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Double-Skin Façade (DSF) Application to Address the Performance Problems of the Contemporary Buildings in Yemen

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Abstract: The double-skin façade (DSF) recently received significant attention from specialists and researchers due to its possibility to improve the building's performance. In Yemen, which has various climates, contemporary buildings suffer from many performance problems due to the weak interaction of their facades with the surrounding environment. Therefore, this paper aims to explore the DSF possibilities in enhancing the contemporary buildings' performance in Yemen by reviewing previous studies investigating the DSF system and the performance of contemporary Yemen buildings to identify and summarize the solutions and treatments offered by the DSF to improve these buildings' performance. The analysis revealed that implementing the DSF system can enhance the performance of the contemporary buildings in Yemen in terms of interior comfort and energy-saving when reaching the proper design of this system that appropriately responds to the region's climate. Yet, there are problems that the DSF may not fully meet, represented by building loads and construction and maintenance costs.

Keywords: Double-skin façade, DSF, contemporary building, Yemen, building performance problems, enhance performance

1. Introduction

A building is built to provide the occupants with a comfortable internal environment and protection against external climate changes [1], [2]. Today, especially in extreme climates, buildings suffer from different performance problems in thermal performance, ventilation, and vision, representing the highest percentage of energy consumption and CO2 emissions, etc. The building envelope represents the barrier between the internal and external environment, which has a vital role in controlling the building's performance and protecting the interior spaces [3], [4]. Facades control solar heat gain, natural ventilation, daylight, vision, acoustics, and the aesthetic value of the building—the facades' effectiveness is measured by their ability to create a comfortable indoor environment. In addition, the suitable design of the façade is one of the most efficient methods to optimize the building's performance [5]. Therefore, there is a continuous pursuit to develop the building's facades to be more interactive and efficient to obtain the best results in improving the building's performance. Recently, many facades appeared to achieve this purpose, such as double-skin facades (DSFs) [4].

The double-skin façade has been presented as a responsive system for performance-enhancing of building [6]. It is one of the technologies used to optimize performance and influence the energy consumption in a building [4]. Many

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researchers consider the DSF one of the best ways to manage the interaction between outdoor and indoor spaces, such as A. Hakim & A. Ghazali [5] and A. Ghazali et al. [7]. There are investigations and findings are reported in the literature on DSF performance. Many researchers mentioned several benefits of using the DSF to improve the building's performance, such as M. M. S. Ahmed et al. [8], T. İNAN [9], and J. C. Vaglio [10]. They consider that the appropriate selection of the DSF type and the design of its components according to the surrounding climatic conditions can provide greater thermal insulation, enhance indoor environmental quality, raise the acoustic insulation level, promote natural ventilation to increase indoor air quality, reduce the high wind pressures on the building, maximize the daylighting, help with energy-saving, and positively contribute to the environmental impact by decreasing the CO2 emissions. Additionally, some consider the DSF an economical alternative to renovating and retrofitting existing and old buildings as G. Kim, L. Schaefer & J. T. Kim [7] in 2013 and B. P. Slavković [11] in 2017.

In Yemen, many contemporary buildings suffer from different problems in terms of performance, such as poor thermal insulation, ventilation, daylighting, etc., due mainly to the weak interaction of these buildings facades with the surrounding outdoor environment. These performance problems lead to several other problems, such as environmental, economic, health problems, etc. [33]. Due to the lack of studies on the application of the DSF system to Yemen buildings, this paper aims to review the literature on the DSF system, its performance, and the possibility of its application, in addition to reviewing the performance problems of Yemen's contemporary buildings, to offer the solutions that the DSF provide to improve these contemporary buildings' performance.

2. Double-Skin Façade's Concept

The double-skin facade concept is not new where is this type of facade has taken its present form over many years. The DSF has appeared, improved, and spread in Europe with cold and temperate climates [12], [13]. It is driven by the need to improve the indoor environment, the acoustics insulation, reduce energy use, and the aesthetic desire that leads to increased transparency [14]. Over the last decades, this system has begun to take its place and appears in the hotter climate regions of different countries (Figure 1) [10].

Fig. 1 - Seattle Justice Centre: example of double-skin façade [15]

2.1 Double-Skin Façade Definition

The definition of the DSF differs from one researcher to another, each according to his point of view. However, these definitions complete each other to give a clear image that clarifies the DSF system's concept. Generally, DSF combines a pair of glass skins by adding an extra external skin of glazing to the main façade. These two skins are separated by an air gap called a cavity, which ranges in width from 20 cm to several meters. However, the system components can be designed in several ways based on the functions desired and the requirements [16], [17].

