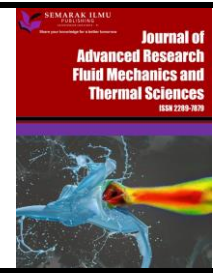




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Aptitudes of Double Skin Façade Toward Green Building within Built Environment

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ABSTRACT

To obtain optimal efficacy toward energy saving in buildings, numerous approaches have been persistently developed and innovated. Double Skin Façade (DSF), one of the keys to energy efficiency and thermal enhancement, is increasingly drawing attention from designers and researchers in speculating its benefits. Nowadays, there are still some doubts about the performance of DSF as it provides pros and cons. Therefore, this review provides a deep understanding of the composition of DSF and its performance, and its startling gaps among researchers toward green building within the built environment. The research studies present evidence of the potential of DSF in various applications with the proper design scheme. However, location and climatic conditions are the most important factors to consider when it comes to designing DSF for building envelopes. Otherwise, the system not only mandates a higher investment cost on double structuring but also higher demand for energy consumption. The findings additionally indicate that DSF has also left some uncertainties on its positive impact within the extensive tropical climate, since there are inadequate studies conducted, such as lighting, heat transfer and ventilation, etc. Accordingly, the system requires more rigorous investigation to be profoundly employed.

1. Introduction

For decades, various approaches have been explored and proposed to improve modern buildings' energy performance [1]. The use of a double skin façade (DSF) is one of the design approaches premeditated by various researchers in terms of its various benefits [52]. A DSF consists of at least two glass façade layers with intermediate space which could span up to several meters and be driven by different ventilation systems [2]. The impact of DSF on energy reduction and thermal enhancement in office buildings has been claimed by various researchers who have investigated the DSF typologies and their influences on the thermal and energy performances in various climatic contexts [3-5]. Most of the studies have provided positivity of DSF on the building design. The benefits of DSF have been widely known in Europe as it is believed to have a great impact on energy

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consumption and natural lighting [6]. Recently, DSF has gotten more attention from researchers on its applications in various climates. Several studies have been conducted to prove its advantages, mostly on building energy efficiency and thermal enhancement. Thermal performance is one of the great factors correlated with energy efficiency in DSF systems. On the other hand, there is no exclusive investigation conducted in a broader climate as most of the studies have only focused on specific locations. It was claimed by numerous researchers that the effects of DSF on the building's performance would be different from one location to another location and from one climate to another climate [7-9]. Hence, it could be a consequence of straightforwardly utilising the system on the buildings in some regions without a proper DSF design. The need for natural lighting is accomplished by utilising glass façades or windows, but an extra layer of glass wall or window could be the component that reduces the indoor lighting quality [49-62]. Alternatively, the lighting performance of DSF has not been claimed by most studies. Nevertheless, there is no plentiful evidence that demonstrates the benefits of DSF with some regard to the broader climatic condition.

In the modern design world, building envelopes play an important role in the functionality, desirability, and sustainability of a whole building. In a tropical climate, heat and glass facade are the most critical influences on a building's energy performance. Glass façade retains a high solar radiation rate, heating up the building and causing thermal discomfort and excessive energy consumption for air cooling systems. Based on the United Nations Environment Programme, buildings make use of over 40% of the world's energy and roughly 60% of the world's electricity consumed by the residential and commercial buildings. In tropical countries, cooling and lighting accounted for 56% and 16% respectively of the whole typical building energy [10]. Even though the technology of DSF has been developed over recent decades, issues still arise when energy saving is not extensively obtained, and its full aptitudes are yet to be discovered [4].

2. History

There were different claims from different sources on the history of DSF's appearance and utilisation [11]. An early known ventilated multiple skin façade with a mechanical system was depicted by the boss of Brussel's industrial museum, Jean-Baptiste Jobard, in 1849, as claimed by Saelens [12].

Ana Maria Leon Crespo described an early commencement of the system that the double skin wall was first applied on the three-story building of the Steiff Factory in 1903 in Giengen/Brenz which was nearby Ulm, Germany, to exploit the quality of daylight and to get extra shield from strong wind in cold weather in Giengen as shown in Figure 1. In the following years, other two buildings with the same structural system were duplicated and built after the first one was successfully beneficial [13].

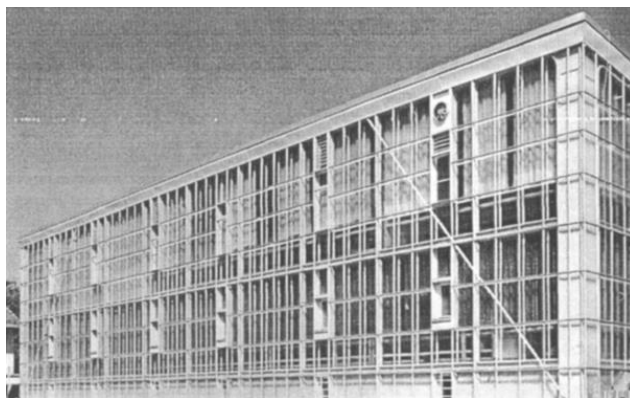


Fig. 1. Steiff Factory, Giengen / Brenz, Germany [62]

In 1912, the Post Office Saving Bank, which was a winning project earned by Otto Wanger, used a double skin system that appeared right in the main banking hall as a double skin skylight [14]. Then in the late 1920s, there were significant projects that were known. Narkomfin building in Russia was developed and experimented with by Moisei Ginzburg in 1928. He applied double skin stripes on the communal housing block for maintenance and then pushed the idea for the window. Le Corbusier spent several years designing a few buildings including Centrosoyus in Moscow, Cite de Refuge in 1929, and Immeuble Clarte in 1930 in Paris. However, none of these buildings had a double curtain wall system. Nevertheless, at the end of the 1920s, Le Corbusier started exchanging ideas on the uses of double skin system with Ginzburg as they met and found similarities between their projects, Narkomfin and Cite de Refuge. The momentum gaining of double skin façades in the 80s and the 90s raised attention from various architects and developers to adopt the system regarding the response to environmental concerns and political influences. The first double skin curtain wall that incorporated the ventilation idea of Le Corbusier came into the limelight when a collaboration project, the Hooker Office Building, by Cannon Design, and HOK Design was to be constructed in Niagara Falls, New York in 1978. The building facade was structured with a roughly 20-centimeter cavity depth with a solar cell equipping louver to create a stack effect to provide the desired temperature. As the popularity gained, there were also similar approaches adopted in other locations in Europe like Lloyd's Building designed by Richard Rogers and Partners, Leslie and Godwin office, also known as the Briarcliff House, designed by Arup Associates, and the SUVA building designed by Schiefer *et al.*, [15]. In Addition, the set of windows with an airflow system was patented in Scandinavia, in 1957 and 1967, and the ventilated window system was operated in the office building of EKONO company in Helsinki, Finland [16]. As its popularity grown, the double layer wall not only caught the attention in the cold countries but also in hot and warm countries in the 2000s since there were many experiments conducted and provided a lot of positive results with the system [6]. In the recent decade, there were many applications of double skin façades adopted in a so call warm climate worldwide [17]. The most remarkable one might have been the Shanghai Tower in China with the largest detachment between the outer curtain wall system and the inner main structure at 15 meters [18].

