SMART AND DYNAMIC FACADES: A PATH TO ENERGY OPTIMIZATION IN ARID ENVIRONMENTS

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Abstract: *The modern movement of architecture has led to a proliferation of buildings featuring transparent facades, which unfortunately amplify the energy needs of these structures. Mitigating this energy consumption necessitates a reevaluation of architectural strategies. Addressing concerns such as overheating, innovative solutions like smart and dynamic double-skin facades have emerged to curtail energy usage while ensuring comfortable indoor conditions. This study focuses on examining the efficacy of smart facades, employing electrochromic glazing, and dynamic double-skin facades, and integrating dynamic shading systems, in reducing energy consumption within office buildings located in hot and arid regions. Parametric simulations were used on a particular office building, comparing scenarios with and without the implementation of smart and dynamic double-skin facades, particularly on south-facing orientations. The simulations varied the wall-to-window ratio (WWR) to gauge energy performance under different configurations. Furthermore, multi-objective optimization (MOO) techniques were employed to analyze and optimize shading device properties. Parameters such as depth, distance from the glass, shade angle, and spacing between shades were optimized as genetic variables to determine the most energy-efficient configuration for office buildings. The study results demonstrate that the use of EC glazing is beneficial in all WWR percentages, achieving 67.65% of energy saving in 90% of WWR., Also it was found that the optimal solution for saving energy is using DDSF with 20 cm of shading depth, 45° of shading angle, and double low-E vacuum in the inner skin, with an energy saving of 70.32% in the case of 90% of WWR compared to the base case.*

Keywords: *smart façade, dynamic double-skin façade, energy consumption, parametric simulation, office building, multi-objective optimization (MOO).*

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Introduction

In the built environment, the focus on sustainable development principles has generated considerable research interest in enhancing the efficiency of building skin. Façades, as integral components of construction envelopes, play a crucial role in safeguarding indoor ambiances and regulating the interaction between outside and inside spaces. Advancements in building technology have facilitated the development of various types of dynamic building elements, aiming to achieve higher levels of sustainability and aesthetics [1,2]. Promising areas of development in adaptive technologies such as phase change materials [3], adaptive solar shading [4], multifunctional facades [5], switchable glazing [6], and double-skin facades (DSF) [7] have been identified. In this research, our focus will be on switchable glazing and dynamic double-skin facades (DSF).

Switchable Devices

Switchable materials, categorized as smart materials, possess the capability to independently and reversibly change color. This change occurs as a result of reduction or oxidation reactions triggered by an electrical stimulus.

Classification of Switchable Glazing

The categorization of switchable glazing systems into active or passive is dependent on their functioning [8]. The passive systems operate independently, reacting to natural excitations such as heat or light without requiring external input. Examples of passive systems include photochromic (PC) glazing [9], thermochromic (TC) glazing [10], photo-electrochromic devices (PECDs) [11], and photovoltachromic (PVC) glazing [12].

In contrast, active systems have the capability to react to an exterior electrical stimulation by adjusting their optical properties. They can adapt to changes in both internal and external environmental conditions, thereby meeting the demands of the user. Examples of active systems include electrochromic (EC) glazing [13], gasochromic glazing [14], suspended particle devices (SPD) [15], and liquid crystal devices (LC) [16].

The focal point of this study revolves around EC windows, which can be likened to electrical batteries. Typically, these windows consist of five stacked layers positioned between plastic substrates or two glasses. These layers are covered in invisible conductive oxides., such as indium tin oxide or fluorine-doped tin oxide. Among these layers, the middle one acts as a transparent electrolyte that is filled with hydrogen or lithium ions, which are small cations. It directly interfaces with at least one EC material and either an ion accumulation layer or another EC layer [17,18]. Inorganic transformation metal oxides, such as nickel oxide (NiO) or tungsten trioxide (WO3), are among the most extensively studied EC materials (Fig.1).

