple skins and can be generally classified into air tight or ventilated [1]. DSF typologies are also classified according to their ventilation strategies in cavity [2]. It is essential to denote that air-tightened DSF enhances the thermal insulation in winter while ventilated DSFs receive heat energy from sun-lit and decrease the heat gain in summer [1].

DSFs are principally categorized into two types of design. In the first type, the internal skin of each level of building is covered by an external skin while the air cavity of that particular level is separated from others or, the entire internal skin is covered by an external layer and the air cavity in all different floors are connected [36]. DSF design classifications and working modes are represented in Fig. 1.

DSFs are categorized according to four conditions of 'closed', 'mechanical exhaust', 'natural convection to outside' and 'window ventilation'. They are similarly categorized according to their level of skin coverage as 'window', 'storey' or 'multiple storey' [37,38].

In addition to the discussed classifications, researchers classify DSFs into box window façade, shaft-box façade, corridor façade and multi-story façade [39,40].

A key principle in the design of DSFs is the airflow. Airflow in different seasonal climates occurs according to different patterns in DSFs as illustrated in Fig. 2.

Table 2
Key findings of recent studies about the benefits of DSFs.

Type of DSF design	Location/climate	Key findings	Key references
Naturally ventilated DSF	Sub-tropical Hong Kong	A set of correction factors for OTTV calculation of air-conditioned commercial buildings constructed with naturally ventilated DSF.	[1]
Novel photovoltaic DSF	Sub-tropical climate	Ventilated PV-DSF provides the lowest solar heat gain coefficient (SHGC), while the non-ventilated PV-DSF better reduces heat loss.	[3]
Multistory DSF	Sunny summer day, Uccle, Belgium	The night natural ventilation is highly effective.	[5]
Single floor DSF equipped with a venetian blind	–	The distance between the blind and the external glazing has significant influence on the velocity profiles inside the facade channel.	[8]
DSF with thermal mass	–	Mechanically ventilated DSFs can save energy from 21% to 26% in summer and 41–59% in winter.	[21]
Typical DSF (clear, absorptive or reflective glass)	Hong Kong	DSF system with single clear glazing as the inner pane and double reflective glazing as the outer pane results in an annual saving of approximately 26% in building cooling energy.	[29]
Typical DSF	Seoul, Korea	Use of DSF is credited with providing 5.62% reduction in energy consumption. Decreasing the cavity depth of the DSF resulted in decreasing the energy consumption.	[47]
DSF with plants	–	Temperature of each layer of the DSF was approximately twice lower for the case with plants than with blinds. Use of plants in the DSFs (in naturally ventilated buildings) decreases the operation time of ventilation in the warm period and increases the operation time in the cold period.	[51]
Typical DSF	Kitakyushu of Japan	10–15% energy saving for cooling in summer plus 20–30% energy saving for heating in winter.	[68]
Typical DSF	Central European moderate climate	7% cooling energy saving compared to double/triple glazed façades.	[89]
Ventilated opaque DSF	–	Exhaust air facade configuration (EAF): heat loss reduction between 43–68%, Supply air facade configuration (SAF): pre-heating efficiency between 9%-20%.	[90]
Mechanical dsf	Summer time, Tokyo, Japan	Temperature reduction of double-skin space by 1 C.	[91]
Double skin glazed façade (DGF)	Sunny Mediterranean climates, Northwest region of Argentina, spring/summer	Well-designed DGFs can decrease the summer energy consumption of buildings, even using West DGFs, in sunny climates.	[92]
Multi-storey naturally ventilated DSF	Belgrade, Serbia	DSF does not necessarily decrease energy consumption.	[94]
Typical DSF	Hot and dry climate, Iran	Increasing airflow velocity within the cavity solves the overheating problem and allows DSFs to perform in hot and dry climates.	[95]

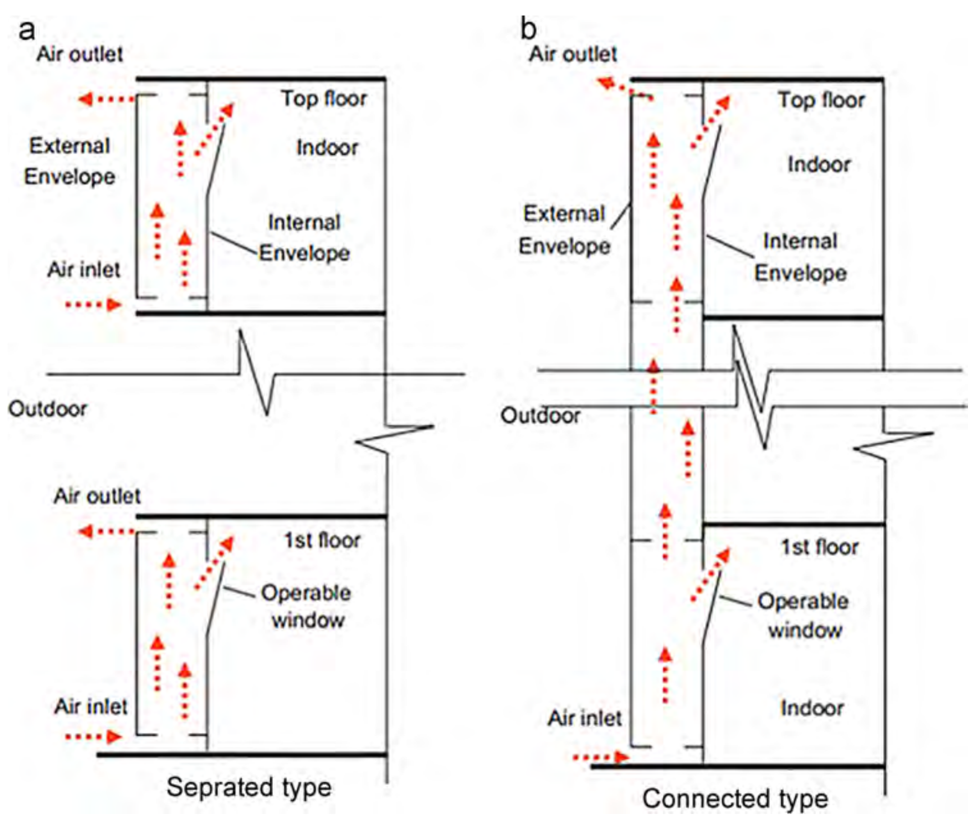

Fig. 1. *Top* Design classification of DSFs, *Bottom* Schematic representation of the working modes for DSFs, Source [36].