2.2 Double-Skin Façade Structure

The structure of the DSF consists of components that form the DSF system (Figure 2), where the DSF's performance mainly depends on the design and combination of these elements. The fundamental components of the DSF structure are the interior skin, exterior skin, and cavity. These elements can be expanded into a more descriptive structure of this system, which relies on the design of the DSF as glazing, openings, and shading [18]. Usually, the exterior façade skin comprises single-pane glazing, and the interior facade skin is double-pane glazing. Depending on the design, the distance between the interior and exterior façade skins can vary from 0.20 m to 2.00 m [16].

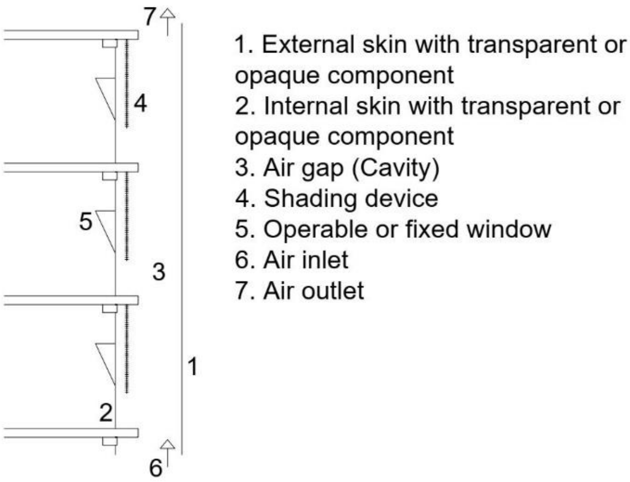


Fig. 2 - Double-skin façade structure [19]

2.3 Double-Skin Façade Typologies

The double-skin façades have many classifications. The main classification of the DSFs depends on the geometry and partitioning of the cavity. Based on the partitioning of the cavity, there are four types of the DSF; box-window facade, corridor facade, shaft-box facade, and multi-story facade (Figure 3). Various configurations can be formed based on the cavity geometry, ventilation type, and airflow mode inside the cavity (Figures 4, and 5). This condition creates a great variety of double-skin facade configurations [9], [18].

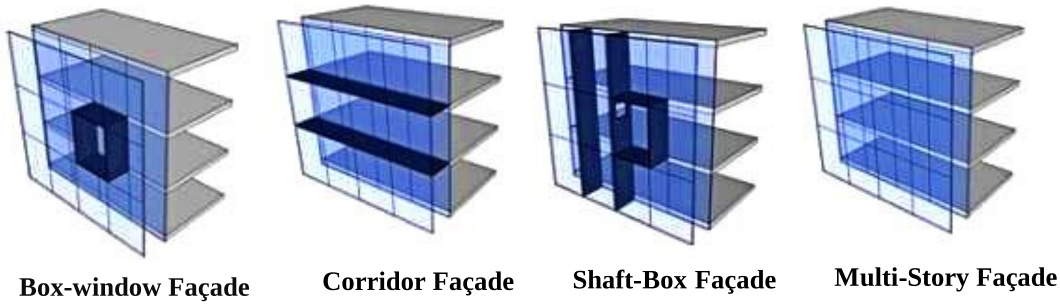


Fig. 3 - Double-skin façade types [20]