3. Definition

In modern buildings, DSF is a pleasing component in architectural design due to the transparency of the glass and the benefits of controlling thermal conditions in the building for energy reduction [4]. Arons [19] gave a short definition of the system as a twin skin façade consisting of two divided planar walls which allow air to move in it. Oesterle [20] stated that a double skin façade has two main layers called interior and exterior façades with an air space in between which allows ventilation to travel through while providing climatic and acoustic protection from the exterior layer. Comparably, Boake *et al.*, [21] described it as “Essentially a pair of glass “skins” separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against the temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins. All elements can be arranged differently into numbers of permutations and combinations of both solid and diaphanous membranes”. To provide ventilation movement, the distance of the intermediate air space can range from 20 centimeters up to 2 meters, which can be operated naturally or mechanically, depending on the climatic location of the buildings [22]. Nevertheless, the outer skin of the double-skin facade usually is transparent glazing which can be far from the inner skin of the building up to 80-100 centimeters, which is slightly different from the statement above on the cavity depth [23].

Loncour *et al.*, [24] elaborated that “A ventilated double façade can be defined as a traditional single façade doubled inside or outside by a second, essentially glazed façade. Each of these two façades is commonly called a skin (whence the widely used name is “ventilated double-skin façade”). A ventilated cavity - having a width that can range from several centimeters at the narrowest to several meters for the widest accessible cavities - is located between these two skins. There exist façade concepts where the ventilation of the cavity is controllable, by fans and/or openings, and other façade concepts where this ventilation is not controllable (the ventilation is produced in this case via fixed permanent ventilation openings). The indoor and outdoor skins are not necessarily airtight (see, for example, the “louver” type façades). Automated equipment, such as shading devices, motorized openings, or fans, are most often integrated into the façade. The main difference between a ventilated double façade and airtight multiple glazing, whether or not integrating a shading device in the cavity separating the glazings, lies in the intentional and possibly controlled ventilation of the cavity of the double façade”.

The other similar explanation by Chan *et al.*, [2] defined that “Double skin facade refers to a building facade covering one or several stories with multiple glazed skins. The skin can be airtight or naturally/mechanically ventilated. The outer skin is usually hardened by single glazing and can be fully glazed. The inner skin can be insulated double glazing and is not completely glazed in most applications. The width of the air cavity between the two skins can range from 200mm to more than 2m. An air-tightened double-skin facade can increase thermal insulation for the building to reduce heat loss in the winter season. On the other hand, moving cavity air inside a ventilated double skin facade can absorb heat energy from the sun-lit glazing and reduce the heat gain as well as the cooling demand of a building”.

Even though definitions of double skin façade have some similarities and contrasts among each explanation, a concluded perspective is that the system usually consists of two glass layers creating a cavity to deliver ventilation which can be operated naturally or mechanically based on the context of a specific climate where the system is adopted.

4. Perception

DSF is one of the attractive elements of a building's wall regarding its environmentally responsive profits with a good esthetical presence [4]. DSF normally overlaps its advantages, perceptions, and applications in both architectural and engineering design [24]. Back in the old days, the value of architecture was mostly relied on the composition of shape, proportion, aesthetics, material, and natural light. Later, the global environmental concerns changed many ways of view of good architecture in the late 20th century. DSF has taken the main role in architecture as an aesthetically environmentally friendly façade since it could fulfill the exterior desires and positively respond to ecological issues at the same time [11]. In this case, transparency of the exterior double skin layers is considered as the design principle in architecture because it has a close interaction with nature and has also influenced the indoor environment and space utilization. Moreover, the glass wall obsession issues could also be unraveled toward the business trends and excitement of the glass envelop [26].

For engineering, DSF is mainly considered advantageous in relation to technical constructions and the physical environment. As explained by Waldner *et al.*, [27], DSF was formed by combining the conventional curtain walls and window system to guarantee the wind and water tightness of the building which was employed in many of the projects that were normally studied and designed by the engineering firm. It has also been explained that “Curtain walling usually consists of vertical and horizontal structural members, connected and anchored to the supporting structure of the building and infilled, to form a lightweight, space enclosing continuous skin, which provides, by itself or in

conjunction with the building construction, all the normal functions of an external wall, but does not take on any of the load-bearing characteristics of the building structure” and “The main difference with windows is that curtain walls are built in front of the building structure, while windows are built into the building openings”.

Therefore, the system of the double glass wall is widely considered in architecture and engineering in terms of its benefits. Principally, aesthetics, ventilation, cost saving, acoustic, client control, comfort, productivity, and security were all positively explained by Arons [19]. For instance, as the second layer of the glazing skin can be partially or entirely extended all over the building structure; and the distance from the internal layer can be up to several meters, it can allow ventilation to circulate inside the cavity predominantly and to stipulate great acoustic insulation for the building [28,29]. Furthermore, the system can also provide natural light, energy efficiency and improvement on occupant’s thermal sensation in the building [30-32].

5. Classification

From various literature, the classification of double skin façade was made based on their characteristics and performances. Loncour *et al.*, [24] classified a double skin façade by three main criteria namely type of ventilation, the partition of the façade, and modes of ventilation of the cavity (Figure 2).

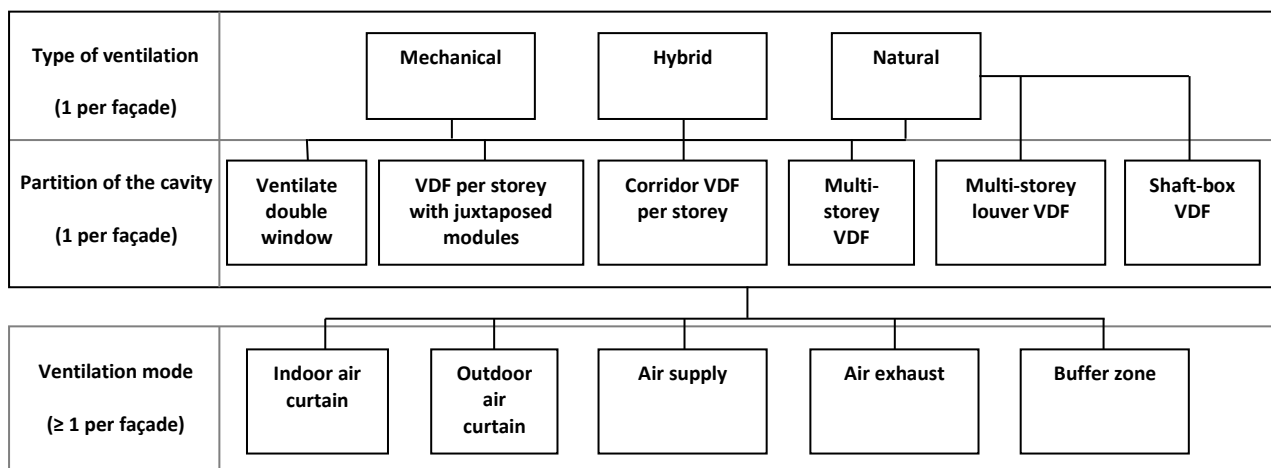


Fig. 2. DSF classification overview (VDF means DSF) [48]

5.1 Ventilation Type

This classification emphasises ventilation of the cavity which can be operated naturally, mechanically, or even both, which is called a hybrid system (Figure 3). There are similarities in explanations of ventilation varieties as follows

- i. Natural ventilation: Loncour *et al.*, [24] defined this classification based on the standard NBN EN 12792 as “ventilation (...) which relies on pressure differences without the aid of powered air movement components.”. It is also called passive ventilation due to the absence of mechanical support to ventilate the building. Natural air is blown into and out of the building through the opening of the wall, whereas temperature and humidity take roles in performing stack effect by the discrepancy of its properties.

