OPTIMIZING ENERGY EFFICIENCY IN NET-ZERO COMMERCIAL OFFICE BUILDINGS IN DESERT CLIMATES

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Abstract. This research investigates the optimization of energy efficiency in net-zero commercial office buildings through the synergistic integration of biophilic design principles and Double-Skin Facade (DSF) systems in maritime desert climates. The study emphasizes the role of biophilic design in enhancing occupant well-being and reducing energy consumption by incorporating natural elements such as daylight, greenery, and natural ventilation. These elements are strategically integrated with DSF systems to create high-performance building envelopes that align with net-zero energy goals. A comparative analysis was conducted to evaluate the impact of various DSF configurations including different cavity depths, glazing types, and orientations against the conventional Single-Skin Facade (SSF) system. Dynamic thermal modeling was employed to simulate the complex interactions within the facade cavity, ensuring precise calculations of the energy performance for each DSF configuration. The simulations revealed that integrating biophilic elements with multi-story DSF systems can lead to significant reductions in annual cooling loads, with potential savings of up to 32% compared to SSF systems. The research further identifies the optimal DSF configurations that maximize energy efficiency while supporting biophilic principles, such as the incorporation of natural light and views to the outdoors. The findings highlight the potential of combining biophilic design with advanced DSF technologies to not only achieve net-zero energy targets but also to enhance the overall environmental quality and sustainability of commercial buildings in maritime desert climates. This study contributes to the evolving discourse on sustainable architecture by demonstrating how the integration of nature and technology can drive the performance of next-generation green buildings optimization.

Key words: biophilic design, double-skin facades, maritime

1. Introduction

In a time when climate change and environmental sustainability are top priorities globally, the demand for energy-efficient buildings has grown increasingly urgent. The built environment plays a crucial role in mitigating climate change outcomes, given its significant impact on greenhouse gas emissions (GHG). It accounts for over 40% of global energy consumption and emits approximately 35% of the world's total GHG emissions (Dano *et al*., 2023; Li *et al*., 2019). The rapid urbanization of cities has led to an increasing number of tall office buildings featuring expansive glass facades, a hallmark of modern architectural styles that emphasize transparency and natural daylighting. While these facades perform well in temperate climates, their adoption in tropical and maritime climates introduces complex challenges related to energy efficiency and occupant comfort (Muraj *et al*., 2023; Ahmed and Fikry, 2019). In these regions, building facades must effectively manage the interaction between the indoor and outdoor environments, controlling factors such as solar heat gain, thermal loads, ventilation, and acoustics to maintain a comfortable and energy-efficient interior environment (Uribe and Vera, 2021; Ahmed and Fikry, 2019).

Globally, the buildings and construction sectors are responsible for over 36% of the total energy consumption (Santamouris and Vasilakopoulou, 2021; Ghonimi, 2017), while half of this amount is related to the Heat, Ventilation, and Air Conditioning (HVAC) systems (Hazem *et al*., 2015). Despite improvements in building technology, between 2010 and 2018, the need for space cooling surged by over 33%, with a 5% increase noted specifically in 2017-2018. Additionally, energy consumption for appliances rose by 18% in 2018 compared to 2010, and for water heating, there was an 11% increase. Meanwhile, space heating demand experienced a slight decrease of 1% since 2010, yet it has maintained a consistent level over the past five years, representing one-third of the total global energy demand in buildings (Global Alliance for Buildings and Construction, 2019). This increasing rate highlights the need to improve the efficiency of building envelopes in cooling dominant climates. In this context, DSFs provide an opportunity to control environmental factors (solar radiation and wind) for energy-saving and occupant thermal and visual comfort (Barbosa and Ip, 2014; Ghaffarianhoseini *et al*., 2016; Ahmed *et al*., 2016; Zhang *et al*., 2022; Ahriz *et al*., 2022).

Traditional building envelopes, particularly SSFs, have historically served as barriers to external environmental conditions. However, the development and implementation of DSF technology has introduced a more dynamic approach to facade design, especially in response to the global push for energy-efficient buildings. Originally developed in Europe for cold climates, DSF systems are now being explored for their potential to enhance thermal performance, improve natural lighting, and reduce energy consumption in a variety of climates, including hot and arid regions (Gentile *et al*., 2022; Hamza, 2008; Zhao *et al*., 2024).

Facades play a critical role in building energy performance, acting as a mediator between external environmental forces and the controlled indoor climate. Recent studies have highlighted the importance of facade design in reducing energy consumption, particularly in office buildings where facades can significantly influence HVAC loads (Giouri *et al*., 2020; Krstić-Furundžić *et al*., 2019; Mahdavinejad *et al*., 2024; Sarihi *et al*., 2021). For instance, facades can account for direct energy losses through heat transfer and indirect impacts on overall energy demand for heating, cooling, and lighting systems (Pomponi *et al*., 2016). The effectiveness of integrated biophilic design with DSF systems of commercial office buildings in maritime desert climates, remains under explored despite its proven benefits in temperate regions, especially in Saudi Arabia. In Saudi Arabia, building facades are exposed to extreme environmental conditions over the years. This has led to high energy consumption for HVAC systems, making the optimization of facade design crucial for achieving net-zero energy goals. Recent reports emphasize the growing energy demands in these regions, particularly in the building sector (Al-Badi and AlMubarak, 2019; Atalla and Hunt, 2016; Al-Maamary *et al*., 2017; Alarenan *et al*., 2020; Alshahrani and Boait, 2018), where office buildings account for a substantial portion of electricity consumption (Al-Tamimi, 2022; Mesloub *et al*., 2023).

This study seeks to address the knowledge gap concerning the effectiveness of integrated biophilic design with DSF systems of commercial building in maritime desert climates, particularly in their application to commercial office buildings designed to achieve net-zero energy status. DSF technology, which involves an additional layer of facade that improves thermal insulation and controls solar gain, is increasingly recognized for its role in reducing energy consumption, especially in extreme climates. Recent studies highlight the importance of DSF systems in enhancing the energy efficiency of buildings by mitigating the impacts of harsh environmental conditions (Liu *et al*., 2024; Al-Shatnawi *et al*., 2024; Sanchez *et al*., 2016; Aldawoud *et al*., 2021), which is critical for achieving net-zero energy goals. By evaluating various DSF configurations and their impact on energy performance, this research provides a detailed analysis of how integrated biophilic design with DSF systems can be optimized to enhance the energy efficiency of commercial office buildings.