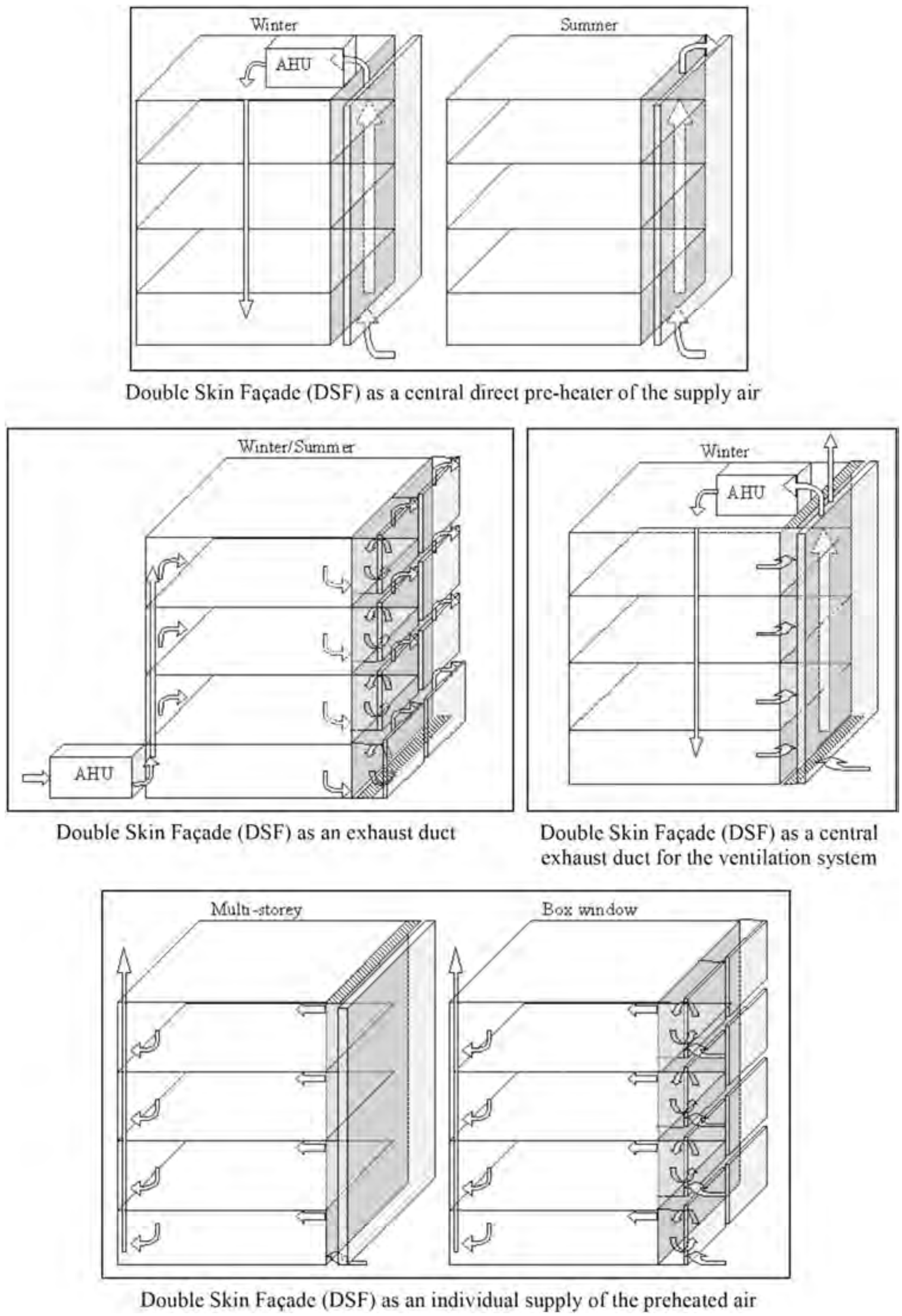

Fig. 2. Different airflow patterns in DSFs. Source [35].

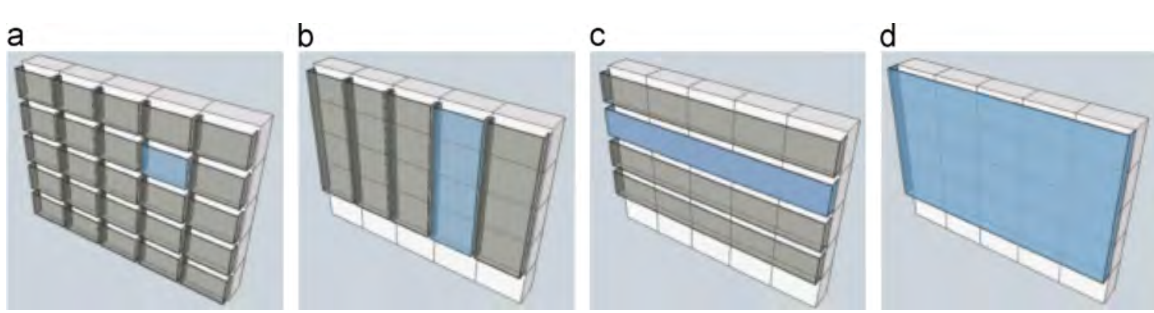

Fig. 3. Another categorization of DSFs: (a) Box window, (b) shaft-box, (c) corridor and (d) multi-storey double skin façade. Source [33].

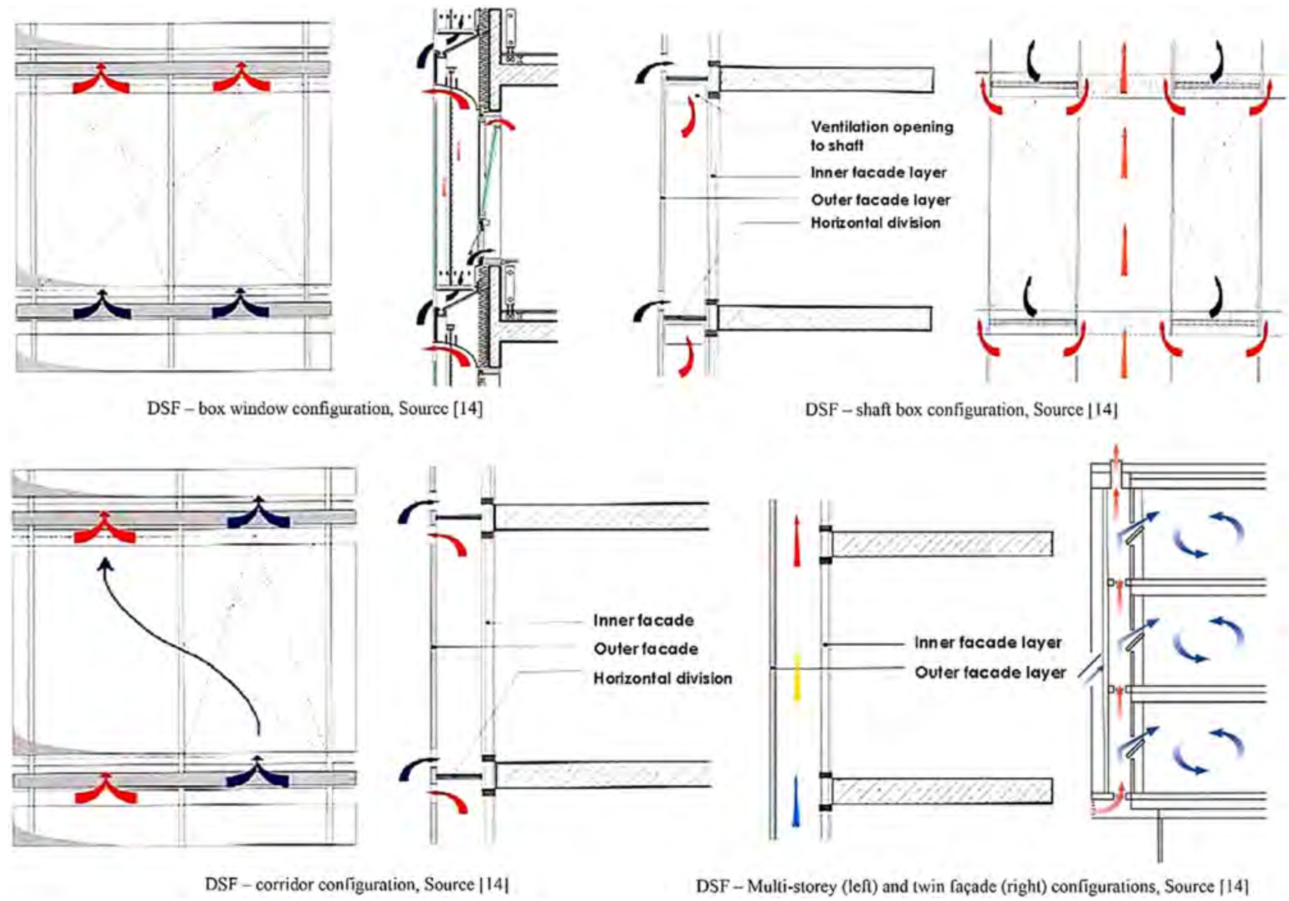

Fig. 4. Different configurations of DSFs, Source [14].