Electrochromic (EC) glazing available on the market exhibits a blue tint, largely attributed to the common use of tungsten trioxide (WO3) as the electrochromic material. This material enables an alternation of transparency, transitioning from clear or bleached (device off) to dark or tinted (device on). In terms of performance metrics, the Solar Heat Gain Coefficient (SHGC) of electrochromic glazing usually ranges from 0.49 in the fully bleached state to 0.09 when completely colored. Additionally, light transmission values (VLT) can vary significantly, with a range from 69% in the clear state to as low as 1% when fully tinted.

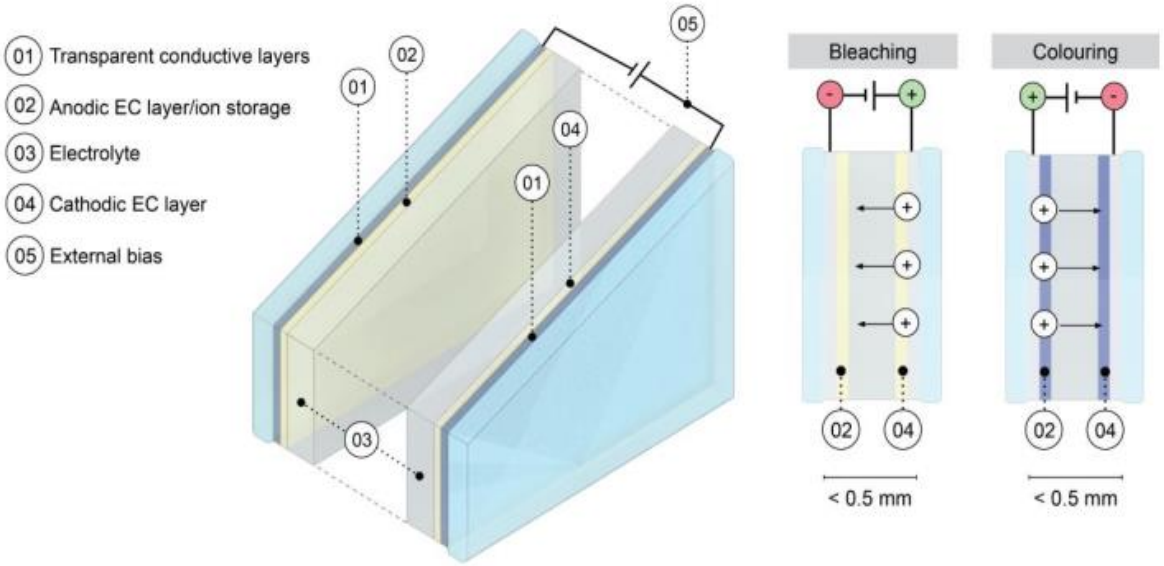


Fig. 1. *EC glazing schematic diagram [19]*

Double-skin facades (DSF)

Double-skin façade is a special type of envelope, where a second "skin", usually a transparent glazing, is placed in front of a regular building façade" [20]. Double-skin facade (DSF) is a façade of the building that spans one or more storey and consists of different glazed layers divided by an air gap. A defining characteristic of DSFs is their controllable shading system and the ability to facilitate airflow due to the cavity in such façade system.

The air gap between the two layers plays the role of an insulation barrier, effectively mitigating undesirable effects such as heat transfer or temperature fluctuations.

Classification of DSFs

Double-skin facades (DSFs) typically encompass multiple levels of a building and feature multiple layers, and they are generally categorized as either air-tight or ventilated [21]. Additionally, DSF typologies are classified based on their ventilation strategies within the cavity [22].

Air-tightened DSFs prioritize thermal insulation, particularly beneficial during winter months. In contrast, ventilated DSFs leverage sunlight to receive heat energy while reducing heat gain during summer [21]. These distinctions highlight the varying thermal performance and energy efficiency characteristics of DSF designs, tailored to different climatic conditions and seasonal requirements.

DSFs are classified based on four conditions: "window ventilation", "closed", "natural convection to outside", and "mechanical exhaust". Additionally, they are categorized according to their level of skin coverage, such as "window", "storey", or "multiple storey" [23,24]. Furthermore, researchers categorize DSFs into various types, including box window facades, shaft-box facades, corridor facades, and multi-storey facades [25,26].