- ii. Mechanical ventilation: Unlike natural ventilation, mechanical ventilation is motorised by mechanical fans or blowers to provide fresh air in the building when there is insufficient regular air circulating in the building. On the other hand, various types of mechanical ventilation could be equipped on any part of the building where needed according to the respective climate. In short, active ventilation is a system that requires the support of forced air circulating mechanisms [24].
- iii. Hybrid ventilation: Also known as mix-mode ventilation, hybrid ventilation is a system driven by both natural and mechanical ventilation to ventilate buildings. The two systems are combined and switched based on different climatic conditions to enhance the thermal environment while providing energy efficiency [24,33].

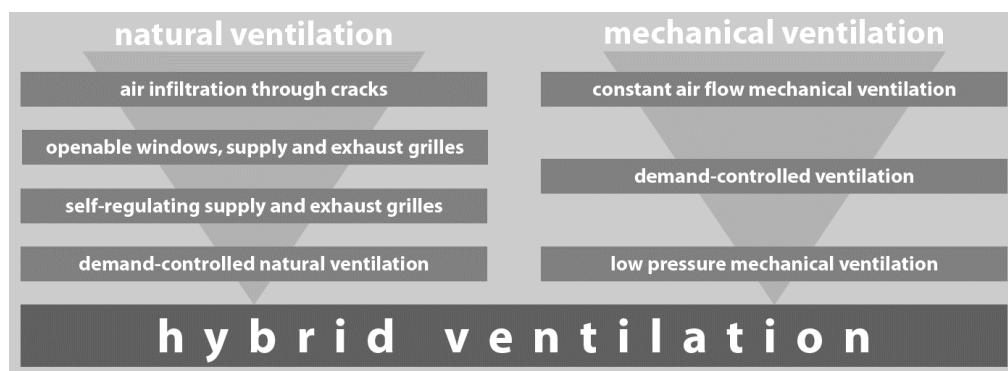


Fig. 3. Development of natural and mechanical systems [30]

5.2 Partitioning

Another classification of double skin façade is defined by the partition of the cavity. Partitioning tells us how ventilation performs in between the two glazing walls and how it is used in different situations. Based on Loncour *et al.*, [24], partitioning of DSF cavity can be classified as Ventilated Double Window, Ventilated Double Façade per story with juxtaposed modules, Corridor Ventilated Double Façade per story, Multi-Storey Ventilated Double Façade, Multi-Storey Louver Ventilated Double Façade, and Shaft-Box Ventilated Double Façade (Figure 2). Similarly, Poirazis [22] provided the four most clearly defined DSF systems by their geometry including Box Façade, Corridor Façade, Shaft-Box Façade, and Multi-Storey Façade (Figure 4).

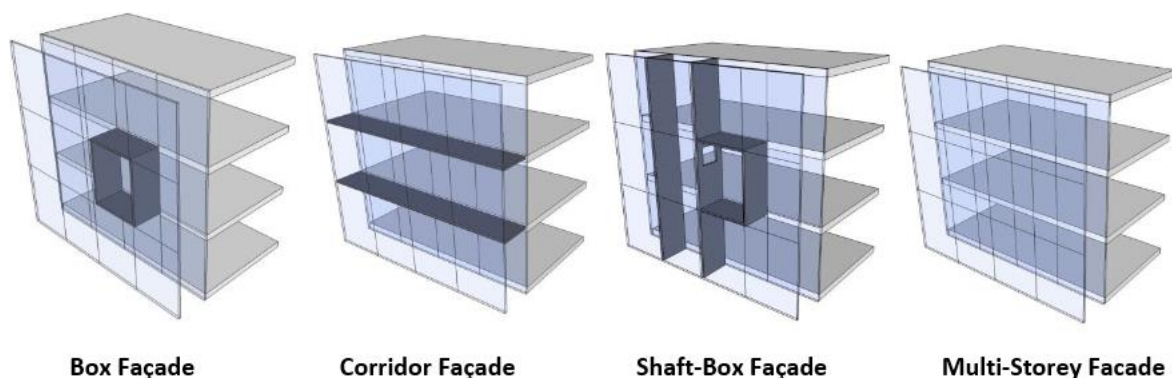


Fig. 4. Classifications of double skin façade [28]

Ventilated Double Window/ Box façade: The system works by composing two parallel windows forming a gap that allows air circulation [34]. It may use windows double inside or double outside by single glazing or by a second window, and it has similarities with a box façade as well. A box façade

is a system where the cavity is separated both vertically and horizontally at each level of the facade [24]. To provide passive ventilation for both intermediate space and living space, the opening of the exterior skin is purposefully provided to introduce fresh air by removing stale air inside the cavity. Due to the requirement of acoustic insulation to prevent noise from both exterior and interior, the Box Façade system has become one of the most DSFs to be established and employed in such circumstances [20]. Similarly, the Box façade is said to be useful in terms of preventing sound from transmitting through additional glass vertically and horizontally. On the other hand, it performs better than the natural ventilation regarding the level of fire security [35].

Ventilated Double Façade Per Story with Juxtaposed Modules: Based on Loncour *et al.*, [24], “In this type of facade, the cavity is physically delimited (horizontally and vertically) by the module of the facade which imposes its dimensions on the cavity”. A module of this façade has a height limit of a single floor only.

Corridor Ventilated Double Façade: A Corridor Façade is isolated horizontally in between each floor [35]. Fundamentally, it can cover partially or entirely the whole façade and normally it is accessible for walking through the corridor cavity [24]. By this means, no vertical division is placed in this corridor system, except at the angle of the corner of the building or when insulation, security and the construction reason is arising [29]. Also, Uuttu [35] indicated that the fundamental perception of the Corridor Façade is decent ventilation, acoustic insulation, and a fire security system of the horizontal division platform in the cavity.

Multi-Storey (Louver) Ventilated Double Façade: Intermediate space of this façade system is not separated vertically or horizontally [20]. The exterior layer could cover a great portion of the building façade and allow the extent of air circulation in the cavity [24]. On a warm day, stale air in the cavity will be warmed up and exhausted through the outlet at the top of the cavity, as a result, cooler air will be introduced through the inlet at the base of the cavity to replace the remaining air [35].