Fig. 5. Düsseldorf city gate DSF, Germany. From the left: The face; DSF cavity; Interior glazing. Source [35].

Furthermore, DSFs are developed in diverse configurations. A recent study [14] represented a series of these configurations as shown in Fig. 4.

Example of DSFs are reported in Figs. 3,5–9.

3. Techinical aspects of double-skin façades (DSFs)

3.1. Overview

Technically, DSFs encompass three main components: external façade layer, intermediate space and internal façade layer [30]. DSFs are developed based on external glazing offset from internal glazing [15]. Shading devices are also integrated into the air channel for reducing the cooling load of indoor spaces cause by highly intensified solar radiation [9]. It is also noted that both internal and external layers encompass adequate openings for ensuring natural ventilation in cavity and interior spaces adjacent to façade [34]. The integration of passive design strategies such as DSF technology in building envelopes is expected to occur at the conceptual design phase, by defining and controlling the factors that have significant influence on building performance. Literature reveals that the performance of DSFs is predominantly influenced by three key parameters, namely the facade parameter (technical attributes of cavity and external layer), the building parameter (physical formation of the building) and the site parameter (outdoor environmental condition) [33].

Performance of DSFs in different climates is diverse. In cold climates, the role of DSFs is to behave as a heat exchanger, keeping the temperature of internal skin layer close to the desired indoor temperature [9]. In hot climates, DSFs can lead to a low shading coefficient [9]. From a critical perspective, [38] reported that in

Fig. 6. Eurotheum DSF, Germany. From the left: The face; DSF interior; Shading devices. Source [35].

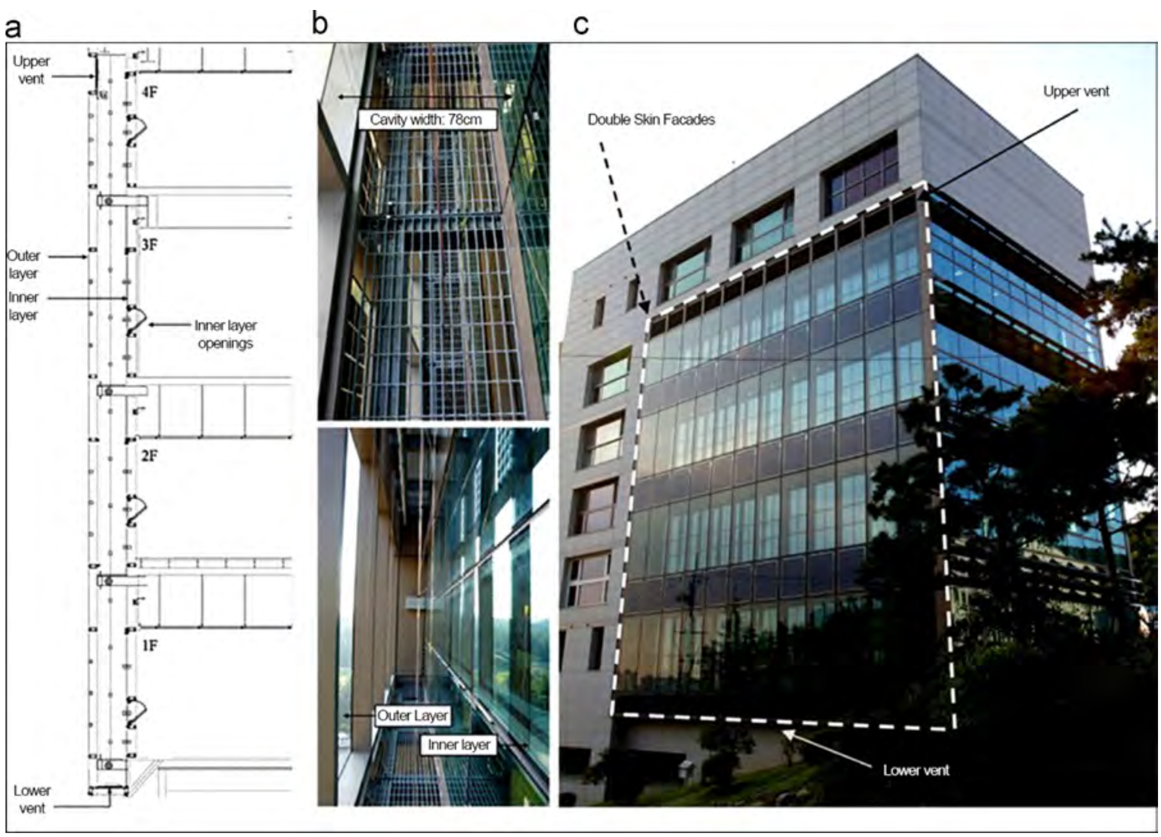

Fig. 7. A multi-story DSF building in Seoul, Korea-From the left: (a) Location of sensors; (b) figure of cavity; and (c) view of the target building. Source [47].

spite of the utilization of DSFs in Central European weather condition is still debatable [44], they are becoming more widespread and popular, mainly due to their aesthetic quality (particularly in commercial buildings). The overall energy efficiency of multiple-skin façades is repeatedly confirmed by many studies.

3.2. DSF cavities

Looking at the technical dimensions, the depth of air cavity or channel has been reported [8] to be between 80 cm and 100 cm. It has been stated that in addition to the maintenance-related issues, the cavity depth relates to the ventilations, green house effects and the energy performance [47]. The depth also needs to be considered according to the climatic conditions of the area where the building is located. By monitoring the influence of cavity depth ranging from 8 cm to 148 cm, researchers found smaller dependence of the energy consumption on the cavity depth compared to the window glazing type. A decrease in initial cavity depth (148 cm) to 78 cm led to similar decrease in heating, as well as an increase in cooling and decrease in total energy consumption by −5.6%. [47] proposed the optimal design strategies regarding the window glazing type and cavity depth. They concluded that the optimal DSF design needs to be considered according to the climatic conditions, price of window glazing types and different lighting energies as well. Furthermore, Fig. 10 represents results of altering DSF glazing types on the building energy performance [33].