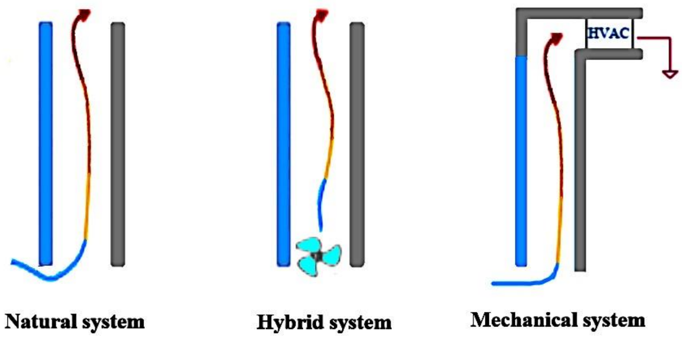


Fig. 4 - Double-skin façade ventilation types

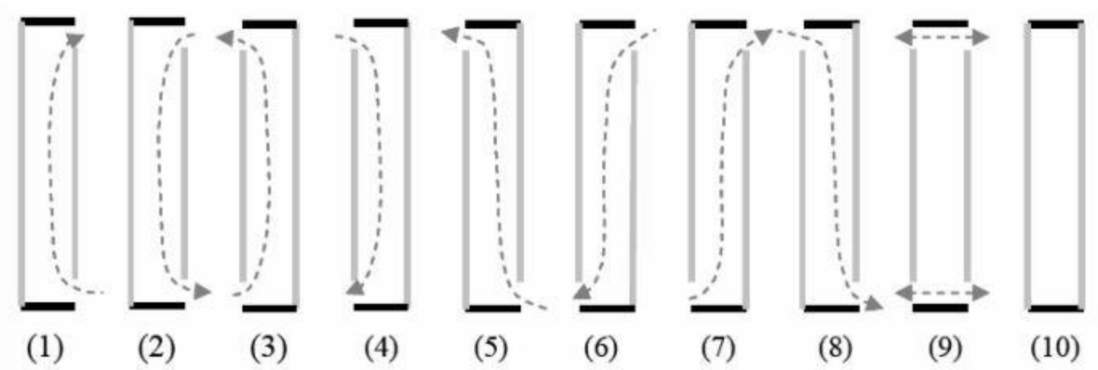


Fig. 5 - Double-skin façade ventilation modes [14]

2.4 Double-Skin Façade Performance

The first impetus for the emergence of the double-skin facade in Europe, especially Northern Europe, was the high energy cost due to the large heating requirements and the desire for improved natural light [20], [21]. The concept of facade performance revolves around adding the external skin and creating an air gap (cavity) between the internal and external skins. Adding the external skin provides the building with natural ventilation, thermal insulation, extra protection against weather, and improves acoustic insulation. In addition, The cavity acts as a thermal buffer against the external environment, whether cold or hot [16], [22], [23].

The double-skin facade could be designed in several ways based on the functions desired and requirements. In hot seasons, the DSF has openings on the external skin (inlet and outlet openings) to encourage air movement inside the cavity to lift the hot air to the upper section of the facade, forcing the cold air to enter from the bottom. The airflow inside the cavity helps extract heat accumulated in the cavity and mitigate the temperature, reducing conduction, convection, and radiation from and to the adjacent spaces; thus, less cooling energy [17]. In cold seasons, the DSF system is closed with no air movement through the cavity, which causes increases in the temperature inside the cavity, thus increasing the inner skin's temperature and reducing conduction and convection (Figure 6) [12], [24].

Energy consumption in buildings with DSFs strictly depends on the thermal performances of the DSF, which differ with seasons [25]. Therefore, many researchers consider the DSF is efficient in energy saving when adequately designed. However, the DSF system is integrated and complex due to the various factors affecting the performance of the DSF, such as the DSF type, the cavity dimensions, glazing type, opening, orientation, surrounding environmental conditions, etc. (Figure 7) [26]. Because of these various factors, the physical behaviour of the DSF (thermal properties, heat transfer, airflow, and effects on energy consumption) would differ [27], [28].