2. Literature review

The DSF system was first developed in Europe and has since been adopted in various regions globally (Hamza, 2008). In the last three decades, numerous buildings worldwide have been built incorporating DSFs. DSFs are sophisticated architectural systems designed to optimize building performance through the use of dual glass layers separated by an air cavity. According to Wigginton and Harris (2013), a DSF typically includes an outer glass layer, a shading mechanism, an air-filled gap, and an inner insulating glazing system, which may also incorporate opaque walls. Aldawoud *et al*. (2021) describe DSFs as comprising two glass "skins" with an intervening air corridor, which provides insulation against temperature extremes, wind, and noise, with sun-shading devices frequently positioned within this space. Similarly, Zhou and Chen (2010) defined DSF as a façade consisting of multiple layers of construction, typically including an outer layer (often made of glass), an intermediate space, and an inner layer (also commonly made of glass), surrounding contemporary structures. The primary glass layer generally functions as part of a conventional structural or curtain wall, while the secondary layer, which may be single glazing, enhances the facade's thermal and acoustic performance by utilizing the air space for insulation.

2.1 Types and Design Configurations of Double-Skin Facade Systems

DSFs have shown a lot of development space regardless of the building class. It provides the formation of high-performance façades with the solution suggestions it brings to building materials and building performance. DSFs are classified according to the partitioning of the façade, type of ventilation and type of air flow (Fig. 1).

The expected double skin façade design should be made according to the requirements of the climate characteristics and indoor comfort conditions (Yaman, 2021). DSFs can be categorized into four primary configurations, each defined by specific design principles, including the origin and direction of airflow within the cavity, the facade's configuration, and the division of the intermediate space. According to recent studies, the four main types of DSFs are:

A. Box Facade
B. Corridor Facade
C. Shaft-Box Facade
D. Multi-Storey Facade

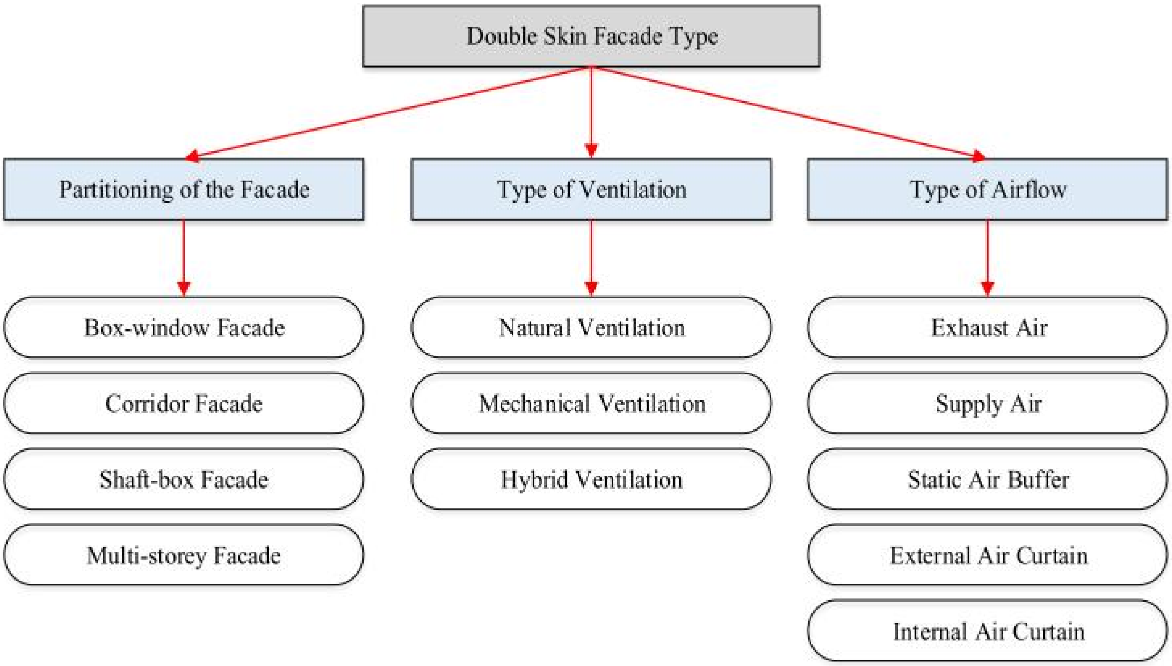

Fig. 1. Double skin façade types (Yaman, 2021).

These configurations differ in how they manage airflow and thermal performance within the facade cavity, providing varied solutions for energy efficiency and environmental control in buildings (Eberhard *et al.*, 2001; Aksamija, 2013).

2.2 Thermal Performance of DSFs in Hot Climates

The thermal performance of DSFs has been widely studied due to their significant impact on the energy efficiency of buildings, particularly in extreme climates (López-Escamilla *et al.*, 2024; Araji *et al.*, 2024; Aksamija, 2018; Pelletier *et al.*, 2023). DSFs function by creating an air cavity between two layers of facade, which serves as an insulating barrier, reducing the transfer of heat between the exterior and interior environments. In cooler regions, DSFs are designed to minimize heat loss by trapping warm air within the cavity, thereby reducing the need for interior heating. In contrast, in hot climates such as the UAE, DSFs are engineered to minimize radiant heat gain from the exterior, with the air cavity acting as a protective buffer for occupied interior zones (Ali, 2023). In hot desert climates, the primary goal of a DSF is to mitigate the effects of high solar radiation and ambient temperatures. The thermal performance of a DSF can be assessed using the steady-state heat transfer equation (1) below:

$$Q= (k \cdot A \cdot \Delta T)/d \quad \ldots(1)$$

Where:
Q is the rate of heat transfer (W),
k is the thermal conductivity of the material (W/m·K),
A is the area of the facade (m^2),
ΔT is the temperature difference across the facade (K), and
d is the thickness of the facade material (m) (Akbari and Konopacki, 2005).