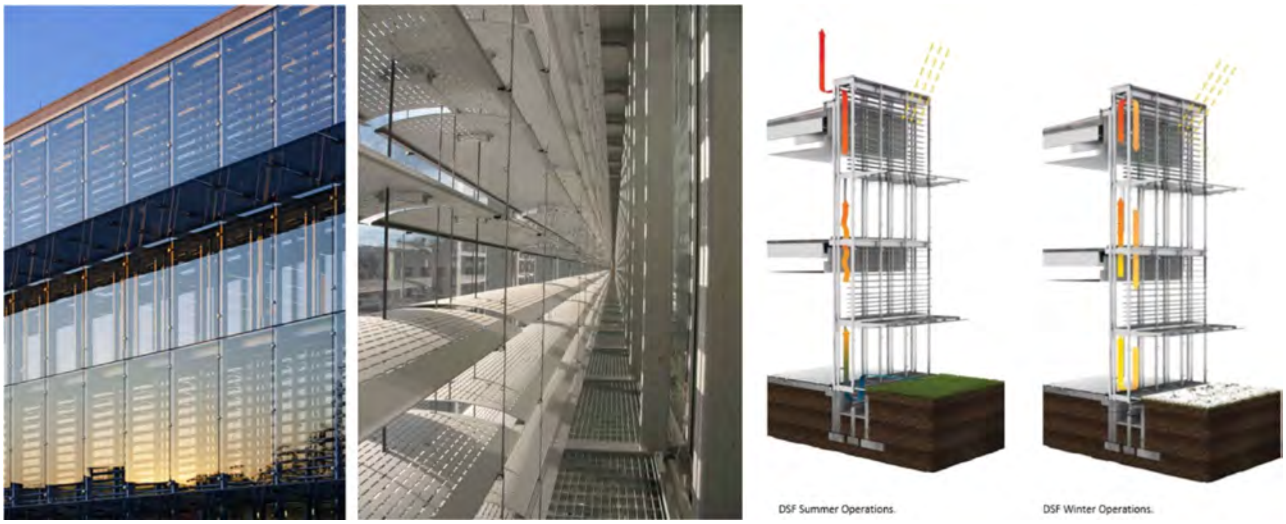

Fig. 8. Cambridge public library, USA. From the left: The face; Cavity; Airflow. Source [43].

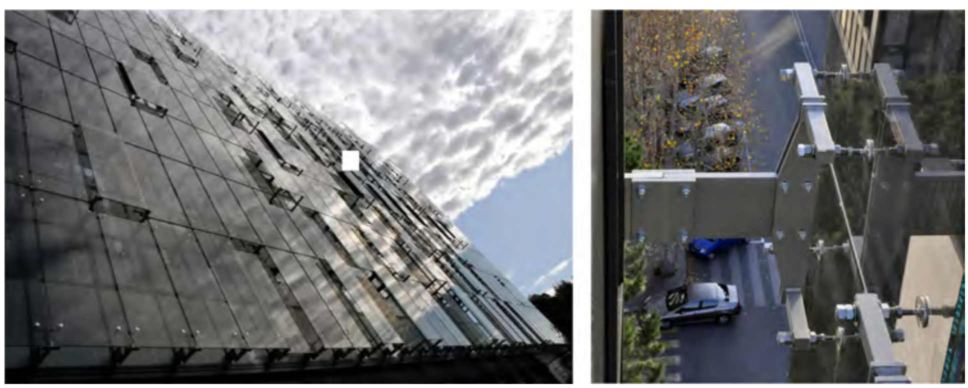

Fig. 9. Piazzale Luigi Sturzo 23–31, Rome, Italy. From the left: DSF; Detail. Source [88].

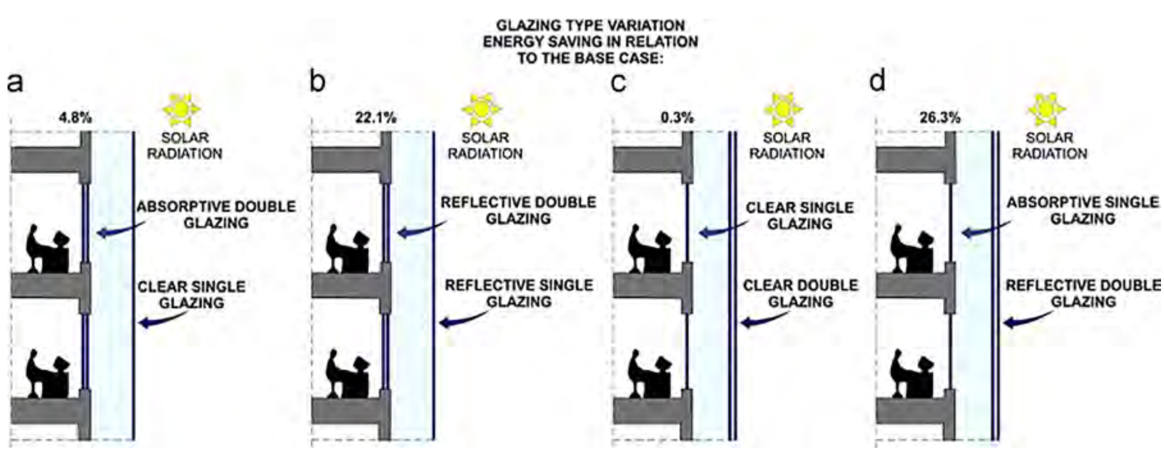

Fig. 10. Performance of a building with DSF under variations of the glazing properties. Source [33,48].

For optimal design of DSFs, a recent study [47] about the typologies of window glazing found that most significant energy consumption alteration was noticed while changing the glazing type of the outside surface of the inner layer (−3.4% to +18.8%). However, the least significant energy consumption alteration was noticed when altering the window glazing type of the inside surface of the inner layer (−1.1% to +4.7%). The results highlight the importance of glazing typologies in the outside surface of the inner layer in terms of heat transfer between a cavity and the adjacent conditioned zones as represented in Fig. 11 [47].

In general, an adjustable shading device such as blinds is integrated with DSFs and located in the air channel for the purpose of thermal control [39,40]. In particular, this is done to protect the interior spaces from increased cooling loads [30,49,50]. Their role is to reduce the heat gain and to behave as pre-heater for ventilation air [51]. The air flow rate and the optical characteristics affect the absorptive temperature increase of the internal shading devices in a DSF system [10]. It has been argued that the temperature of blinds is usually high as an advantage in cold regions and a challenge in hot areas; hence, application of