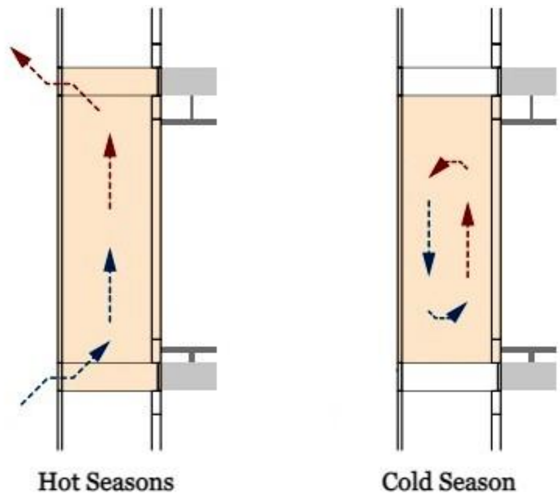


Fig. 6 - DSF performance concept according to the season

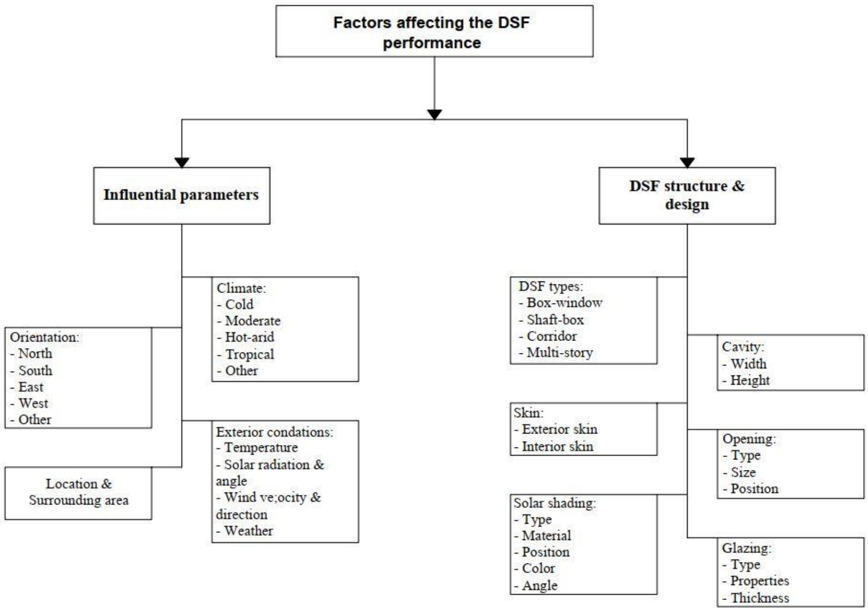


Fig. 7 - Factors affecting the DSF performance

3. The Contemporary Building in Yemen

Yemen's terrain and climate vary from hot-humid in the coastal plains, hot-dry in Hadhramaut and the interior desert regions, to temperate summers and cold winters in the highlands [29], [30]. This diverse climate and geographical environment played a significant role in defining the features of traditional Yemeni architecture in the past, which led to the diversity of building materials and the multiplicity of methods, construction techniques, and solutions used by the builders to construct eco-smart buildings (Figure 8). Old traditional buildings in Yemen have achieved comfort for occupants, especially thermal comfort, where simple, traditional, and available materials were used in construction, making these buildings adapted to the surrounding environment [31], [32]. After the revolution in 1962, there have been significant transformations in Yemeni architecture. The contemporary buildings have taken a different approach due to the openness to the world and the entry of modern building materials, which have made the contemporary buildings take a different approach in construction and design (Figure 9) [31]. However, these transformations were accompanied by many problems and defects in the performance of these buildings, in addition to other problems associated with their performance problems, such as environmental, economic, social problems, etc.

There are many reasons for the performance problems of contemporary buildings, which include:

- Usually, the surrounding environment and climatic factors are not considered when designing, orienting, or using building materials [31].
- Not benefiting from the great legacy of traditional architecture and the treatments used [33].
- Using modern materials without appropriate treatments (cladding, insulating materials, shading devices, treated glass, etc.) does not meet the requirements for comfort and consumes more energy [33].

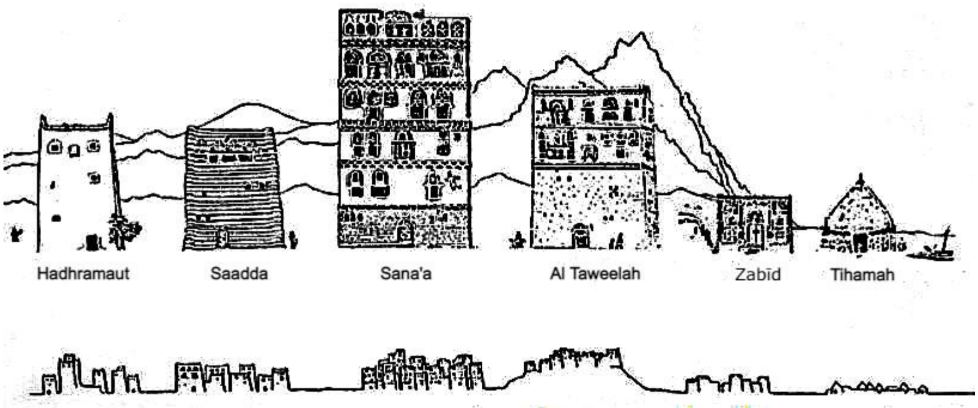


Fig. 8 - Traditional buildings in Yemen and their differences according to the region's nature [33]

Fig. 9 - Contemporary buildings in Yemen

3.1 Performance Problems of Contemporary Yemeni Buildings

The building should achieve the primary criteria of performance, which are indoor thermal comfort, energy- saving, and aesthetic value (Figure 10). In addition, there are other building performance criteria that architects and engineers strive to meet and consider, such as sustainability, security, safety, maintenance, cost, etc. [34].