The fundamental aspect of DSF conception is airflow management. The airflow patterns in DSFs vary depending on seasonal climates, as shown in Figure 2.

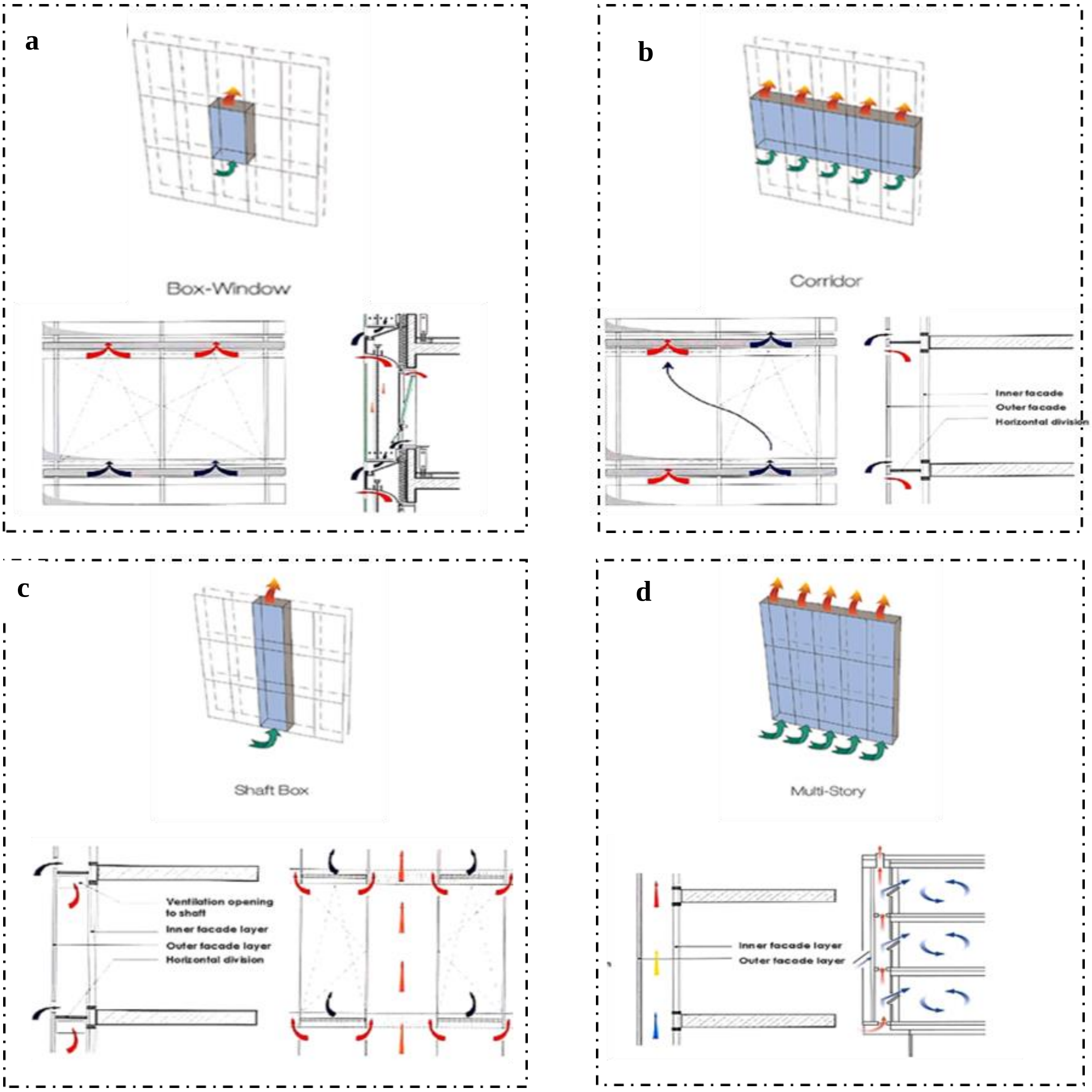


Fig. 2. *Different DSFs configurations.* **a.** *box window configuration,* **b.** *corridor configuration,* **c.** *shaft box configuration,* **d.** *Multi-storey configuration [27,28]*

Mechanism

The primary mechanism and associated energy balance are indeed crucial aspects of a double-skin facade (DSF) system. DSFs rely on natural ventilation technology, utilizing the solar chimney effect to facilitate airflow and regulate heat transfer. It's important to highlight the system's heat transport and airflow phenomena, as illustrated in Figure 3. This diagram likely demonstrates the convective airflow patterns driven by temperature and solar radiation differentials between the exterior and interior layers of the DSF. Understanding these phenomena is vital for optimizing the performance and energy efficiency of DSF designs.