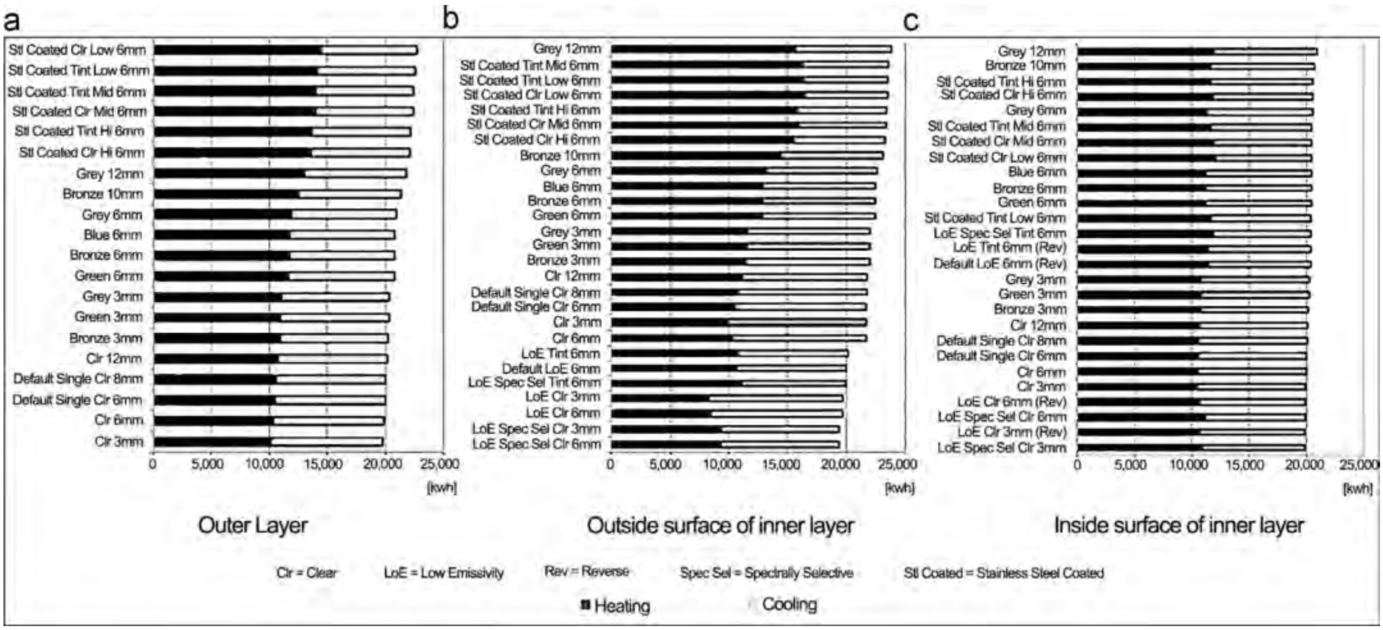

Fig. 11. Parametric study of window glazing types. Source [47].

plants is proposed to tackle this issue [51]. Vegetation in DSFs cavities can lead to other benefits including enhanced thermal insulation, noise reduction, enhanced air quality, Oxygen production, and improved aesthetic [26]. A further enhancement has also been proposed in the form of venetian blinds inside the air cavity – which is similarly suggested to improve the airflow and ventilation [52].

3.3. Glass types in DSFs

The interest in the utilization of glass for coverage of building skins, particularly in commercial buildings, has always been considerable. Recent studies have shown that glass façades could be highly beneficial in winter due to their great potentials for decreasing the costs associated with illumination and heating through maximizing the use of daylight [53,54].

DSFs encompass multiple skin layers, commonly including an external and internal façade skins. Both skins are made of single glazed or double glazed glass panes of float glass or safety glass [39,40]. The external façade skin is commonly a hardened single glazing while it could even be fully glazed [29]. On the other hand, the inner façade skin can be double glazed and in most cases, it is not fully glazed [29]. It is similarly inferred that in DSFs, the external skin is typically made of a hardened single-glazed pane, while the internal skin is made of an insulating double-glazed unit [31]. Other studies proclaimed that solar-control glazing and clear low-emissivity (low-e) coating can also be integrated into the design of DSFs [55]. A small number of studies have investigated thermal characteristics of the glazing type and hereby the energy performance of DSF systems. Studies [56,57] agreed that the energy-related behavior of both Single Skin Façades (SSFs) and DSFs relies on the window glazing type. [47] conducted a parametric study of window glazing types in Korea, consequently for the inner and outer layers, 27 and 20 types respectively. The inner layer appeared to have stronger role on the thermal behavior of the adjacent conditioned zone. Explicitly, the largest variation of energy load was observed when the window glazing type of the outside surface of the inner layer changed (up to almost 19%). In contrast, the smallest change was observed when the inside surface of the inner layer changed.

More recently, many studies have proposed the incorporation of DSFs and PV glazing leading to PV-DSFs. PV-DSFs not only drastically reduce the energy consumption but also generate electricity and thermal energy in situ [45] – thus becoming a net contributor to building power requirements. Deploying *EnergyPlus*, a simulation study conducted by [60] showed 23% and 16.4% reduction in the total energy use for a PV window with window wall ratio of 50% compared to single-glazed and double-glazed windows, respectively.

3.4. Heat transfer in DSFs

According to [9], "*energy consumption of buildings with double-skin façade strictly depends on the thermal performances, especially the thermal heat transfer and solar heat gain which differ with seasons and latitude location*". DSFs could significantly reduce heat transmission into the building envelope [29]. The moving channel air within the intermediate space can absorb the heat energy of sun-lit which may decrease the heat gain and reduce the cooling loads. Likewise, air-tightened DSFs enhance the thermal insulation which could contribute to decreasing heat loss in cold seasons as illustrated in Fig. 12 [29].

In order to assess the thermal performance of DSFs, different aspects such as the *Overall Thermal Transfer Value (OTTV), Air Velocities, Moving Air Temperature and Pressure Balance* are expected to be measured.

OTTV is "*a measure of average heat gain transferring into a building through the building envelope*"[62]. It is generally utilized to compare different building designs in terms of thermal performance. OTTV was initially proposed by ASHRAE in 1975 [63]. OTTV is calculated based summing the components by the wall area "*(i) conduction through opaque wall* (Qwc)*, (ii) conduction through fenestration* (Qgc)*, and (iii) solar radiation through fenestration* (Qgsol)" [62].

Fig. 13 represents the airflow and heat transfer in a naturally ventilated DSF.

The temperature difference between the exterior and interior spaces of DSFs in addition to the flow resistance of the flow passage are the key players towards ascertaining the air velocity in DSF cavity space. In order to calculate the respective air velocity and temperature, researchers have developed a pressure-balance equation. "*The pressure balance equates the buoyancy pressure*

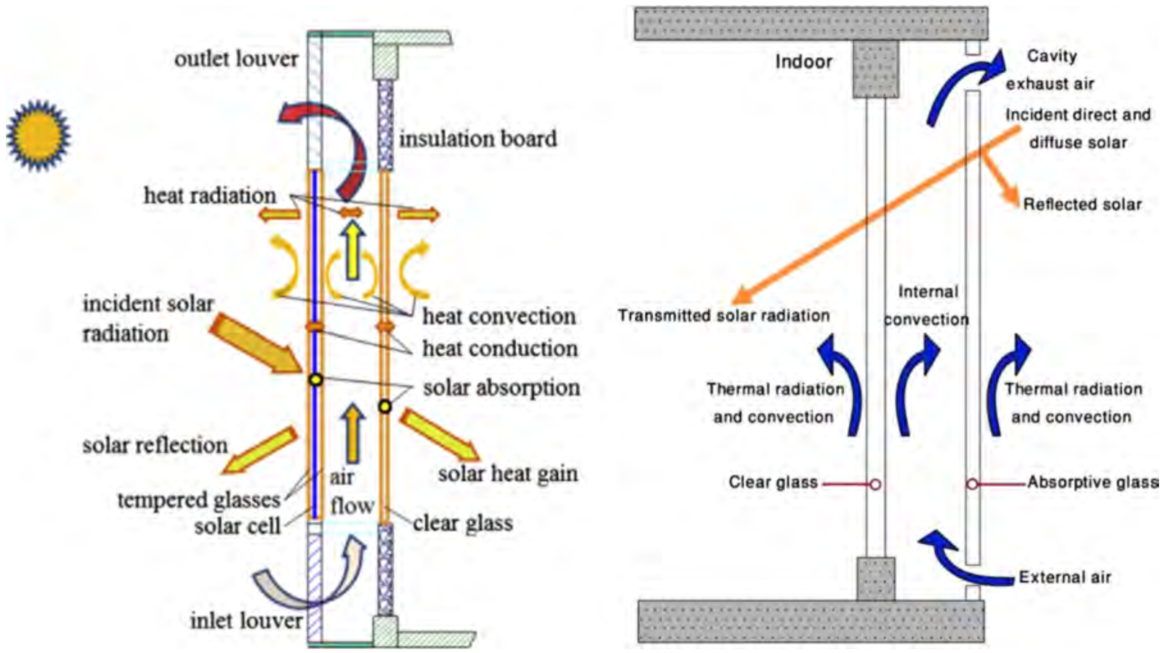

Fig. 12. Right: Airflow and heat transfer within a naturally ventilated DSF system, redesigned from [1] – Left: Energy flows and heat transfer in the ventilated PV-DSF system, Source [61].