In this context, a lower Q indicates better thermal performance, which is essential for reducing the cooling load in buildings. Air circulation within the DSF cavity is crucial for its performance. İnan (2016) emphasized that airflow through the cavity effectively extracts accumulated heat, reducing the temperature within the cavity and lowering the thermal load on adjacent spaces. This process is critical in decreasing the building's reliance on mechanical cooling systems (Knaack *et al.*, 2014). The convective heat transfer within the DSF cavity can be modeled using the equation (2) below:

$$Q_{conv}=h_c \cdot A \cdot (T_{cavity}-T_{ambient}) \quad \ldots(2)$$

Where:
Q_{conv} is the convective heat transfer (W),
h_c is the convective heat transfer coefficient (W/m^2·K),
A is the surface area of the cavity (m^2),
T_{cavity} is the temperature inside the cavity (K), and
$T_{ambient}$ is the ambient temperature (K).

By enhancing airflow, the cavity temperature Tcavity is reduced, which decreases the convective heat transfer Qconv into the building. Radiative heat transfer is another significant factor in DSF performance, particularly in hot climates. The radiative heat exchange between the facade layers can be expressed as in equation (3).

$$Q_{rad}= \epsilon \cdot \sigma \cdot A \cdot (T_1^4-T_2^4) \quad \ldots(3)$$

Where:
Qrad is the radiative heat transfer (W),

ϵ is the emissivity of the facade material,
σ is the Stefan-Boltzmann constant (5.67×10−8 W / m2K4),
A is the surface area (m²), and
T1 and T2 are the temperatures of the two facade surfaces (K).

Reducing Qrad is essential for maintaining lower interior temperatures and reducing cooling energy demands. The effectiveness of DSFs in such environments is increasingly relevant as buildings in regions like the Middle East strive to meet sustainability and energy efficiency standards, particularly in the context of net-zero energy goals. Recent studies confirm that optimized DSF designs can significantly reduce cooling loads, contributing to overall energy savings in commercial office buildings (Saroglou *et al*., 2019; Ziasistani and Fazelpour, 2019; Fazelpour *et al*., 2022; Ahriz *et al*., 2022).

2.3 Adaptive Skin Façades

Active façade systems are designed to create a dynamic interface between indoor and outdoor environments, offering adaptability and responsiveness to external conditions. These facades optimize indoor comfort by leveraging environmental factors such as sunlight, airflow, and temperature fluctuations. Key performance parameters include thermal insulation, ventilation control, moisture regulation, precipitation management, solar energy utilization, acoustic insulation, fire resistance, structural stability, and aesthetic appeal (Attia *et al*., 2018). The primary goals of active façade designs are to enhance the building's energy performance, meet daylighting requirements, and provide the highest level of thermal comfort are among the most basic requirements for façade design as shown in Fig. 2 below.

Adaptive façades may be operated manually or through automated digital systems, with the latter being preferred for achieving higher efficiency and consistent performance. The design of these façades must be tailored to the specific climatic conditions of the building’s location, ensuring that the integration of such systems is both effective and sustainable (Attia *et al*., 2018). During the initial design phase, architects and engineers should perform climate analysis using advanced simulation tools to optimize façade performance and conduct cost-benefit analyses to evaluate the long-term viability of these systems (Sharaidin, 2014; Ben Bacha and Bourbia, 2016). Recent studies emphasize the importance of incorporating adaptive façades in the early stages of building design to achieve optimal energy efficiency and occupant comfort, particularly in response to evolving climatic challenges (Mohtashami *et al*., 2022; Attia *et al*., 2018; Attia *et al*., 2020).

2.4 Vertical Green Façades with Biophilic Features

Vertical green façades, which integrate plants into the exterior wall systems, are increasingly being utilized to enhance building performance by improving indoor comfort and responding to environmental conditions (Fig. 3).

These systems are composed of various layers, including habitat, carrier, filter, thermal insulation, waterproofing, vapor barrier, and exterior wall elements, all designed to optimize their functionality. The primary advantage of vertical green façades lies in their ability to reduce the urban heat island effect, improve outdoor air quality, and offer ecological benefits by providing habitats for various organisms. Additionally, these façades act as protective barriers against rainwater and solar radiation, contributing to the overall energy efficiency of the building and enhancing its aesthetic appeal (Ibrahim Momtaz, 2018).

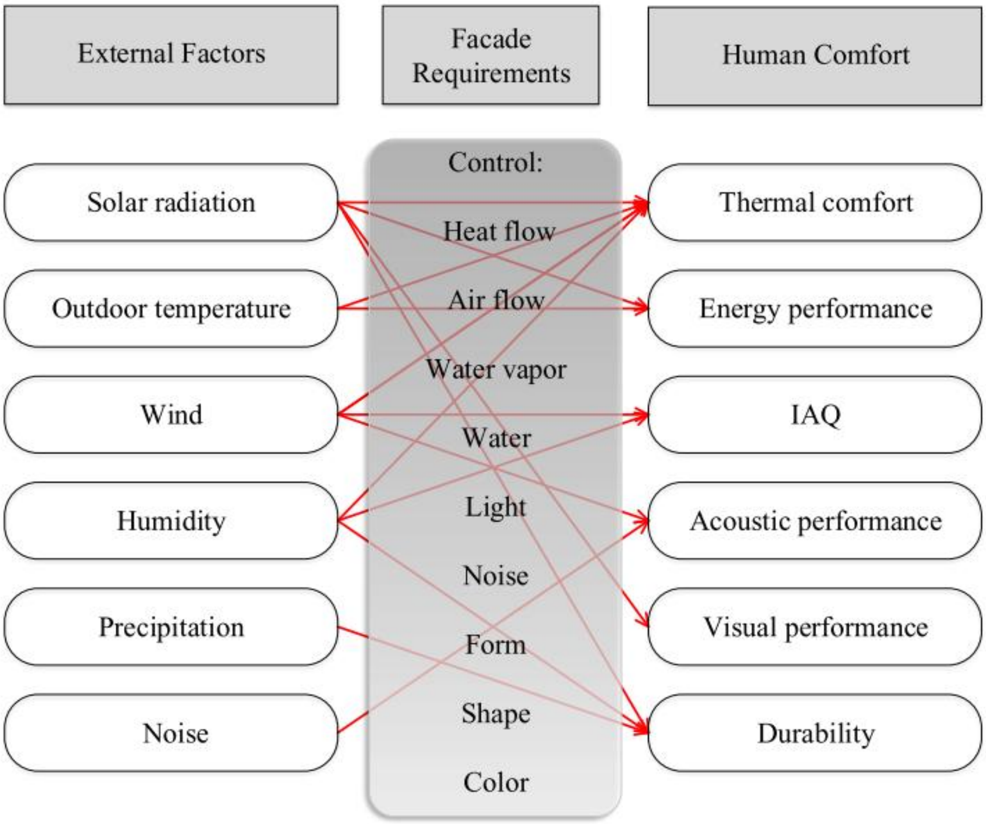

Fig. 2. The relationship between the outdoor environment and indoor comfort conditions of adaptive façades (Aelenei *et al*., 2016).