To understand the thermal reaction of the double-skin facade (DSF) system, several areas of heat transfer play significant roles: convection, conduction, and radiation. A sufficient temperature differential over the exterior skin triggers the stack effect. This phenomenon draws air upward in the cavity of DSF, effectively exhausting solar or building heat gains out the top. Moreover, wind pressure distributions at openings and exterior facades can impact the airflow rate through the cavity.

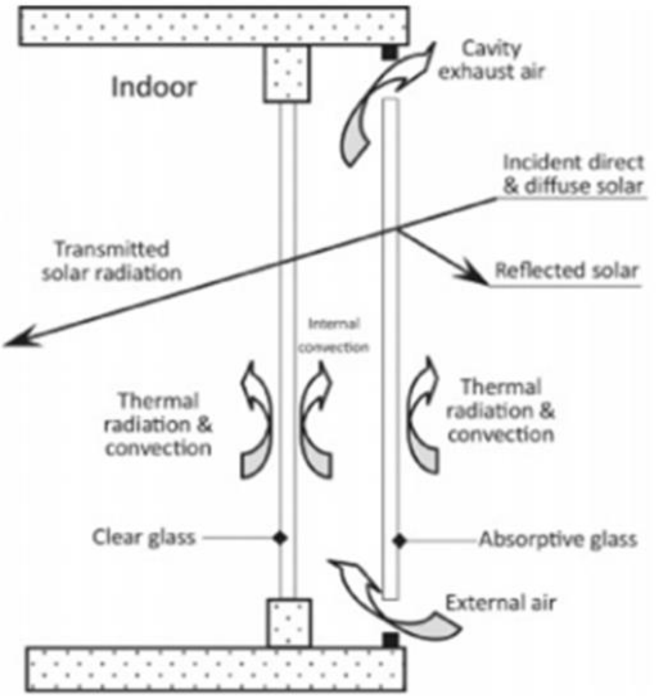


Fig. 3. *Heat transfer and airflow of natural ventilated DSF system [29]*

Transparent DSFs commonly incorporate shading systems in the cavities to mitigate solar heat gain and glare during the warmer season. However, the efficiency of these shading devices is contingent upon their orientation related to the azimuth and solar altitude and form for the specific period.

The performance of double-skin facades (DSFs) varies significantly across different climates. In cold climates, DSFs function as heat exchangers, working to maintain the temperature of the internal skin layer close to the desired indoor temperature [30]. On the other hand, in hot climates, DSFs can contribute to a low shading coefficient [30]. This indicates that DSFs can effectively reduce solar heat gain and mitigate thermal discomfort in warm weather conditions.

Literature review

Various research studies emphasize the significance of smart windows, such as electrochromic (EC) glazing, and dynamic double-skin facades, in different window-to-wall ratio (WWR) configurations for enhancing the energy performance of buildings. A study conducted by Sibilio et al. [31] concluded, in their review paper focusing on smart windows for residential applications, that the utilization of EC glazing can lead to energy savings ranging from 9% to 59% compared to conventional static glazing. However, the extent of energy conservation depends on different parameters, such as climatic conditions, control strategies, and building orientation.

Another research study, as documented in [32], conducted an investigation on the performance of electrochromic (EC) window prototypes using a full-scale office experimental setup. The findings of this study revealed significant energy savings of up to 59% when compared with classic windows.

In 2009, Rudolph et al. conducted a study on electrochromic (EC) glazing systems in collaboration with the California Energy Commission [33]. The study highlighted a notable 44% reduction in energy consumption used for lighting compared to a base case without daylighting strategies. Additionally, the study observed a reduction in window cooling loads, with peak demand decreasing from 26% to 19% on clear sunny days.