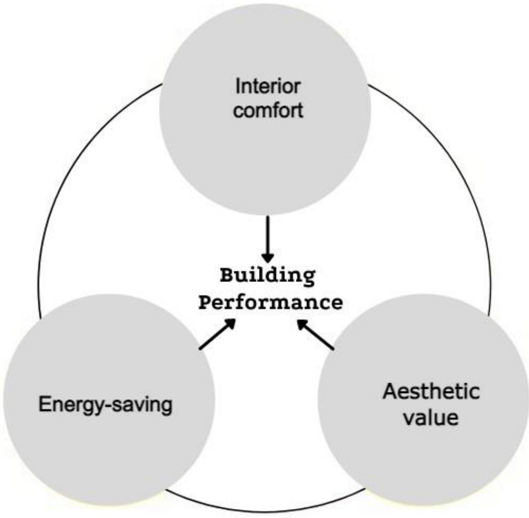


Fig. 10 - The primary criteria of buildings' performance

Investigate the reality of Yemeni architecture and learn about the changes that have occurred in contemporary architecture, which disregards the passive design and solutions of traditional Yemeni architecture in favour of superficially imitating some aspects of Western architecture. These factors negatively affected the output of contemporary Yemeni architecture, causing many performance problems as well as environmental, urban, and economic problems, etc. [33].

There are many problems with the performance of contemporary buildings in Yemen. One of the most visible problems with these buildings' performance is the failure to achieve internal comfort (thermal comfort, adequate daylighting, and good natural ventilation), which increase the energy consumption, especially in the summer season and in hot cities [35], [36]. However, due to a lack of consideration for design criteria, surrounding climatic conditions, appropriate materials, and insulation, contemporary Yemeni buildings suffer from various performance issues, as summarised below:

- Using materials with high thermal conductivity in building facades and exposing windows to direct sunlight results in thermal discomfort and significant energy waste[37].
- The temperature of the interior spaces of the floors rises with the height of the building, causing thermal discomfort in the summer [36].
- High energy consumption, especially in hot cities, results in atmospheric pollution due to CO_2 emissions, one of the leading causes of global warming. In addition, the high cost of energy represents a significant economic burden on the individual or the country's general economy [38], [39].
- The large windows and extensive glass areas of facades have poor sound insulation and cannot control the intensity of daylighting and glare, causing visual discomfor [33], [40].
- Using high metallic curtains to solve the privacy problem in residential buildings negatively impacts the aesthetic value of buildings, daylighting, thermal comfort, etc. (Figure 11) [33].

- The increasing use of stone and marble in building facades raises building loads and costs (Figure 12) [41].
- Poor in providing security and safety, and an inability to control the natural ventilation [33], [40].
- Aluminium and wood windows cause heat and air leakage (Figure 13) [31].
- Increase internal relative humidity in cement brick buildings, mainly with insufficient ventilation [33].