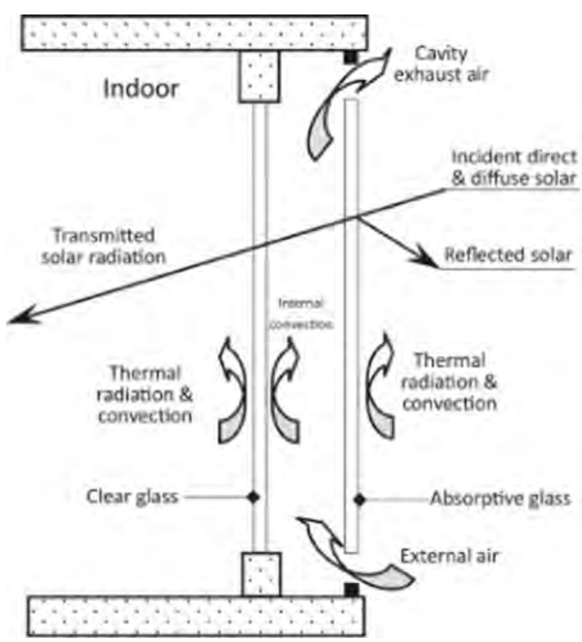

Fig. 13. Airflow and heat transfer within a naturally ventilated DSF system. Source [62].

acting on the cavity air to the pressure losses associated with cavity airflow between the inlet and outlet openings " [62]. The research by [62] suggests the following equations to be used in order to evaluate the discussed measurements.

The pressure-balance:

$$\Delta p_T = \Delta p_B + \Delta p_{HP} + \Delta p_Z \tag{1}$$

Δp_T (driving pressure difference between the outdoor air and cavity air).

$$\Delta p_T = \rho_o T_o g H \sin\phi \frac{|T_{gap} - T_{gap,in}|}{T_{gap} T_{gap,in}} \tag{2}$$

Δp_B-caused by the acceleration of air to velocity v (Bernoulli's law)

$$\Delta p_B = \frac{\rho}{2} v^2 \tag{3}$$

Δp_{HP} (pressure drop due to friction with the inner and outer glass surface as the air flows throughout the cavity)

$$\Delta p_{HP} = 12\mu \frac{H}{s^2} v \tag{4}$$

Δp_Z (sum of the pressure drops at the inlet and outlet openings)

$$\Delta p_Z = \frac{\rho v^2}{2}(Z_{in} + Z_{out}) \tag{5}$$

Z_{in} and Z_{out} (inlet and outlet pressure drop factors)

$$Z_{in} = \left(\frac{A_{gap}}{0.66 A_{eq,in}} - 1\right)^2 \tag{6}$$

$$Z_{out} = \left(\frac{A_{gap}}{0.66 A_{eq,out}} - 1\right)^2 \tag{7}$$

The temperature of air in the cavity as a function of distance, h, from the inlet opening:

$$T_{gap}(h) = T_{ave} - (T_{ave} - T_{gap,in}) e^{-h/H_o} \tag{8}$$

T_{ave} (average temperature of the glazing panes facing the air cavity)

H_o $\Big($characteristic height which is calculated through : H_o

$$=\frac{\rho C_p s}{2h_{cv}}v\Big) \quad (9)$$

The air temperature at the outlet opening:

$$T_{gap,out} = T_{ave} - (T_{ave} - T_{gap,in})e^{-H/H_o} \quad (10)$$

The thermal equivalent mean temperature of the air cavity:

$$T_{gap} = \frac{1}{H}\int_0^H T_{gap}(h)dh = T_{ave} - \frac{H_o}{H}(T_{gap,out} - T_{gap,in}) \quad (11)$$

Heat transfer from surface convection

$$Q_c = h_{cv}A(T_{surf} - T_{air}) \quad (12)$$

Q_c (rate of exterior convective heat transfer)
h_{cv} (exterior convection coefficient)
A (surface area)
T_{surf} (surface temperature)
T_{air} (outdoor air temperature)
Moreover, in order to measure the airflow parameters in the DSF cavity the following equations have been proposed by [64]. During this progress, wind and thermal pressure difference due to the stack and wind effects are measured. The respective sum is taken to attain the airflow inside the DSF cavity.
$\Delta P_{tot} = \Delta P_T + \Delta P_W$
$\Delta Ptot$ (total pressure difference)
ΔoT (thermal pressure difference)
ΔPW (wind pressure difference) [Pa].
For the stack effect component:

$$\Delta P_T = g(\rho_e - \rho_{gap})\frac{H}{2} \quad (13)$$

g (gravitational acceleration) [m/s^2]
H (vertical *distance* between the upper and lower louvers) [m]
ρgap and ρe (*internal* (gap) and external air densities) [kg/m^3]
According to the Boussinesq approximation $\Delta\rho/\rho \approx -\Delta T/T$, plus referring to the perfect gas law $\frac{\rho}{\rho_0} \approx \frac{T_0}{T}$, the new equation becomes:

$$\Delta P_T = a\Delta TH \quad (14)$$

with

$$a = \frac{\rho_0 g T_0}{2T^2} \quad (15)$$

T [K] (a chosen temperature of the system)
$\Delta[$ [temperature difference [K] between the air inside the cavity and the outdoor air (*Tgap-Te*)]
T0 [a reference temperature (293 K)]
ρ0 (correspondent air density) [kg/m^3].
For the temperatures ranging 293 K $< T <$ 313 K, the previous equation gives 0.0203 $> a >$ 0.018 Pa/m.K, supporting the likelihood of using a constant value a=0.02 Pa/m K [64].
The pressure difference in the DSF cavity (Considering the wind effect) can be measured through:

$$\Delta P_W = \frac{1}{2}\rho_e U_\infty^2 \Delta C_p \quad (16)$$

U_∞ (wind velocity registered on site [m/s])

ΔCp (pressure coefficient difference between upper and lower louvers of the outside pane of the façade)
Respectively, the air velocity inside the DSF cavity can be measured by:

$$U = \pm\sqrt{\frac{2}{\rho}|\Delta P_T + \Delta P_W|} \quad (17)$$

ρ [air density inside the cavity (in fact ρ may be any of ρe, ρgap or $\bar{\rho}$ due to the minor (3%) airflow difference between them]
It is essential to note that, air velocity is positive in the upward direction, when $\Delta itot = itT + \Delta PW > 0$, and negative when $\Delta ntot < 0$
Correspondingly, estimated airflow, in turn, is articulated as:

$$G_{est} = C_d G_{pot} \quad (18)$$

Cd (discharge coefficient that accounts for the head losses through the DSF system)
Gpot (maximum potential airflow rate) [m^3/h]