A study conducted using the eQuest building simulation tool [34] examined three distinct climate zones in the United States. The research focused on a commercial office building with a window-to-wall ratio (WWR) of 60%, comparing the efficiency of static glazing with electrochromic (EC) glazing. The findings revealed energy savings of up to 45% across different climate zones.

In another study [35], a simulation was undertaken to assess the lighting energy-saving potential of an electrochromic (EC) window. The performance in a south-facing office was simulated using two separated EC windows, approximately a 48% of reduction in energy consumption was observed compared to simple glass.

In another study [36], which utilized EnergyPlus dynamic simulation software, an investigation was conducted in an office building situated in Milan. The objective was to identify the best glazing type among the three of them (EC glazing, standard glass, and glass with an exterior Venetian blind system) in comparison to the standard glazing type. As a consequence, the results demonstrated that EC glazing minimize 39.5% of energy consumption, whereas the use of an external Venetian blind device led to a reduction of 26.2%.

The potential applicability of a double-skin facade (DSF) was investigated in [37] through the optimization of the relationship between window-to-wall ratio (WWR), shading coefficient (SC), and envelope thermal transfer value (ETTV) of a building.

The study revealed that an increase of WWR (0.9) reduces a DSF's ability to prevent solar heat gain. Conversely, the decrease of WWR (0.3) minimizes significantly the ETTV, about 45%.

Moreover, the increase of the shading coefficient (SC) from 0.3 to 0.7 of the interior glass increases the ETTV from 18W/m² to 59.6W/m². This relation indicates the importance of finding an ideal balance between ETTV and SC for a specified WWR, suggesting that different combinations of these parameters can affect the overall efficiency of a DSF system.

In another study [38], the energy performance potential of photovoltaic double-skin facades (PV.DSF) was evaluated. The study simulated the performance of PV.DSF in a south-facing office in a humid subtropical climate zone in Changsha, China.

During winter conditions, with a 12°C temperature differential between the DSF and external temperature, the ideal operating angle was determined to be between 10 and 20 degrees. During summer, wall temperatures and air were minimized by 0.5°C and 2°C, respectively, leading to a 10% reduction in cooling energy consumption. The optimal operating angle during summer was determined to be 30 degrees.

For intermediate conditions, when the DSF was open, the difference in temperature between the DSF and the exterior environment was less than 3°C. The optimal operating angle remained at 30 degrees during these intermediate conditions.

In 2020, M. Shakouri et al. [39] conducted a study on double-skin facades (DSF) with photovoltaic (PV) systems under Tehran, Iran's climate conditions, focusing on an office building with a south-facing orientation. The study reported significant annual reductions in energy consumption used for cooling and heating, amounting to 251,623 kWh and 17,811 kWh, respectively. Additionally, the PV system, with 10.6 kW as peak power, was found to produce approximately 18,064 kWh of grid-connected electricity annually. This implementation resulted in an impressive improvement in the energy efficiency index of the building, achieving a reduction of 34.3%.

In the context of Changsha, China (HSCW zone) [40], it was discovered that increasing the slat angle in a box-window double-skin facade (DSF) led to a decrease in the temperature of the inner glazing. The airflow rate exhibited a reduction when the slat angle ranged from 0 to 60 degrees. However, when the slat angle exceeded 60 degrees, the airflow rate increased. This observation pertained to a naturally ventilated cavity.

On a related note, [41] investigated the impact of changing the tilt angle of blinds between 0 and 90 degrees across three different controlled ventilation rates (200, 400, and 600 m^3/h). They found that adjusting the tilt angle of blinds resulted in a decrease of the inside interior glass temperature as the tilt angle increased, especially with high ventilation flow rate, in the case of a box-window DSF.

In the study conducted by [42], a south-oriented multi-storey double-glazed facade (DSF) with both horizontal (90-degree angle) and vertical (45-degree angle) louvers was evaluated to enhance natural airflow in office buildings in Isfahan, Iran. The CFD (computational fluid dynamics) technique software was employed for this evaluation using ANSYS.