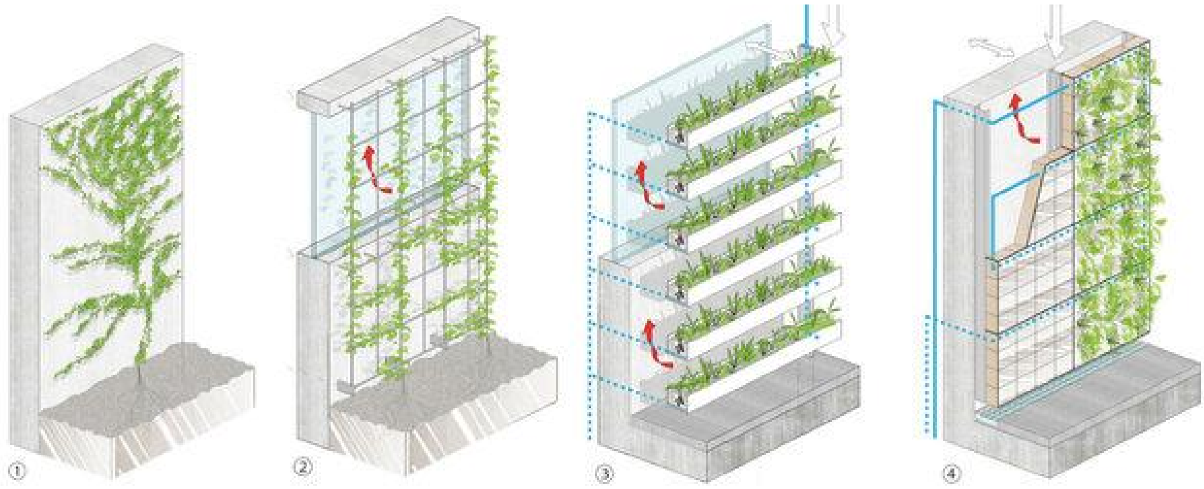

Fig. 3. Different vertical green systems:1) ground-based, 2) overgrown rope façades, 3) balcony boxes system, 4) living wall (Source: Arnold *et al*., 2021).

Despite these benefits, vertical green systems do have challenges, particularly regarding their maintenance and initial investment costs. Regular upkeep is necessary to manage plant growth and seasonal changes, and the selection of plant species must be carefully aligned with the local climate to ensure long-term viability. While the initial costs may be high, they can be offset by the long-term energy savings and environmental benefits these systems provide. Moreover, the integration of biophilic design principles into vertical green façades can further enhance occupant well-being by fostering a connection with nature, which has been shown to reduce stress and increase productivity, making these systems a valuable component of sustainable urban architecture (Zhang *et al*., 2019; El-Zoklah and Refaat, 2021; Revell and Anda, 2014).

3. Materials and Methods

The primary objective of this study is to optimize the energy efficiency of net-zero commercial buildings by integrating biophilic design principles with DSF in maritime desert climates. The study employs a dynamic simulation model to evaluate the energy performance of various DSF configurations, focusing on their impact on reducing cooling loads and overall energy consumption. The analysis compares these DSF configurations with a baseline SSF in a hypothetical office building located in Dhahran, Saudi Arabia. The IES-VE (Integrated Environmental Solutions-Virtual Environment) software is selected for its robust capabilities in simulating complex building systems, incorporating both biophilic design elements and DSF configurations to accurately predict energy performance.

3.1 Data Collection

The methodology involved several crucial steps as illustrated in Fig. 4 to ensure the precision and reliability of the simulations and analyses:

1. Simulation Model Selection: The IES-VE Pro was chosen as the primary simulation tool due to its advanced features that allow for the integration of biophilic design strategies with DSF systems. The software's capabilities in detailed HVAC system modeling, DSF configuration, daylighting analysis, and generating comprehensive energy performance data were key factors in its selection (Arnold *et al*., 2021). IES-VE's ability to simulate natural elements such as green walls, indoor plants, and other biophilic features alongside traditional building systems makes it an ideal tool for this research.

2. Climate Data Preparation: Accurate local climate data files for Dhahran were prepared, ensuring that they reflect the maritime desert climate's unique conditions. These data files were essential for simulating the real-world performance of DSF systems combined with biophilic elements under extreme environmental conditions. The climate data was sourced from the Saudi Arabian National Meteorology Center and fit for use within the IES-VE software.

3. Prototypical Office Building Design: A prototypical net-zero office building was developed as the baseline model. The building's design included biophilic elements such as vertical green façades and indoor gardens, alongside conventional architectural features. Detailed specifications regarding the building's geometry, orientation, material properties, and biophilic elements were meticulously defined to represent typical construction practices in the region, with the goal of achieving net-zero energy performance. This baseline model served as the benchmark for evaluating various DSF configurations integrated with biophilic design principles.

3.2 Data Acquisition and Modeling

In the initial phases of the research, a preliminary model was created to test key variables and refine the understanding of the IES-VE software's capabilities. This initial model included the integration of biophilic design elements with DSF configurations to assess their combined impact on energy efficiency. The model underwent iterative refinements to enhance accuracy and reliability in the simulation results, focusing on the interaction between natural elements and façade systems in reducing cooling loads and enhancing overall energy efficiency. Parametric analysis was conducted to explore a range of DSF typologies, including variations in cavity depth, glazing types, ventilation strategies, and the incorporation of biophilic elements. The results were analyzed to identify the most energy-efficient DSF configurations that when combined with biophilic design optimizes energy performance and contribute to achieving net-zero energy status for commercial buildings in challenging climates.