“The multi-storey louver naturally ventilated double facade is very similar to a multi-storey ventilated double facade. Indeed, its cavity is not partitioned either horizontally or vertically and therefore forms one large volume. Metal floors are installed at the level of each storey in order to allow access to it, essentially for reasons of cleaning and maintenance. The difference between this type of facade and the multi-storey facade lies in the fact that the outdoor facade is composed exclusively of pivoting louvers rather than a traditional monolithic facade equipped (or not) with openings. This outside facade is not airtight, even when the louvers have all been put in the closed position, which justifies its separate classification. However, the problems encountered with these facades are generally comparable to those encountered in the other VDF’s” [24]. Like other façade systems, the Multi-Storey Façade provides great sound insulation, ventilation, fire security and protection for the device equipped in the intermediate zone [35].

Shaft-Box Ventilated Double Façade: Shaft-Box system is similar to single-storey height module or Box Façade in the way that its modules are linked with the building. The circulating air from the box window connects to the vertical shaft where the air is discharged and drawn to the top of the opening by the thermal stack effect [24,29]. The Shaft-Box Façade Structure provides a very strong buoyancy effect and is normally used as a part of low-rise construction [20]. On top of acoustic insulation, this façade system provides great ventilation and a building security scheme [35]. Each type of DSF has a different role based on the design in response to climate variations.

5.3 Ventilation Mode

Another classification of DSF is done by the demonstrative of air circulating in the cavity and how it is introduced into the cavity [36]. According to Loncour *et al.*, [24] five main characteristics of

ventilation modes in the intermediate space of double skin façade were categorized as follows (Figure 5)

- i. Outdoor air curtain: This ventilation mode extracts air from the outside into the cavity and exhausts instantly to the outside, consequently, creating an air curtain wall in front of the façade.
- ii. Indoor air curtain: This ventilation mode works the opposite the outdoor air curtain mode. The cavity extracts air directly from the room and air is constantly returned into the room through the ventilating system, therefore creating an air curtain wall inside the façade.
- iii. Air supply: This system introduces outside air into the interior or ventilation system of the room. The air is supplied constantly through the opening of the exterior layer and drawn into the room through the opening of the interior façade.
- iv. Air exhaust: This system works the opposite way the air supply does. The air inside the room is drawn into the outdoor environment through the inlet of the interior façade and the outlet of the exterior layer.
- v. Buffer zone: This ventilation mode provides no ventilation system, as the stale air is strapped tightly, creating a buffer zone in the cavity of the façade.

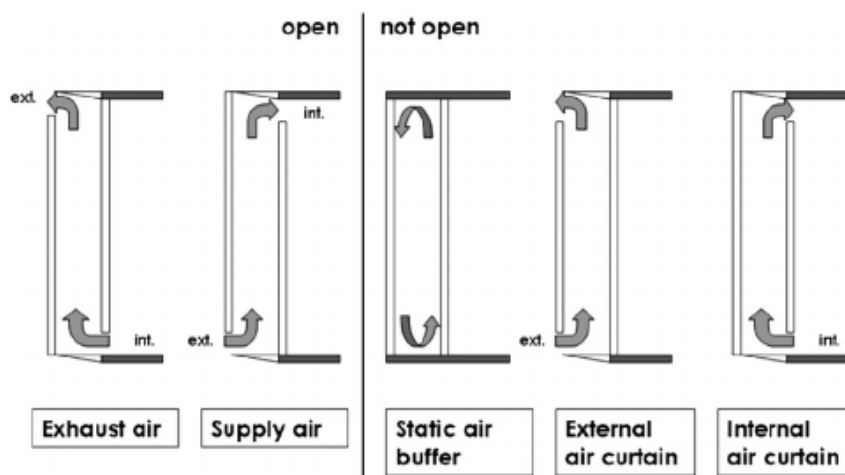


Fig. 5. Air movements in versatile types of double skin façades [37]

6. Technical Aspects

When we talk about DSF, people normally think of double glass walls with a cavity inside. However, there are many aspects of configurations to be considered when designing a DSF system. The three main aspects of a double façade are cavity depths, glass materials and shading devices. These aspects play such an important role in the system and can be designed inversely to enhance the performance of the DSF system.

6.1 Cavity

The intermediate space of the DSF can range from centimeters up to several meters based on how the designer wants it to perform. Correspondingly, aesthetical design, variety of shading devices, maintenance consideration, and ventilation mode take a key role in how the depth opening is determined [31]. The airflow characteristic of a naturally ventilated DSF is influenced by the size of the window opening [38]. On the other hand, the temperature in the intermediate space of the DSF

is significantly affected by the opening size variation [39]. For instance, Regazzoli [28] proved that one meters cavity depth of multi-storey DSF system is the most efficient; with roughly 16 percent of building energy consumption saving compared to a conventional single skin façade in his study. Likewise, Rahmani *et al.*, [9] also recommended one meter as the most effective depth for DSF despite the study being conducted on a full air-conditioned office building in the tropical climate of Malaysia. Moreover, Aksamija [41] also stated that one-meter air-gap size of a DSF provided better results in terms of reducing cooling loads in the building.

6.2 Glass

A recent study by Tao *et al.*, [38] indicated that the right glazing used on the DSF façade provides a significant enhancement to ventilation. The study was done on a naturally ventilated double-skin façade and found that a thirteen percent rate of ventilation was increased by just replacing the normal clear glazing with the Low-E glazing on the building's DSF façade. On the other hand, climatic context is also the main influence on glazing choice [31]. Streicher *et al.*, [11] raised a theory that glazing types of the internal and the external layer of DSF are primarily decided by the typology of the DSF systems. They also added that single glazing is normally applied on the exterior skin and the insulating pane (thermal break) is normally applied on the interior skin when the system utilizes outdoor air for ventilation. If the system utilizes indoor air instead, the materials are applied the other way around. However, Haase and Amato [42] recommended using two clear glazing for both interior and exterior layers of ventilated DSF to achieve potential heat gain reduction. Whereas Aksamija [41] suggested that the double-glazing exterior could improve the overall performance of the facade and lead to energy saving by emphasizing that e-glazing is a great parameter for DSF's layers.

6.3 Shading

Without any shading devices, DSF already has the potential to improve building energy efficiency. Yet, the presence of shading devices in or on the DSF cavity could improve even better performances. A recent study by Kim [39] indicated that the temperature in the cavity is reduced by the existence of shading devices in the cavity. Another study by Kim *et al.*, [43] demonstrated that the highest annual total load reduction in the building is attained by using the middle blind for ventilated DSF, while the second highest is with the use of an exterior blind in their study. A study done by Lee *et al.*, [44] gave initial findings on the influences of shading device positions on air temperature and airflow patterns between the two layers of DSF. The study also mentioned that the thirty-, sixty- and ninety-degree angles of the horizontal devices are more operative to energy efficiency than the zero. Good positioning of shading devices is one of the key components to estimating the heat transfer through the intermediate space of DSF [45]. On the other hand, the properties of the device could also reduce the heating of the facades [46]. The study also added that the light colour blind may allow a higher percentage of light to enter the room. Furthermore, energy performance in DSF is claimed to be functioning and efficient when shading gadgets are deliberated and controlled properly [47]. According to Oesterle *et al.*, [20], "Determining the effective characteristics of the sun shading in each case poses a special problem at the planning stage since the properties can vary considerably, according to the type of glazing and the ventilation of the sun shading system. The sun shading provides either a complete screening of the area behind it or, in the case of the louvers it may be in a so-called "cut-off" position". As the authors concluded that "for large-scale projects, it is worth investigating the precise characteristics of the combination of glass and sun shading, as well as the proposed ventilation of the intermediate space in relation to the angle of the louvers".