Eventually, [64] presents calculation of a global discharge coefficient value based on averaging the *Cd* values:

$$C_{d_\theta} = \frac{\sum_d \sum_c C_{d_{\theta,d,c}}}{n_d n_c} \quad (19)$$

It has been repeatedly argued that unlike the conventional buildings, the prediction of the amount of solar gain captured in the DSF buildings by the air channel is highly complex and multifaceted, specifically once naturally ventilated systems are applied. In this regard, the following key concerns [86] are demonstrated:

1. The solar position, in relation to the glazing panes of the DSF, changes continuously. At the same time the amount of solar radiation received on the DSF surface vary with the cloud cover, solar intensity, etc. Furthermore, the optical properties and thus the amount of absorbed, reflected and transmitted solar radiation by the DSF glazing depends both on solar position and on solar radiation intensity.
2. Estimation of longwave radiation exchange in a DSF as well as in a conventional building requires detailed view factor calculations. However, in presence of error, the consequences will be less notable in the conventional building, due to the smaller deviation between the surface temperatures of the constructions, while in the DSF the surface temperature of a shading device or inner window pane can be rather high and can result in additional heat gains to occupied zone when it is highly undesired.
3. Dealing with the convective heat transfer is a particularly difficult task. Choice of expressions for convective heat transfer coefficient is always difficult. The convective heat exchange is defined by the thermal conditions, flow rate and flow regime, which are subjected to the rapid changes, especially in a naturally ventilated cavity. This leads to the circumstances when more than one expression might be needed and the building simulation tool should be able to handle the change in the flow regime and thus in the convective heat transfer.
4. The air entering the DSF is heated up/cooled down due to the convective heat transfer at the DSF surfaces and shading device, then the air raises up/falls down, due to the buoyant forces. The strength of the buoyancy strongly depends on the air temperature and thus on the convective heat transfer at the surfaces. The higher temperature, the higher strength of the buoyancy force will result.
5. The other component of the driving forces is the wind force. The main characteristic of the wind forces is their random and extremely fluctuating nature. Still now, the wind phenomenon

is difficult to simulate or estimate and this obstructs the development and application of the natural ventilation principles. The same is applicable for the naturally ventilated double-skin facade, where the driving forces (wind and buoyancy) may counteract or act together, determining the mass flow rate in the cavity.

4. Environmental benefits of DSFs

4.1. Reduction of energy consumption

Growing attention to analyzing the energy performance of DSFs is observed in recent years. Various studies have utilized different types of simulations, modeling systems and measurement approaches to prove the energy saving with of DSFs [7,60,66,69]. The available results on DSF energy performance are not consistent. Energy saving by using DSFs is reported from the negative range to 50%. A reduction up to 26% of annual cooling energy consumption was observed for a ventilated DSF in Hong Kong by both internal and external clear glasses rather than a single-glazed curtain wall [3]. Similarly, the annual cooling load declined by 26% once [29] replaced a conventional absorptive glazing SSF by a DSF with single clear glass inner pane and double reflective glass outdoor pane. The decrease of energy consumption was expressed by [67] as respectively 26% and 61% for the single-glazed and naturally-ventilated PV instead of a normal absorptive-glazed window. Research conducted by [68] indicated 10–15% cooling energy saving in summer and 20–30% heating load reduction in winter by using DSF. This study also argued that a large temperature adjustment is possible using the different operation mode of DSF system. [69] reported 20% energy saving for the SSF rather than DSF alternative without increasing the period of time with extensive temperatures. Using the cavity of DSF as the preheater supply air was found by the study as a way to achieve further energy saving. [54,60] discussed that due to the full use of daylight and sunlight, glass façades are able to reduce the energy consumption in winter by lowering both illumination and heating loads. However, the authors proposed the use of smaller glass panels because the temperature differences between the edge and center of bigger panels are considerable.

Nevertheless, [45] expresses DSFs are not able to decrease both annual cooling and heating load unless by combining typologies or adjusting the system. This is due to the individual situation particularly when insulated glazing is coupled with exterior shading devices. [70] related the energy performance of various DSF systems to the window technologies whereas. In their research, PV laminated glass displayed higher solar heat gain coefficient (SHGC) in comparison with clear glass and low-e coating glass. The double-glazed PV glass window was found to reduce the room temperature respectively by 200% and 53% against the double-glazed clear glass and low-e glass windows. The average total and the secondary (convective and infrared) heat gain by the PV double-glazed window were reported by [61] as approximately 54% and 46% of that of the PV single-glazed window.

According to the highlighted discrepancies, it is postulated that one of the main criteria for ensuring optimized energy performance is to correctly design the system as a specific to the single building case. In other words, the performance of DSFs depends on the system characteristic, ventilation mechanism, glazing type, cavity depth and blind position [10]. Furthermore, in natural and mixed-mode ventilation DSF systems, the slat angle of the used shading devices and the openings which supply air to and exhaust air from the cavity influence the energy performance [10].

[28] advised a balanced wall-window ratio (WWR) to mitigate the heat transfer into the building. By increasing WWR from 0.5 to 0.7, a reduction of overall heat transfer into a building in Singapore was observed in [72]. However, the heat transfer of the model with WWR = 0.9 was higher than that of the case with WWR = 0.7. [73] observed almost 26% energy saving in the model with WWR of 0.32 compared to that of WWR = 0.9. Looking into the energy saving outputs, a simulation study concluded that DSFs could lead to 30% annual energy saving in building cooling and 10% in heating in comparison to a conventional façade [74].

To tackle DSF overheating problems in hot seasons and climates, application of passive thermal mass techniques within the air cavity are proposed which may enhance the thermal energy performances [21]. Findings denote that mechanically ventilated DSFs can lead to 21-26% energy saving rate in summer and 41–59% in winter in comparison to typical DSFs with no thermal mass [21]. Lastly, [75] stresses that DSFs with well-designed structure could generally lead to increased energy savings.

4.2. Improvement of ventilation, airflow and thermal comfort

It is observed that the majority of studies on DSFs concentrate on ventilation and thermal performances [23]. Similarly it is noted that ventilation is the most important factor of DSFs studied in recent years. It is postulated that replacing the contaminated air with fresh air as the essence of ventilation plus improvement of human thermal comfort could be achieved by application of DSFs in different climatic regions [2]. Despite the privilege of air-tight DSF in reducing heat losses during cold seasons, [29] claimed that ventilated DSFs are more appropriate for hot and even subtropical climates. This is due to the substantial decrease of the heat gain and thus the cooling loads of the buildings.

It is necessary to consider the impacts of wind pressure on the DSF layers as it can directly influence the airflow in a building [76]. Wind pressure coefficient is found to be highly dependent on the direction of building while the geometry of the building [77]. Evaluating the aerodynamic effects on the layers of DSF is indeed more complicated than single-layer façades. Due to the rapid growth of taller and greener buildings integrated with DSFs, this assessment becomes critical [23,78].

By deploying Thermal Analysis Simulation (TAS) software, [5–7] found natural ventilation is affected by both buoyancy and wind force. Meanwhile; it is suggested to consider integrating solar chimney as thermal storage above DSFs [30]. The circumstances of providing natural ventilation is also analyzed through the use of TRNSYS and LOOPDA simulation models according to internal airflow paths moving through the entire buildings height between floors [79]. It is inferred that DSFs are predominantly developed for cold climates [2]. Nonetheless, a study analyzed their performance in both hot and cold seasons of China and concluded that DSFs could be utilized in hot climates once adjustable shading devices are integrated as part of the system [80].