It was observed that the buoyancy forces of the DSF equipped with horizontal louvers in the cavity were stronger, resulting in a higher ventilation rate compared to the model with vertical louvers. Furthermore, the cavity with horizontal louvers had a larger heat flux on the inner glass than the cavity with vertical louvers, owing to enhanced convective flow. As a result, heat from the cavity is transferred to the occupied pieces via the internal skin. On the contrary, in vertical louvers, the heat flux from interior glass was low, nearly zero, related to the obstruction of sun radiation.

Interestingly, other researchers have also supported the notion that for multi-storey DSFs, positioning louvers closer to the outer layer allows for sufficient airflow on both sides while maintaining an adequate distance from the interior glass [43].

As evidenced by previous studies, the energy efficiency of buildings is affected by a multitude of interactive parameters. This underscores the necessity of adopting a parametric approach to accurately model building behavior, considering the dynamic interplay among these factors.

However, despite the extensive research in this field, there remains a significant gap concerning the impact of utilizing smart and dynamic double-skin facade (DSF) systems in Algeria, particularly in office building located in hot, arid regions. Addressing this gap was the primary focus of the present study. By concentrating on this specific context, the research intended to provide significant insights into the potential advantages and challenges associated with implementing smart and dynamic DSF technologies in such climatic conditions.

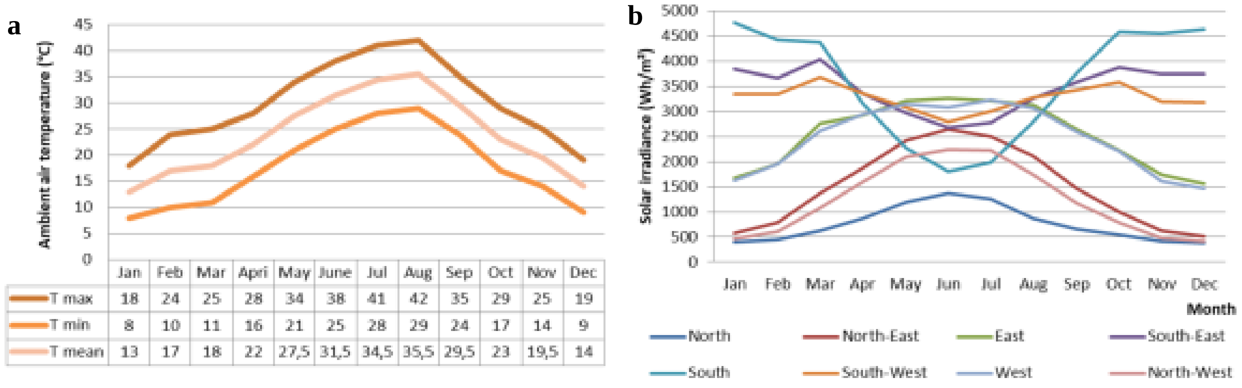
Climate conditions

The study case of this research was located in the Algerian desert exactly in the northeastern region, at 34.80°N latitude and 5.73°E longitude, with 82 meters of altitude above sea level. The Köppen–Geiger classification system identifies this zone as a hot, dry climate zone.

The International Weather for Energy Calculations database provides climatological data used for this study, in this case, the city of Biskra. The climate of Biskra is heavily impacted by sun radiation. Figure 4(b) summarizes monthly average sun irradiation levels for various exposures, illustrating the significant impact of solar radiation on the region's climatic conditions.

According to the temperature of the ambient air data for the city of Biskra presented in Figure 4(a), the hot season lasts from June until September. During this period, the mean maximum temperature is 35.5°C, and the minimum is 29.5°C. August is the warmest month, with an average high temperature of 42°C and a minimum of 29°C.

Conversely, the second half of November to the first week of March is a cooler season. During this period, the average maximum temperature is 19.5°C, with 13°C as the minimum temperature. January is considered the coldest month, with a mean maximum temperature of 18°C and 8°C as the minimum temperature.