7. Energy Performance

The glazing extent of the façade is directly associated with the heating and cooling energy consumption of the DSF since it is the main component influencing heat losses and heat gains through the surfaces of the glass [25]. Airflow path, cavity, and type of DSF are the main aspects to determine the efficiency of DSF as claimed by Aldawoud *et al.*, [47] and Alberto *et al.*, [48] who investigated the energy performance of DSF in the hot and humid, and mild climates respectively. Similarly, from the differences in the DSF system, the thermal performance in the cavity may also diverge, influencing the different levels of energy consumption in the building [49]. In 2012, Ignjatović *et al.*, [50] investigated the energy performance of the various DSF typologies in an office building during the heating season and found the potential heating energy reduction when triple glazing was used for the inner layer of the cavity. Whereas Haase and Amato [37] supposed that the major energy-consuming discrepancy was based on the changes in the glazing nature of the exterior surface, the interior cavity layer and decreasing of the cavity depth. Another study conducted by Saelens *et al.*, [36] assessing the energy performance of multiple skin façades shows that DSH provides better energy savings over conventional cladding façades by falling transmission losses. From their conclusion, “It is shown that it is possible to improve the building’s energy efficiency in some way by using multiple skin facades. Unfortunately, most typologies are incapable of lowering both the annual heating and cooling demand. Only by combining typologies or changing the system settings according to the situation, a substantial overall improvement over the traditional insulated glazing unit with exterior shading is possible. This implies that sophisticated control mechanisms are inevitable to make multiple skin facades work efficiently throughout the year. To correctly evaluate the energy efficiency, an annual energy simulation focusing on both heating and cooling load is necessary. Furthermore, the analysis shows that the energy performance strongly depends on the way the cavity air is used. To correctly evaluate the energy efficiency of multiple skin facades, it is imperative not only to study the transmission gains and losses but also to consider the enthalpy change of the cavity air and to perform a whole building energy analysis”.

8. Thermal Performance

Structural configurations provocatively affect the thermal performances of DSF differently in different climatic contexts [51]. DSF could theoretically control heat gained from the various temperature differences between the indoor and outdoor temperatures along with the differences in glass surface temperature [52]. However, the DSF needs a proper design to avoid overheating experiences, especially during the hot season [54]. R-value and U-value are the two main factors influencing the thermal performance of materials which means the R-value is a measure of the resistance of heat flow through the material regarding its thickness. Thus, the material has more thermal resistance and better insulation when it has a higher R-value. However, the U-value is a measure of how much heat is lost through a material with its certain thickness, but it includes the three main methods of how heat is lost: conduction, convection, and radiation.

8.1 Heat Transfer

Theoretically, the method of transferring heat consists of conduction convection and radiation; where the process of transferring heat through a solid requiring physical interaction between objects is known as conduction, whereas heat transferring caused by temperature (density) differences of the fluid or air is known as convection. However, radiation is the process of heat transferring through

electromagnetic waves by the temperature differences between objects which do not involve any physical or fluidical contact but do need an air opening or other transparent medium between surfaces to make radiation exchanges [55]. Solar radiation is the main actor in heat transferring through the DSF exterior glazing layer. It goes straight through the glazing layer with approximately fifteen percent of initial reflection depending on the outdoor environment and the remaining radiation passes through the glass (Figure 6) [56]. As the exterior skins are heated by solar radiation, the temperature in the cavity becomes warmer and pushes air circulation creating a greenhouse effect in the cavity [57].

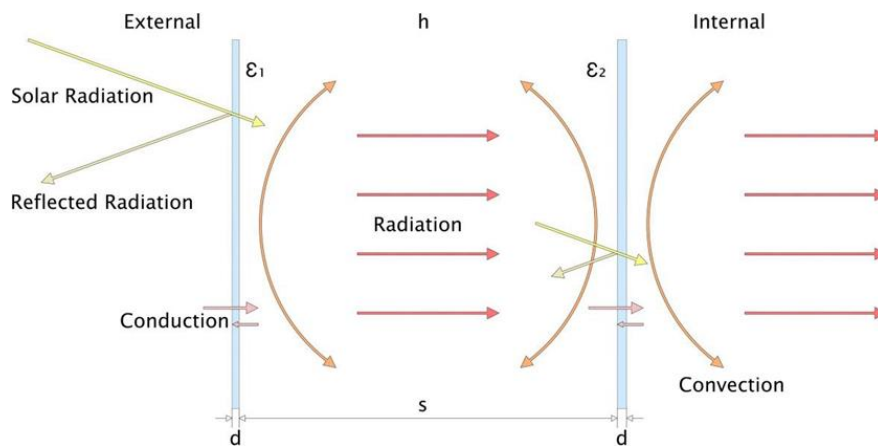


Fig. 6. Diagram of heat transfer through a Double-Skin Façade [28]

8.2 Thermal Buoyancy

According to Loncour *et al.*, [24] “The stack effect (or chimney effect) is a phenomenon related to the rising of the hot air which is lighter than cold air.” This effect naturally influences heating and cooling demand in the building when applied with DSF [57]. When the air in the intermediate space gets warmer than the outdoor air, the air in the intermediate space tends to discharge at the very top of the façade increasing the air flow rate in the façade cavity [24].

As explained by Tascon [56], creating a greenhouse effect between the two layers of DSF could promote thermal performance by increasing the density of the air inside the cavity to differentiate pressure and temperature. Thus, cooler air tends to enter the cavity from the lowering and warm air is naturally exhausted through the top of the façade opening. During winter, vents at the top and bottom of the façade cavity are disabled or closed to generate a thermal shield by heating trapped air inside the cavity, contrastingly vents are opened during summer to generate a thermal curtain by adopting a chimney effect as illustrated in Figure 7 [58].