Fig. 11 - Using high metallic curtains

Fig. 1 - Stone and marble in buildings facades

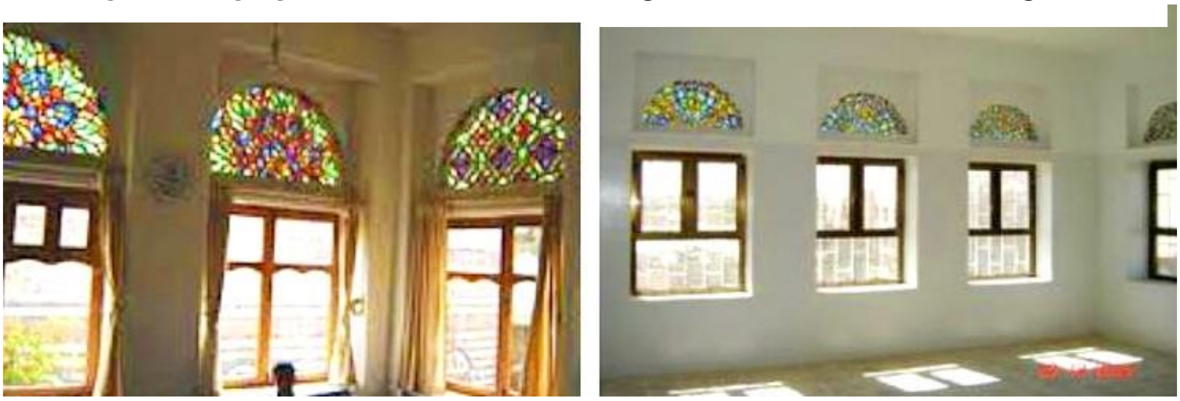


Fig. 13 - Aluminium and wood windows

3.2 DSF Solutions for Contemporary Buildings' Performance Problems

The performance problems of the contemporary buildings in Yemen are summarized in the weak interaction of their facades with the surrounding environment due to their failure to consider many aspects, such as orientation, opening ratios, appropriate treatments for the used materials, etc. These contemporary buildings' facades, as conventional façades, usually lead to lower levels of daylighting, poor natural ventilation, thermal discomfort, and an increase in energy consumption. Applying the DSF to overcome these problems is widely accepted, where it offers significant opportunities to improve the building's performance with environmental and economic benefits [3]. Based on reviewing the previous studies on the DSF and contemporary Yemeni buildings' performance, this paper looks into the DSF system as an approach to improve the performance of contemporary Yemeni buildings, considering the diverse climate of Yemen, the peculiarities of Yemeni architecture, and the possibility of applying the DSF system to these buildings.

Several studies confirm the ability of the DSF on improving the building performance in different climate conditions, such as temperate climate by F. Pomponi et al. [42] in 2016, summer and winter seasons by M. Torres et al. [43] in 2007, hot climate by S. A. Mousavi & H. Z. Alibaba [44] in 2015, subtropical climate by A. L. S. Chan et al. [45] in 2009, hot-arid climate by N. Hashemi et al. [46] in 2010, tropical climate by B. Rahmani et al. [47] in 2012. Moreover, many researchers mentioned the benefits of applying the DSFs, such as M. M. S. Ahmed et al. [8] in 2016, T. İNAN [9] in 2016, J. C. Vaglio [10] in 2015, and M. A. Shameri et al. [48] in 2011, which can be summarized in balancing the demand for energy use, thermal and visual comfort, natural ventilation, and acoustic insulation, in addition to safety and security, when this system is appropriately designed and considerate of the surrounding environment.

Furthermore, the DSF can be used to retrofit and renovate existing and old buildings to improve their performance according to the need and required performance by adding an external skin facade to the building. This approach is an effective and economical alternative to renovating the construction, preserving existing stock, and upgrading the aesthetic of the building [4], [10]. The building facade (whole or parts of the facade) can be covered, which helps save the building's character [16], [49]. Therefore, recently, renovation and implementation of the double-skin facade system on existing buildings have been widely seen as a necessary application to provide the required thermal comfort in the building (Table 1) [7], [11].

Referring to the performance problems of the contemporary Yemen building in point (3.1) and taking into account the variety of climates in Yemen cities, (Table 2) summarizes the benefits of using the DSF to overcome these performance problems. Although there is agreement that the application of DSF's appropriate design positively affects building performance and the environment, there are consensus on this system's high maintenance and construction costs compared to the conventional façade [50]. However, some consider that the DSF is cost-efficient, where the initial investment cost can be balanced with running costs due to energy-saving [21].

Table 1 - Renovation and improvement of buildings using DSFs

Type of Covering	Example	Description
Whole Facade		Köln Triangle building in Deutz, Cologne: Based on the requirements, the building's facades in this example offer different functions with a single-skin façade (on the right), and an additional layer (on the left) has been added to create a DSF with a ventilated cavity [16].
Whole or Part of Facade		On the right, an early example of a DSF was created by adding a layer of glass outside the primary façade. On the left, a window element is added to form a box-window façade [16].
Facade's Open Spaces		Box window: In summer, the outer layer can be opened to allow natural ventilation. In the winter, the extra layer can be closed to help prevent heat and air leakage [51].
		DVV building, Brussels (centre): It consists of a double window system separated by 15 cm. The shading device is situated in the air cavity and controlled according to the orientation and the storey of the façade [15].
Retrofit Old Building		SUVA Insurance Company: The building was constructed in the 1950s; a new glazed façade was added to improve its thermal and lighting performance [49].