	Jan	Feb	Mar	Apri	May	June	Jul	Aug	Sep	Oct	Nov	Dec
T max	18	24	25	28	34	38	41	42	35	29	25	19
T min	8	10	11	16	21	25	28	29	24	17	14	9
T mean	13	17	18	22	27,5	31,5	34,5	35,5	29,5	23	19,5	14

Fig. 4. a. *Temperature of the ambient air in* (°C), **b**. *Incident global irradiation on a vertical plane [44]*

Case study modeling

The building context in this research is a standard office building project situated in the city of Biskra. The building has two floors, with two office sections on each floor, separated by a corridor. Specifically, there are six offices on each floor, with the circulation area accounting for 15% of the total surface area [45].

The focus of the case study was on a south-oriented office within this building. The office has a window-to-wall ratio (WWR) of 10% and occupies 25 m² of the total area surface. Additionally, it is located on the ground floor, as illustrated in Figure 5.

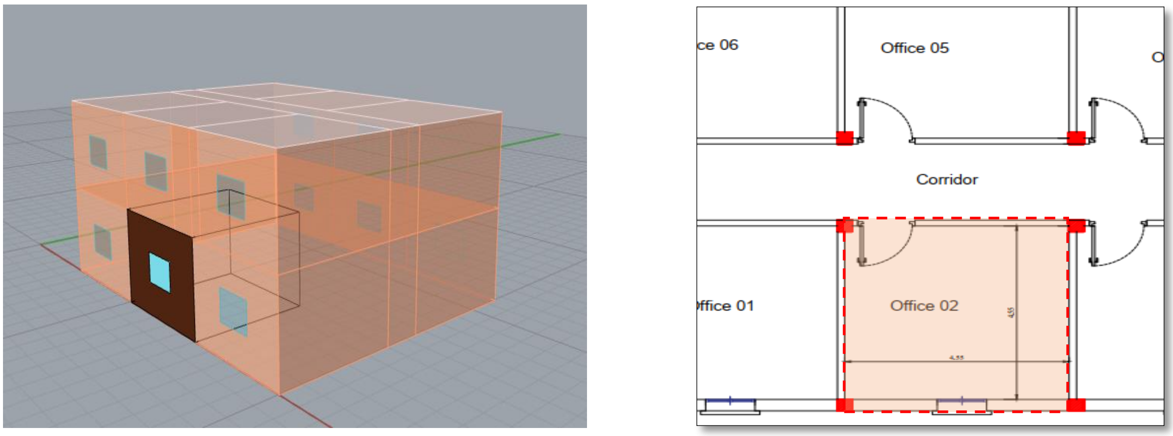


Fig. 5. *Case study 3D model and plan*

Materials

Table 1 shows the construction properties of the present model.

Table 1. Thermal properties of the building materials

	Thickness	U-Value W/(m^2·K)
Exterior wall	0.02 m of cement plaster	1.14
	0.15 m of hollow brick	
	0.05 m of air barrier	
	0.1 m of hollow brick	
	0.01 m of coated plaster	
Interior wall	0.01 m of coated plaster	2.49
	0.1 m of hollow brick	
	0.01 m of coated plaster	
Roof	0.02 m of flooring	2.42
	0.04 m of mortar	
	0.16 m of concrete blocks hollow	
	0.04 m of concrete slab	
	0.01 m of coated plaster	
Floor	0.15 m of clay	2.25
	0.15 m of stones of valley	
	0.04 m of concrete slab	
	0.04 m of mortar	
	0.02 m of flooring	

Windows material properties (Table 2)

Table 2. Thermal properties of the windows

Windows	Overall thickness (mm)	U-Value W/(m^2·K)	SHGC	Tvis
Single clear	3.05	5.84	0.74	0.60
Double low -E air	21.54	2.707	0.589	0.548
Double low -E vacuum	6.20	0.628	0.355	0.699
EC glazing	24.7	1.9	0.44(0.10)	0.64(0.01)

Modeling Tools

To comprehend the behavior of smart and dynamic facades in such specific buildings, energy analyses were developed using software based on parametric simulation. These tools offer the advantage of incorporating multiple plugins within the same platform. For instance, Grasshopper plays a pivotal role in parametric modeling, while software and simulation engines such as Ladybug and Honeybee serve as a comprehensive framework for visualization processes and energy and comfort simulation. Within this framework, Energy Plus and Open Studio handle energy simulations, while daylighting analysis is tasked by Radiance and Daysim.