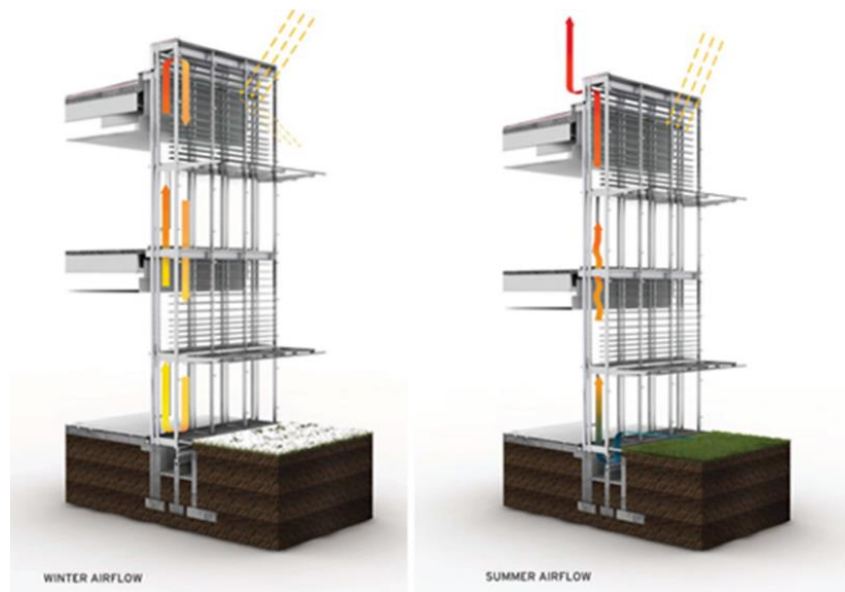


Fig. 7. Double-skin façade winter and summer operations [26]

9. Discussion

9.1 Advantage

Ghaffarianhoseini *et al.*, [31] gathered the benefits of DSF from numerous studies and found that the system is well known for its numerous environmental and economic benefits as shown in Table 1. On the other hand, various benefits and key findings from the various studies on different DSF typologies, climates and locations have also been indicated and summarised in Table 2. Furthermore, DSF is also supposed to help lowering the greenhouse gas emissions and indoor temperature, while maintaining the quality of light as plain window systems [59]. Poirazis [22] has similarly summarised the benefits of DSF from various study findings which include lower construction cost, sound insulation, thermal insulation, nighttime ventilation, energy saving and environmental impacts reduction, better protection of the shading or lighting devices, wind pressure effects reduction, transparency, natural ventilation, thermal comfort, fire escape, low U-value, and g-value. Nevertheless, there are only some benefit variables including thermal performance, energy saving, thermal comfort, and lighting which are being focused on and constantly investigated. Perhaps, thermal performance and energy efficiency are the two main areas among other variables. Table 2 indicates approaches and key findings from various research studies in various climates and highlights the greater portion of the focus on thermal and energy.

Table 1

Key findings of DSFs' benefits from various studies [31]

No	Main identified benefits	Key references (author/year)
1	Environmental benefits Energy consumption reduction Ventilation, airflow, and thermal comfort enhancement Daylighting and glare control Sound insulation, noise reduction and acoustic enhancement Visual and aesthetic quality enhancement	Kim <i>et al.</i> , [64]; Chan <i>et al.</i> , [2]; Shameri <i>et al.</i> , [60] Kim <i>et al.</i> , [64] Shameri <i>et al.</i> , [60] Shameri <i>et al.</i> , [60]; Mingotti <i>et al.</i> , [61] Kim <i>et al.</i> , [64]
2	Economic benefits Reduced long-term cost	Shameri <i>et al.</i> , [60]; Kim <i>et al.</i> , [64]

9.2 Disadvantage

Although DSF provides many significant benefits as proven, it can also be problematic if it is not cautiously planned. For instance, Manubawa *et al.*, [62] found that the extra layer of DSF reduces the natural light level of the room and causes visually comfortable glare. However, the drawback of DSF as addressed by most investigators is the expense of the façade compared to conventional SSF [63]. On the other hand, Poirazis [22] summarized other disadvantages of DSF which include higher construction costs, reduction of rentable office space, additional maintenance, and operational cost, overheating problems, increased airflow velocity, and increased construction weight, daylight, and acoustic insulation. However, the most problems identified with DSF are usually high construction cost, overheating and light quality. Table 2 has also indicated that the great portions of the DSF issue are a high-cost investment, energy deficiency due to thermal overheating and natural light reduction.

9.3 Gap

Initially, DSF could provide a positive impact on building thermal performance which is the main factor to define the efficiency of the whole building. Numerous benefits have been discovered and scientifically proven. However, there are still some negative impacts found in the specific studies (Table 2). For instance, Inan and Basaran [8] found both positive and negative impacts of DSF in their investigation that DSF could usually provide positive impacts while it showed better energy performance in July, yet it could still provide the unfavorable result for the external airflow mode in the cavity in January. Even though DSF could effectively control heat gain caused by the differences in indoor and outdoor and surface temperature, it could still not prevent internal heat gain caused by direct solar radiation in the tropical climate [52]. While the naturally ventilated DSF has been broadly employed, the thermal performance of the system is not thus far entirely understood [65]. On the other hand, Aksamija [3] also signified the use of all DSF varieties in various climatic conditions for building thermal improvement, but all types of DSF have caused energy consumption increase for lighting. Comparably, Manubawa *et al.*, [62] investigated the natural light quality of the building with a DSF system following the standard lighting level. It was found that the additional skin to the glass wall tends to shade the building interior and causes insufficient lighting level which leads to below the standard as required. However, without the second skin to the exterior wall, the lighting level in the building interior is way too high than the standard lighting limit which causes glare and discomfort visual. In a similar study, lighting loads can be reduced during the summer due to the longer day which means that the lighting loads may also vary from the daily climatic variations [7]. Additionally, shading has also an important responsibility for regulating lighting quality and efficiency for building with DSF [53]. Regarding investment, DSF has been demonstrated to be very beneficial for building development. The drawback of DSF is to be much more expensive than the conventional glass building, but so far it is more economical for the long-term phase [63]. Therefore, further enhancement for DSF is quite critical to assure the efficient application of DSF broadly for green building.

Table 2
 Summary of double skin façade research's key findings

Year	Reference	Weather/location	Classification	Approach/tool	Key findings	
					Thermal/energy	Technical aspects
2012	Rahmani <i>et al.</i> , [9]	Tropical climate/ Johor Bahru, Malaysia	Multi-storey DSF	CFD/ FLOVENT simulation tool	-	- The average temperature data for DSF with a 1 meter air gap size is 3° colder than the room temperature for SSF.
2013	Hong <i>et al.</i> , [1]	Monsoon climate/Seoul, South Korea	Shaft box DSF (winter) Multi-story DSF (summer)	DesignBuilder/ EnergyPlus	- The seasonal approaches to energy efficiency were successful in both the summer and winter. - Smaller investment costs and greater savings with advantages were produced by the ideal DSF.	- For multi-storey DSF, using airflow operating methods such as natural ventilation in the summer can cut cooling energy use by up to 12.62%.
2013	Regazzoli [28]	Dublin, Ireland	Multi-storey DSF	IES Virtual Environment (VE) software	- Compared to the usage of a typical single-skin façade, the combination of DSF construction boosts yearly percentage energy efficiency by 31% and results in significant cost savings.	- The most effective cavity depth is found to be 1 meter.
2013	Joe <i>et al.</i> , [40]	Yongin, South Korea	Multi-storey DSF	EnergyPlus	- Energy usage for heating and cooling is reduced by 15.8% and 7.2%, respectively, in comparison to the SSF.	-
2014	Azarbayjani [7]	Hot continental climate/ Michigan	Multi-storey DSF	DesignBuilder/ EnergyPlus	- A multi-storey façade significantly improved performance and reduced energy consumption. - Lighting loads are reduced during the summer, as the longer days and day lighting can meet a larger portion of the lighting need.	-
2014	Carli <i>et al.</i> , [30]	European climatic zones	Typical DSF	DIGITHON software/ calculation	- Pre-heating efficiency ranged from 10.7% in November to 14% in March, when it attained its highest percentage. 3.21% was the upper limit of the seasonal average pre-heating efficiency for the entire heating season. - Pre-heating efficiency negative values occurred on an hourly basis over all heating months, with the overall ratio to the total number of hours reaching 87.7%. During the majority of the HVAC	-