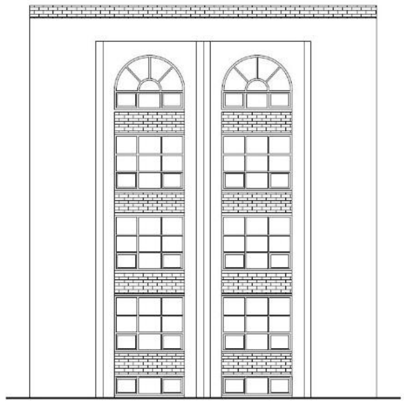
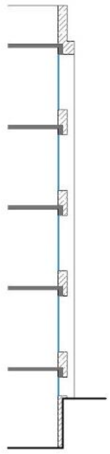
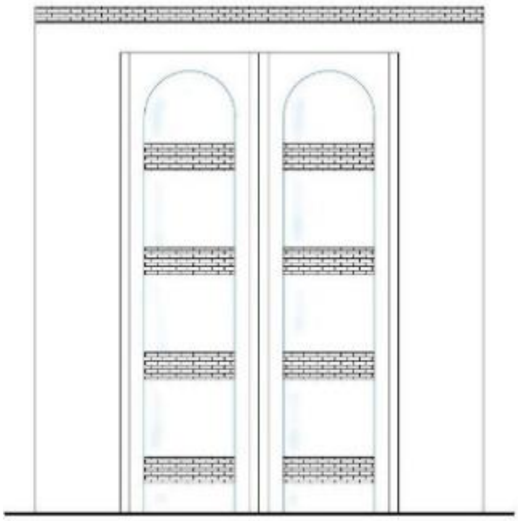
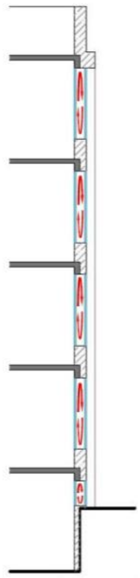
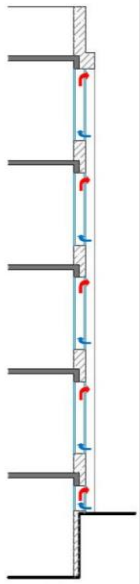
Table 2 - Using DSFs to address performance problems of the contemporary Yemeni building

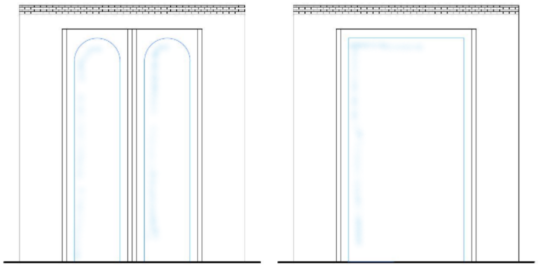
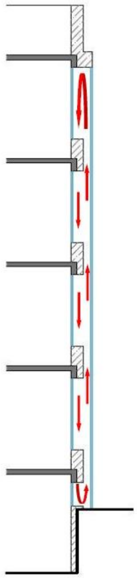
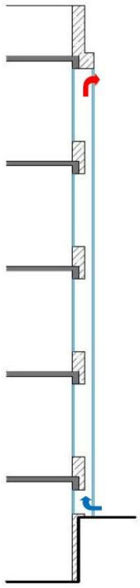
Performance Problems of C.Y.B.	Double-Skin Facades' Solutions
Thermal discomfort	* The air cavity acts as a buffer zone, making the indoor spaces close to the windows more usable, decreasing the inner temperature fluctuations, and providing greater overall thermal comfort [18]. * Improve the building's interior thermal comfort by trapping the heat in the cavity in cold weather, while in hot weather, by exhausting the hot air out of the cavity [10], [18].

	* Installing the shading devices in the cavity reduces the solar heat gains, thus enhancing the inner thermal comfort for buildings in hot cities [17], [52]. * In hot cities, the natural ventilation in the DSF system cools down the indoor temperature [12], [53].
The temperature increase in the higher stories	* At high-rise buildings, the DSF system absorbs the wind velocities. Therefore, windows can be opened for natural ventilation, thus mitigating inner temperatures on higher floors [9], [12]. * Applying the corridor façade type to upper stories reduces overheating [4].
High energy consumption	* The cavity acts as a thermal insulator, thus reducing heating and cooling energy needs. In cold weather, the heated air in the cavity can be used as an input for air conditioning units [54]. * Reduce energy consumption due to reducing fans and cooling equipment use and artificial lighting through increasing natural ventilation and daylighting levels [9], [53]. * The mechanically ventilated DSF could increase the building's energy-saving from 21% to 26% in summer and 41% to 59% in winter [3], [55].
Poor control of natural ventilation	* The external skin shields the entire building structure, allowing natural ventilation without fear when rain or high wind pressures occur, even on higher floors where windows can be left open for night-time ventilation [10], [18]. * Increase natural ventilation in the cavity due to the stack effect [21].
Poor daylighting and visual discomfort	* The outer glazed skins improve internal visual comfort by providing good daylighting, increasing the exterior view [9], [21]. * Glare (direct glare, contrast glare, or reflection glare) can be avoided by the appropriate use of the type of external skin glass and the material's colour of shading device [10].
Poor sound insulation	* The cavity acts as a buffer zone that provides acoustic insulation from outside the building to the inside [8], [53].
The relative humidity increase	* Fans or mechanical-driven openings can manage humidity and temperature to achieve inner thermal comfort [56].
Privacy and facade aesthetics problems	* A double-glazed skin maintains privacy and a quiet environment [53]. Therefore, this would help reduce the need to use high metallic curtains. * Transparency and uniformity give many buildings an aesthetic look and a sense of openness, such as commercial buildings [18].
Poor security and safety	* The external skin allows DSF systems to preserve the building and add more security and safety [10].
Heat and air leakage	* The external skin with the buffer zone (cavity) provides great thermal insulation; this mitigates the air leakage effect [8], [10], [13].
Increase building loads, and cost	* Increase the investment in the first cost due to the external skin construction. Still, considering the benefits of energy savings throughout the building's life cycle, DSF could reduce running costs [21].
CO_2 emissions and global warming	* Enhancing the natural ventilation and energy savings reduces fans and HVAC system use, which means a reduction in environmental impact and CO_2 emissions, thus reducing the building’s impact on global warming [21], [53].