3.3 Formation of base case

The Al-Subaie Towers, situated in a maritime desert climate, served as the reference building for modeling the prototypical office structure in this study (Fig. 5a, and 5b). The building features a rectangular layout, comprising two identical square office blocks (A and B) designed for an open-plan configuration. Each floor within the blocks is geometrically and functionally identical, with a total building height of approximately 35 meters and individual room heights of 3.5 meters, including suspended ceilings. For this study, only Block A, with dimensions of 15 meters by 15 meters and an area of 225 m² per floor, was selected for energy and airflow simulations using the IES-VE software (Fig. 6a and 6b). The module consists of six stories, totaling 1,350 m², and features a fully glazed façade with 6 mm single-pane glass and aluminum frames. The study did not include the interior design and workspace layouts. The building material description and thermal conditions are indicated in Tables 1 and 2 are shown respectively below:

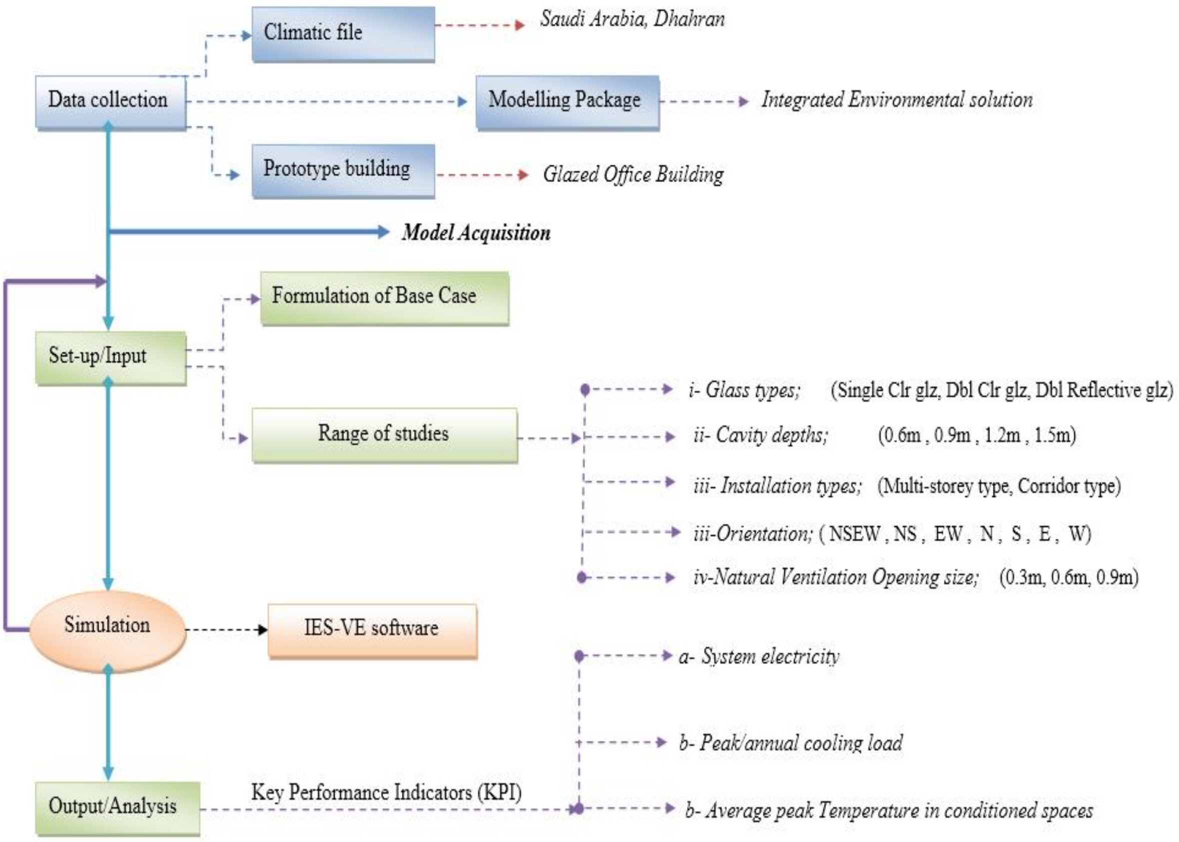

Fig. 4. Methodological flow process (Source: Authors, 2024).

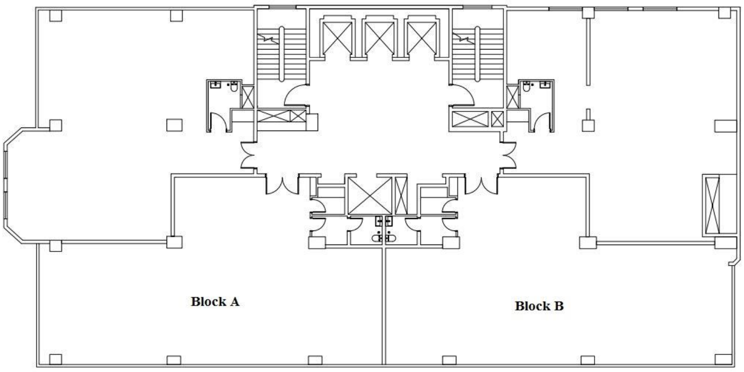

Fig. 5a. Al-Subaie Towers, office floor plan.

Fig. 5b. Al-Subaie Towers, King Fahd Rd, Al Khobar.