4.3. Optimization of daylighting and glare control and enhancement of acoustic

Transparency is an important architectural characteristic of DSF systems, providing visual exposure to the surrounding environment of the building and to daylight [2,97]. However, little attention is paid to the evaluation of daylighting performance of DSFs. Recent studies elaborate the transparency of DSFs and the substantial capabilities for maximizing the daylighting without glare [2]. Indeed, due to the fact that DSFs are normally highly glazed, the issue of glare needs to be considered while designing the system. Fully glazed façades are able to provide abundance of daylight for the interior spaces as an important factor of energy saving. On the other hand they can cause glare unless sun fluxes carefully assessed and integrated into building design.

Prediction of interior daylight illuminance is a key step to evaluate DSF design. [81] reported using DSF as a way to reduce energy consumption for lighting. In addition to taking the location and orientation of the building and interior spaces into account, applying internal blinds and screens can ensure the daylight does not adversely impact occupants. Furthermore, use of special coatings, selecting appropriate position and orientation of the glazing skin according to the sunlight angles contribute to address the potential of outward reflections.

[82] studied a Bruxelles-located office building with a DSF for performance in terms of daylight factors and illuminance levels. Thirteen DSF options were assessed for its refurbishment based on scale models in an artificial sky and computer simulations. They concluded that a solar shading device or a light shelf; reflectivity; degree of perforation and level of walkways can be shown separately to increase daylight penetration. They also indicated that glazing orientation and area would have significant effects on daylighting designs. [31] simulated the daylighting characteristics of 12 existing DSF office buildings situated in various climates including tropical, subtropical and cold temperature using the IES VE software. They found that the indoor daylight illuminance values inside the DSF office zones were in a comfortable light range and no cases was subjected to glare at the entrance of the office. The rational utilization of daylight such as photoelectric lighting controls can effectively reduce building energy consumption together with the likely pollutants and greenhouse gas emissions. A systematic computer simulation was conducted to assess the lighting energy performance for a daylight dimming control installed in a small office space with DSFs under a variety of sky conditions [39,83]. In the simulations, photo sensors were placed at three different locations in three shielding conditions under three sky conditions. As the result, a partially shielded condition with clear and intermediate cloudy skies showed appropriate dimming function.

They provide acoustic protection for buildings located in noisy environments such as high traffic urban areas, highways or railway lines [65]. The outer skin actually obstructs the noise while the inner skin allows the ventilation. Indeed, the aesthetic aspect is an attractive value for architects and owners [84]. However, few studies in literature have addressed all the design- and installation-related aspects of DSF system according to acoustic issues. To achieve acceptable results a complete and uninterrupted barrier to the noise should be provided. Furthermore, attention should be paid to the noise reflections, which can impact the surrounding properties. Operable windows in the interior layer compromise the acoustic benefit, especially if openings of the exterior layer are large [65].

5. Advantages and challenges vs. economic feasibility

A growing attention is observed towards increasing the integration of DSFs for decreasing the operational energy demands and environmental impacts of buildings [85,96]. It was discussed that DSF systems are not the best option for energy saving in every location [66]. In particular, using DSFs lead to particular disadvantages such as "*higher investment costs than that of traditional single-façade; the risk of overheating on warm sunny days; or acoustics, moisture and fire safety*" [9].

One of the main challenges of DSFs is the initial cost related to design and construction as well as high cleaning, operating, inspection and maintenance costs [86] in comparison to the conventional façades; hence, it is obvious that the economic feasibility of applying these façades in buildings is undeniably important. However, lifecycle analysis demonstrates that application of DSFs can have long-term economic benefits. Likewise, local governmental promotion and support can foster successful application of DSF systems and mitigate their high costs.

The annual heating demand for both SSF and DSF cases was found almost the same once the basic windows were replaced by improved U-value windows [69]. Nevertheless, the DSF case was estimated to be cost-efficient in a 35-year period. The authors ignored the economic points as the reason of choosing DSF systems because the amount of energy saving did not defend the additional cost which these systems constitute. [29] conducted an experimental study in an office building and applied the measured data to verify the model established by *EnergyPlus* program. Although the results showed 26% annual energy saving in the cooling energy load, the study reported the economic infeasible concept of DSF due to the long payback period of circa 81 years.

Another obstacle towards the integration of DSFs in buildings is the high risk of unacceptable performance based on the contradictory reported results in recent years, specifically with view to the economic viewpoints [69,86]. Other observed challenges include uncertainties in geometric attributes and glass type selection, shading and ventilation strategy and wind loads, as well as maintenance and cleaning costs [46]. Similarly, high fire hazard risk is another inevitable challenge of current DSFs which require in-depth research for proposing solutions [2]. One of the main challenges of DSFs is the overheating problem during summer and hot sunny days resulting in a relatively higher cooling energy demand of the building to overcome this repeatedly reported challenge [64]. Additionally, use of DSFs in hot and humid climate is argued to be less experimented and analyzed which requires further explorations [2]. To conclude, it is perceived that cost effectiveness of DSFs is the most challenging parameter among the discussed factors.

6. Conclusions

Buildings account for approximately 40% of global final energy use and this clearly indicates the necessity to adopt effective sustainable techniques for optimizing the performance of green buildings. One of the most critical aspects of designing energy efficient systems for integration in green buildings is to draw sufficient attention to the façades during the early stage of design. This is due to their direct impacts on the overall energy budget, user's comfort and cost of the building services. In this line, the study developed a holistic overview of available literature on DSFs with viewpoint to their analytical procedures, ultimate benefits and challenges. This research aimed to oversee the current implications and implementations plus the future prospects of DSF systems. Findings confirmed that DSFs are globally widespread as a generally acceptable energy saving technique, an attractive option for improving the sustainable energy performance and an architecturally sleek option of building envelopes. Various attempts have been done to quantitatively measure and analyze their effectiveness. On the contrary, some studies criticized that only well-designed/ventilated DSFs can perform efficiently and their overall performance is highly dependent on the climatic conditions.

Review of recent studies shed more light on the potentials of DSFs towards creating healthy and stimulating built environments. Findings presented that DSFs can play a significant role in managing the interactions between outdoor environment and internal spaces of a building. In conclusion, despite the available critics, it is stated that; DSF systems offer versatile positive influences. These include; 'energy consumption reduction', 'ventilation, airflow and thermal comfort enhancement', 'daylighting and glare control', 'sound insulation, noise reduction and acoustic enhancement' and 'visual and aesthetic quality enhancement'. Nevertheless, the analysis showed that there is still little knowledge and experience of the DSF's behavior in operation towards obtaining the optimized overall performance. Likewise, to tackle DSF overheating problems in hot seasons and climates, future studies should look into the development of more effective thermal management control strategies for the optimization of the performance of DSFs. On the other hand, the key drawback of DSFs is their high investment costs in comparison with single glass façades although some studies have demonstrated their cost efficiency over a longer period of time based on their economic return, long lasting essence and higher level of durability.

Future research is accordingly essential to further explore and analyze the life cycle assessment and the energy payback period of DSFs in different regions. Overall, scientific studies ascertained that proper design and fabrication of DSFs based on the assessment of the impacts of different design configurations on the energy and thermal performance during the preliminary design phase while considering the local parameters of climate can substantially resolve the observed challenges.

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