2014	Joe <i>et al.</i> , [49]	Yongin, South Korea	Multi-storey DSF	EnergyPlus	<p>system's operation in the winter, when the building needs to be heated, pre-heating efficiency is fairly low.</p> <ul style="list-style-type: none"> - In comparison to the initial design, the conditioned zone's energy consumption varies from +22.2% (outside surface of inner layer in parametric research) to -5.62% according to the DSF design. 	<ul style="list-style-type: none"> - The depth of the cavity and the kind of window glazing can both reduce energy use by 0.46 and 1.52-3.79%, respectively.
2015	Lee <i>et al.</i> , [44]	USA	Naturally ventilated DSF	CFD/FloVENT Sefaira simulation software	<ul style="list-style-type: none"> - Horizontal shading devices at angles of 30, 60, and 90 degrees were more successful than those at 0 degrees in reducing energy use by 0.4%, 2.6%, and 6.4%, respectively. 	<ul style="list-style-type: none"> - The shading device configuration has a significant impact on air temperature and airflow patterns.
2015	Parra <i>et al.</i> , [65]	Mediterranean climates/ Barcelona, Spain	Ventilated DSF	CFD	<ul style="list-style-type: none"> - 	<ul style="list-style-type: none"> - Venetian blinds can reduce solar heat gains by up to 35%, but not just because of the heat reflected from them, but also because they absorb heat when forced ventilation is employed in place of natural ventilation. - The thermal performance of the DSF is improved by increasing the emissivity of the venetian blinds' outer surfaces or the absorptivity of their inner surfaces.
2016	Ahmed <i>et al.</i> , [63]	-	-	Reviews	<ul style="list-style-type: none"> - DSF has been shown to be extremely beneficial and important in energy conservation. - The main drawback to DSF is that it is rumored to cost more than the standard single glass façade. - DSF is more cost-effective in the long run. 	<ul style="list-style-type: none"> -
2016	Ghaffarianhoseini <i>et al.</i> , [31]	-	-	Reviews	<ul style="list-style-type: none"> - DSFs can be quite helpful in controlling how the interior spaces of a building interact with the outside environment. - DSF systems provide a variety of advantageous influences. In particular, 	<ul style="list-style-type: none"> -

					energy consumption reduction, ventilation, airflow, and thermal comfort enhancement, daylighting and glare management, sound insulation, noise reduction, and acoustic enhancement, and visual and aesthetic quality enhancement are among them.	
2017	Alberto <i>et al.</i> , [48]	Mild climate/Southern European countries	Multi-storey DSF	DesignBuilder/ Energy Plus	<ul style="list-style-type: none"> - 30% less energy use for HVAC-related purposes. - Internal gains turned out to be one of the main contributors to the structure's energy efficiency. - The orientation of a façade can cause a variation in energy demand of up to 40% between a north- and south-oriented façade. 	<ul style="list-style-type: none"> - The airflow path is the most crucial factor for a DSF's effectiveness. - The most effective cavity depth is found to be 1 meter. - Single tinted + Double tinted - Multi-storey DSF
2017	Barbosa and Ip [32]	Tropical climate/ Rio de Janeiro, Brazil	Naturally ventilated DSF	Dynamic simulation program IESVE	<ul style="list-style-type: none"> - With DSF and a mixed mode ventilation approach, natural ventilation may offer the thermal comfort for more than 34% of the year, potentially using 21% less cooling energy than a fully air-conditioned model. - The energy savings brought about by the adoption of DSF alone are minimal, amounting to 15% in a fully air-conditioned model and 6% in a mixed mode ventilation model. 	<ul style="list-style-type: none"> -
2017	Faggal [5]	Alexandria, Cairo and Aswan, Egypt	Typical DSF	IES VE simulation program	<ul style="list-style-type: none"> - The expected percentage of dissatisfied people was 21% and 27.5% in Alexandria, a Mediterranean coastal location, and Cairo, a semi-desert region, respectively, according to the thermal performance of the standard wall materials. While Aswan's extremely parched desert region recorded the higher anticipated number of dissatisfied people with 34%. 	<ul style="list-style-type: none"> - Buildings in hot climates perform best when they are facing north and south, have horizontal shading systems, automatically open their windows, and have cavity spaces that are 30 cm wide.

2017	Su <i>et al.</i> , [51]	Cold season/ China	Typical DSF	CFD	<ul style="list-style-type: none"> - DSF thermal performance is highly impacted by DSF structural characteristics. The primary factors influencing DSF thermal performance vary depending on the climate zone. 	<ul style="list-style-type: none"> - In Guangzhou, the overall heat gain is essentially unaffected by cavity diameter. However, from Shanghai to Beijing to Harbin, the impact of cavity width tends to increase. - In Harbin, the total heat gain rises 12.3% when the cavity diameter is increased from 0.2 to 0.8 m. Beijing and Shanghai both saw increases of 5.6% and 4.3%, respectively.
2017	Aksamija [3]	Various climates	Different types of DSF	Design Builder/ Revit simulation	<ul style="list-style-type: none"> - In comparison to the base case scenario, energy performance would increase for all DSF kinds. - DSF varieties have a U-value that is significantly lower than a typical curtain wall, indicating improved thermal performance. 	<ul style="list-style-type: none"> - While there are only minor changes across the various DSF typologies, the multi-story DSF would have the lowest U-value, followed by box window and corridor type DSF.
2018	Aleksandro wicz and Yezioro [66]	Hot and humid climate/ Tel Aviv, Israel	Box window DSF	Monitoring/ digital calculation tool	<ul style="list-style-type: none"> - Box window with mechanical ventilation DSF has the ability to lower indoor temperatures by up to 2°C when integrated blinds are used (excluding the effect of air conditioning). - Limiting solar heat gains without sacrificing visual comfort indoors. - At the same time, they revealed an intrinsic weakness in the system's ability to prevent air cavity overheating: in all facades exposed to direct sun irradiance, air cavity temperatures were 10 to 30 degrees Celsius higher than outdoor temperatures. 	<ul style="list-style-type: none"> - Low-E glazing is found to be the most efficient.
2018	Johny and Shanks [67]	Hot arid climate/UAE	Naturally ventilated DSF	CFD/IES-VE Apache/ CFD based IES-VE Microflo	<ul style="list-style-type: none"> - All DSF variations limit the amount of solar gain that enters indoor climate-controlled spaces and create an air envelope that is cooler than the surrounding environment. 	<ul style="list-style-type: none"> -