(Source: Authors, 2024)

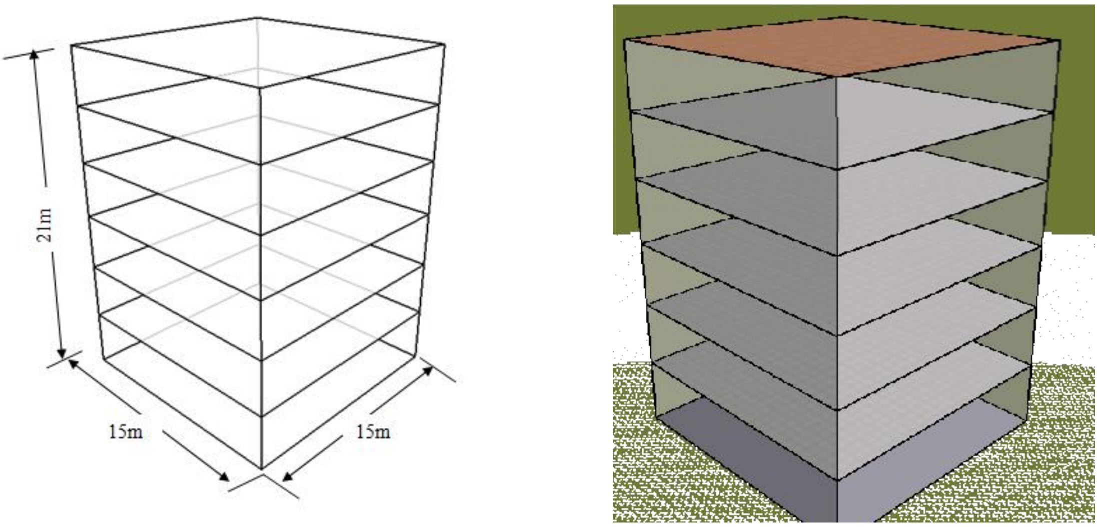

Fig. 6a and 6b. 3D six floor of the base case design office building ‘Block A’ (Source: Authors, 2024).

Table 1. Description of building construction.

Building Construction	Material type (From outside to inside)	Thickness (mm)	Conductivity W/ (m.K)	Density (kgm-3)	Specific Heat capacity J/(kg.K)	U-Values (Wm-2K-1)
External wall	Face Brick	101.6	1.331	2083.0	921.0	0.5490
	Insulation board	50.8	0.43	32.0	837.0	
	LW concrete block	101.6	0.38	609.0	837.0	
	Plaster board	19.1	0.16	801.0	837.0	
Grade floor	Soil	750.0	1.14	1900.0	1000.0	0.7333
	Brickwork (outer leaf)	250.0	0.84	1700.0	800.0	
	Screed	100.0	1.13	2000.0	1000.0	
	Synthetic carpet	10.0	0.060	160.0	2500.0	
Intermediate floors	Reinforced-Cast Concrete	100	1.400	2100.0	840.0	3.4931
Roof	Asphalt	19.0	0.50	1700.0	1000.0	0.7817
	Fiberboard	13.0	0.06	300.0	1000.0	
	Cavity	25.0	-	-	-	
	Glass-Fire quilt	25.0	0.04	12.0	840.0	
	Gypsum plasterboard	10.0	0.16	950.0	840.0	

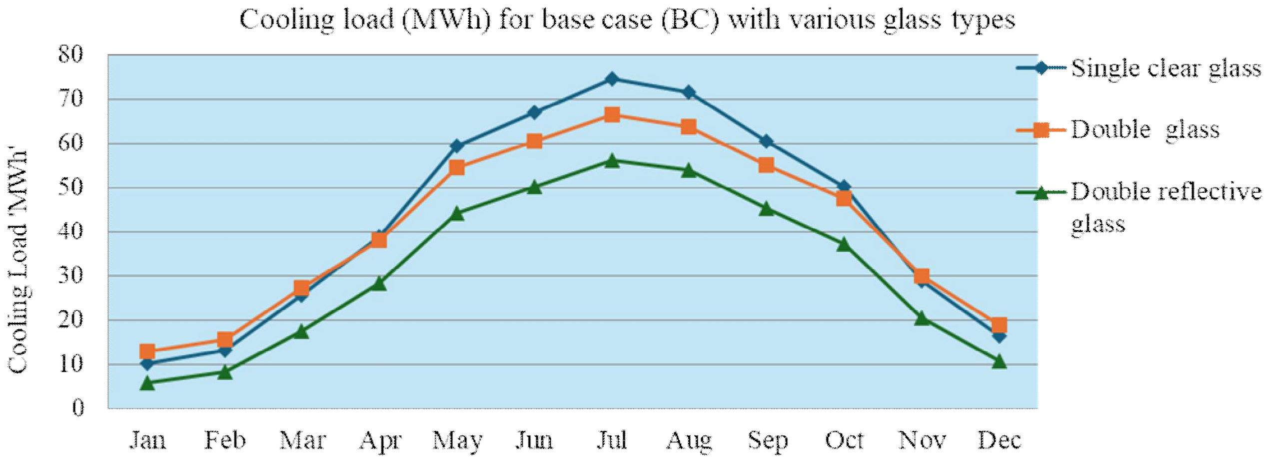

Fig. 7a. Base Case cooling load (MWh) for various glasses.

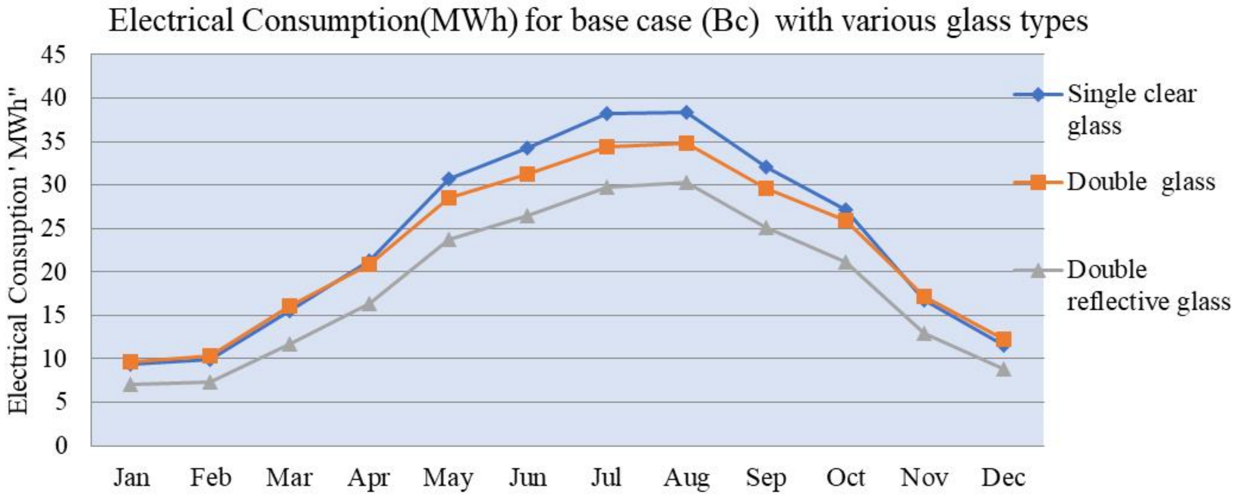

Fig. 7b. Base Case Electrical Consumption (MWh) for various glasses.