Based on Table 1 and Table 2, Table 3 gives an example of applying the DSF to a contemporary building in Yemen.

Table 3 - Example of applying the DSF system to a contemporary building in Yemen

DSF Application	Building's Facades	Cold Weather	Hot Weather
Main Facades	 Central Organization for Control and Auditing (COCA) building in Sana'a city		
	COCA building represents one of the contemporary buildings in Yemen. The building is located in the northern highlands. Facade openings are large windows of regular glass distributed on all building facades. Stone was used on the facades to give the building the character of Yemeni architecture. **In winter**, the interior spaces are very cold, especially northern ones. **In summer**, building users suffer from high temperatures, especially in southern spaces, due to exposure to direct sun radiation.		
First Application	 Applying the DSF system to the facade's open spaces		
	Creating an air gap (cavity) around the facades' opening only by adding an external glazed skin to preserve the building character. **In winter**, close the external skin to trap the heat in the cavity to reduce the heat lost from the inner spaces, thus reducing the energy used in heating loads. **In summer**, opening on the external skin allows the airflow inside the cavity, thus extracting the heat from inner spaces, reducing direct sun radiation, allowing natural ventilation, and reducing the cooling loads. Shading devices can be added inside the cavity to enhance the protection from sun radiation.		

Second Application	 Applying the DSF system to the whole or parts of the facades.		
	DSF system can be applied by covering a part of the facade or the whole facade by adding an external glazed skin to create an air gap. **In winter**, theoretically, covering a wider area of the facade would increase the heating of interior spaces by the trapped heat inside the cavity. **In summer,** having a high cavity would increase the airflow inside the cavity due to the stack effect.		

4. Conclusion

The double-skin façade (DSF) has been proposed as a responsive system and one of the technologies that optimize the building performance. This paper aimed to review the concept of the DSF system, its performance, and the benefits of applying this system to summarize the solutions it provides to address the performance problems of the contemporary buildings in Yemen under different climate conditions. There is general agreement on the ability of the DSF in improving sound insulation and protecting the building from external environmental conditions (rain and wind). Many researchers also agree on the possibility of double facades in raising the level of thermal insulation, natural ventilation, and daylighting, as well as the effectiveness of this system in reducing energy consumption in buildings under different climate conditions.

Theoretically, implementing the DSF can solve several performance problems of the contemporary buildings in Yemen, represented in poor thermal performance, control of natural ventilation, sound insulation, daylighting, privacy, and increased energy consumption. Though, there are problems that the DSF may not fully meet, such as increased facade loads, relative humidity unless fans or air conditioners are used, and adding more construction and maintenance costs. However, the effectiveness of the DSF system depends on reaching the proper design of this system that can interact positively with the surrounding environment.

Adopting this system may improve the performance of buildings in Yemen, whether for under-construction buildings or existing buildings, even renovate and retrofit the old buildings. In addition, the implementation of this system could reduce the number of traditional treatments to solve performance problems of buildings while adding an aesthetic value that does not overwhelm the character of Yemeni buildings when applied in a studied manner, as well as reduce the consumption of natural building materials.

This study generally reviewed the concept of the double-skin facade system and its capabilities to enhance contemporary buildings' performance in different climates to open the door to more studies on this system as a new approach that can be adopted in Yemen. Therefore, investigations are required into applying this system through experimental and detailed studies for specific regions with specific climatic conditions to address specific problems in buildings performance in Yemen.

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