2018	Kim <i>et al.</i> , [43]	Daejeon, South Korea	Typical DSF Box window DSF	EnergyPlus/ Daysim daylighting simulation program	<ul style="list-style-type: none"> - Increasing the number of perforations up to 45.6% of the external skin area has a substantial influence on PCM external skins while having minimal effect on the degree of reduction in DSF cavity temperature for glazed and concrete DSF. - Without any shades or controls, the DSF model can save up to 40%, 2%, and 5% for heating, cooling, and total loads, respectively. 	<ul style="list-style-type: none"> - DSF and exterior blind models may be able to reduce building thermal loads and lighting energy consumption by about 27-52%, respectively, when combined with daylight-based dimming control based on indoor illuminance levels and the blind raise/lower control.
2018	Ayegbusi <i>et al.</i> , [68]	Hot and humid climate/ Malaysia	Naturally ventilated DSF	DesignBuilder/ EnergyPlus	<ul style="list-style-type: none"> - Naturally ventilated cavity helped to reduce solar heat gain and thermal transmittance in DSF. - Integrating a naturally ventilated cavity on all orientations would reduce the cooling load over traditional single skin building by a range between 46% and 84%. 	<ul style="list-style-type: none"> - 600 mm cavity depth is found to be the most efficient on all four orientations (east, south, north and west).
2019	Inan and Basaran [8]	Unsteady outside boundary conditions/ Istanbul, Turkey	-	Experiment/ calculation	<ul style="list-style-type: none"> - The cooling loads decreased by up to 26% when using DSF in all orientations compared to SSF. - In Istanbul, the use of DSF with external airflow mode in the cavity produced unsatisfactory results in comparison to SSF, although it performed better in terms of energy efficiency in July. 	
2019	Li <i>et al.</i> , [53]	Hot-summer and cold-winter/ Ningbo, China	Typical DSF	Experiment/ Numerical Simulation	<ul style="list-style-type: none"> - The integrated PCM blind system was able to maintain the DSF's average summertime air temperature below 35 °C. - When compared to the exterior skin surface temperature, the inner skin of 	<ul style="list-style-type: none"> - Thermal performance tests revealed that the PCM blind outperformed a typical aluminum blind.

2019	Qahtan [52]	Tropical climate/ Kuala Lumpur, Malaysia	Multi-storey DSF	Measurement	<p>the DSF was likewise cooled down by roughly 2.9 °C.</p> <ul style="list-style-type: none"> - DSF is useful in preventing the emergence of heat gain because of the variations in surface temperatures between indoor and outdoor environments. - Inadequate to prevent tropical direct sun radiation from entering indoor spaces. The peak indoor air temperature in the general space next to the DSF ranges from 26.4 °C to 27.6 °C, increasing the need for building cooling. 	-
2019	Yoon <i>et al.</i> , [69]	Daejeon, South Korea	Box window DSF	EnergyPlus/ Measurement	<ul style="list-style-type: none"> - The apartment on the first story uses the least amount of heating power, while the one on the 25th floor uses the most. Between the first floor and the 25th floor, there was a variation in outdoor air temperature of roughly 0.4 °C. - The apartment's 21st floor has a 30% energy reduction in heating. 	-
2020	Aldawoud <i>et al.</i> , [47]	Hot humid climate/ Dubai, UAE	Box window DSF Shaft box window DSF	DesignBuilder/ EnergyPlus	<ul style="list-style-type: none"> - A naturally ventilated air cavity DSF system reduces cooling energy use by 22% annually. - The annual cooling energy consumption of the building can be decreased by 32% by adding mechanical ventilation to the air cavity. 	- 1.2 meters cavity depth is found to be the most efficient.
2020	Saroglou <i>et al.</i> , [17]	Mediterranean climate/Tel Aviv, UAE	Naturally ventilated DSF	EnergyPlus/ SketchUp	<ul style="list-style-type: none"> - DSF has potentials to save energy with this climatic context. 	<ul style="list-style-type: none"> - 1-2 meters cavity depth is found to be the most efficient. - Wider cavity is more appropriate for a hot climate, as they reduce high cooling loads. - Low-E glazing on the outside layer of a ventilated DSF lowered cooling loads by 15% on average, while Low-E glazing

2020	Yang <i>et al.</i> , [70]	Various climate zone/ Darwin, Sydney and Canberra, Australia	Naturally ventilated DSF	TRNSYS/ TRNFlow	<ul style="list-style-type: none"> - A naturally ventilated DSF incorporating a perovskite-based solar cell might be the best setup for maximizing savings. In Darwin, Sydney, and Canberra, respectively, total yearly energy savings of 34.1%, 86%, and 106% were achieved in compared to the conventional. - DSF could further reduce the building's heating and cooling loads by harvesting thermal energy generated within the air cavity. - The harvested electrical and thermal energy from the façade could cover a significant share of building's energy consumption. 	<ul style="list-style-type: none"> - on the interior layer reduced cooling loads by an average of 50%.
2020	Manubawa <i>et al.</i> , [62]	Indonesia	Typical DSF	Sketchup/ dialux measurement	<ul style="list-style-type: none"> - The secondary skin works in generating shade within the structure, however the natural lighting level is only 30 lux, less than the classroom's conventional lighting level of 250 lux. - The average light intensity without the additional skin is 310 lux, which generates glare and makes things visually uncomfortable. 	<ul style="list-style-type: none"> -
2021	Hou <i>et al.</i> , [71]	Cold season/ China	Naturally ventilated DSF	CDF simulation	<ul style="list-style-type: none"> - The curtain wall with a height of about 4 m has the best air preheating effect, and the air supply temperature is inversely proportionate to the curtain wall thickness. - The amount of air circulation in the room can reach the standard of healthy ventilation if the natural ventilation chamber is passively preheated. - As an air cushion layer, the DSF has excellent heat preservation properties, 	<ul style="list-style-type: none"> -

2021	Tao <i>et al.</i> , [72]	Istanbul, Turkey	Naturally ventilated DSF	CFD software/ ANSYS Fluent 2020R1	making it easier to control indoor temperatures. - The size of window openings has a secondary impact after the dimensions of naturally ventilated DSF.	- The Low-E glazing is found to be the most efficient. - 0.15-0.3 meters cavity depth is found to be the most efficient.
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10. Conclusion

In order to optimize the overall façade performance, the DSF scheme has been researched and developed incessantly and applied to the modern building exterior. It is arguable that DSF could be a passive façade system or could be the opposite. To obtain positive effects from DSF, concentrated planning and design of the system are important along with the climatic condition of any distinctive location. Otherwise, DSF may alternatively cause negative impacts such as excessive heat and light quality reduction, etc., which lead to thermal discomfort and energy deficiency. To the extent finding of this review, DSF has the potential on enhancing the indoor environment and obtain energy efficiency with long-term investment, yet it has not been broadly studied and employed in the comprehensive tropical climate region due to uncertainty of its benefits and the high possibility of overheating. Therefore, it is recommended that more profound studies on the system to be carried out for the broader application of DSF passively and efficiently toward green building within the built environment.

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