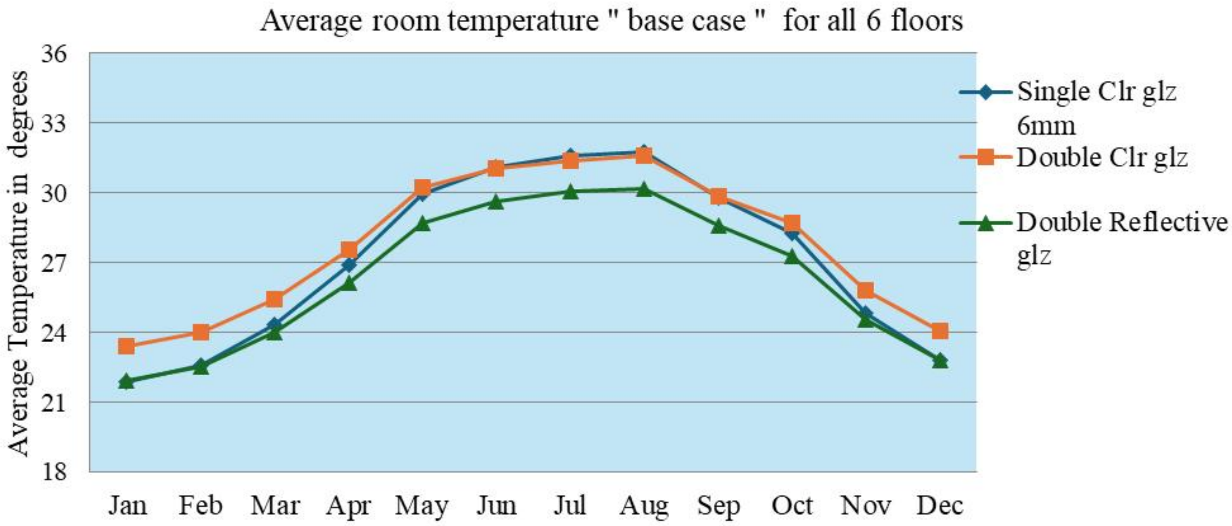

Fig. 7c. Base Case Average monthly temperature distribution (^{o}C) for various glasses.

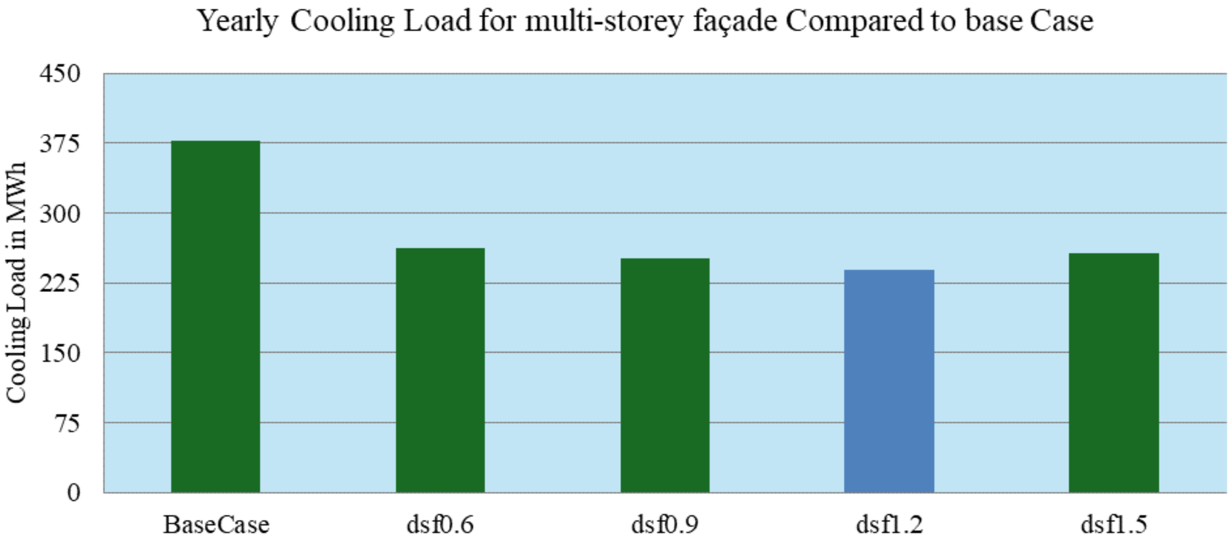

Fig. 7d. Base Case Average monthly temperature distribution (°C) for various glasses.

Table 2. Description of thermal conditions.

Heating set point temp (°C)	Cooling set point temp (°C)	Operation schedules (hrs.)	HVAC System	Internal gains		Air exchangers	
18.0	24.0	8am –6pm With no lunch Break	VAV Single Duct	Fluorescent light Computers People (approx. 20persons per floor) Miscellaneous		Infiltration Natural ventilation	
				Total Sensible gain (W / m2)	Total Latent gain (W / m2)	[a]	[b]
				62.237	5.861	0.7ach	0.3ach

4. Results and discussions

This study evaluates the energy efficiency of commercial office buildings in maritime desert climates by comparing a base case with various DSFs configurations. The base case, featuring single clear glass, double clear glass, and double reflective glass, serves as a benchmark for assessing DSFs performance (Fig. 7a, 7b, 7c, and 7d). The DSFs variables examined include installation types (multi-storey and corridor cavity), cavity distances (0.6m to 1.5m), DSFs positioning across all cardinal directions, and ventilation opening sizes (0.3m to 0.9m). Key performance indicators, such as monthly and yearly cooling loads, electrical energy consumption, and temperature distribution, were used to determine the impact of these variables as indicated below.

Fig. 7b demonstrates that the use of double reflective glass significantly reduces thermal conduction, which is consistent with findings in the literature (Matour *et al*., 2022; Pomponi *et al*., 2016). For the base case scenario, the analysis confirms that the optimal glass configuration for energy performance in a maritime desert climate is the "double reflective glazing". This is further supported by the monthly average temperature distribution shown in Fig. 7c, which aligns with the analysis, indicating superior performance of this glazing type. Therefore, Double reflective glazing will be established as the baseline glass type for subsequent comparisons with various glazing options in the DSF configurations.

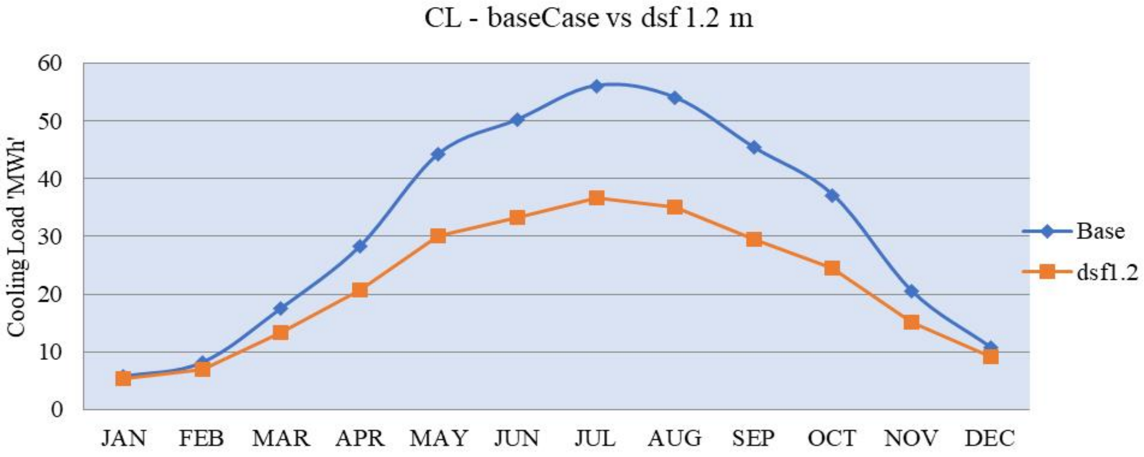

Fig. 8. Cooling Load of Base Case vs. 1.2m DSF cavity Main space.

The analysis reveals that using double reflective glazing in office spaces significantly reduces summer peak temperatures compared to conventional single clear glass, enhancing thermal comfort within maritime desert climates. This finding is crucial as it establishes the baseline for evaluating DSF scenarios. Before implementing the DSF configurations, a detailed analysis of glazing types was conducted, focusing on the most common cavity sizes found in literature (Naddaf and Baper, 2023; Fallahi *et al*., 2010; Alibaba and Ozdeniz, 2016) (0.6m, 0.9m, 1.2m, and 1.5m, all unvented). This preliminary analysis, based on cooling load (MWh), was necessary to streamline the number of outputs for subsequent comparison, ensuring that the most effective configurations are identified without overwhelming the analysis with excessive variables. This approach aligns with recent studies that emphasize the importance of optimizing facade elements to enhance building energy performance in harsh climates.

DSF system with a cavity size of 1.2m indicates a significant yearly reduction in cooling load, identifying it as the optimal cavity dimension. This result is consistent with other studies conducted in similar climatic conditions, which have also demonstrated the efficacy of DSF systems in enhancing energy performance in hot climates (El-Darwish and Gomaa, 2017). Fig. 7d illustrates the monthly cooling load distribution for this cavity size compared to the base case. Notably, during peak winter months, the heating requirements for both the SSF and the DSF with this cavity size are comparable. However, the DSF shows a marked reduction in cooling load during the warmer months, demonstrating its superior performance in reducing energy consumption relative to the SSF.

The average temperature within occupied spaces is a key performance indicator (KPI) in evaluating the energy performance of buildings. Fig. 8 indicated the temperature distribution for the Multi-Storey DSF of 1.2m unvented cavity size was compared against the Single-Skin Facade (SSF) base case. The analysis shows that DSF-equipped spaces require about 15% less heating during winter and less cooling in summer, indicating superior insulation and temperature stability with DSF systems (Ghaffarianhoseini *et al*., 2016; Pomponi *et al*., 2016). This improvement in thermal performance enhances overall energy efficiency, making DSF a more effective option for maintaining indoor comfort in extreme climates.

5. Conclusion

This study explored the potential of optimizing energy performance in net-zero commercial buildings in maritime desert climates by analyzing various DSF configurations. Through thermal dynamic simulations, the study assessed the impact of DSF typologies on reducing cooling loads and overall energy consumption, comparing the results to a baseline SSF scenario. The findings indicate that multi-storey DSF configurations, particularly with an unvented cavity size of 1.2 meters, significantly improve energy efficiency, reducing annual cooling loads by approximately 35% compared to the SSF baseline.

The study confirmed that the optimized DSF design, specifically when applied to the northern and southern elevations, offers substantial energy savings, validating the hypothesis that DSF systems can significantly reduce energy consumption in maritime desert climates. However, it was observed that the introduction of vent openings in the DSF configuration did not lead to further improvements in cooling load reduction, indicating that unvented designs may be more suitable for such climates. Similar findings have been reported in the literature, where unvented DSF systems have shown greater effectiveness in reducing energy consumption in hot, arid environments (Saelens *et al*., 2003).

While the study highlights the potential benefits of DSF systems, it also acknowledges that achieving these energy savings comes at a high incremental cost and requires extensive design considerations. Therefore, while DSF technology offers promising energy efficiency improvements, it should be considered alongside other emerging technologies and design strategies that may offer comparable or even superior energy performance with potentially lower costs and complexity (Alibaba and Ozdeniz, 2016; Pomponi *et al*., 2016). Future research should explore the integration of DSF with other sustainable building technologies to maximize energy efficiency in net-zero buildings.

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Received: 3 October 2024 • Revised: 6 November 2024 • Accepted: 7 November 2024