After the parametric study, a genetic method - based on algorithms - is applied to improve solutions via the Galapagos plugin. Galapagos possesses the ability to perform multi-objective optimization, as depicted in Figure 6. This integrated approach enables a thorough examination of various design alternatives and facilitates the identification of optimal solutions for enhancing the energy efficiency of office buildings with smart and dynamic facades.

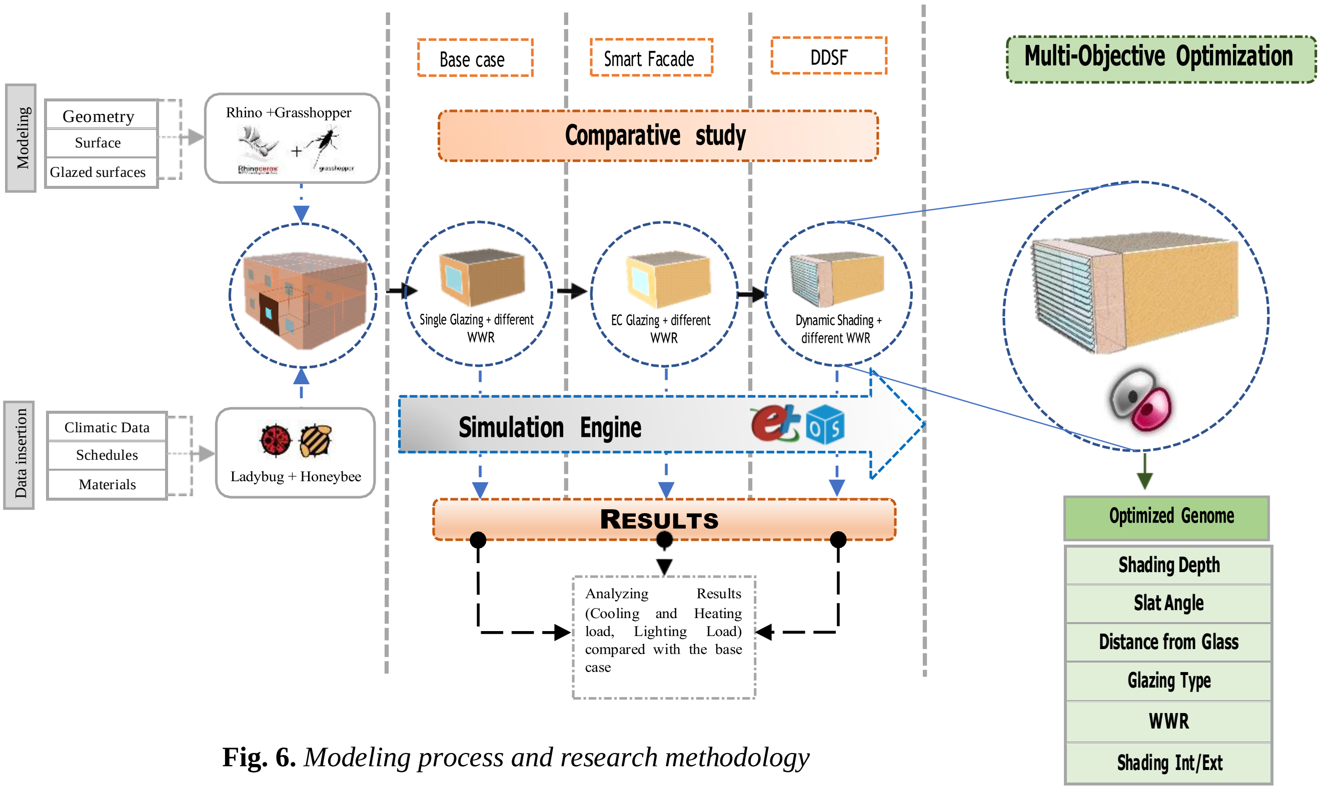


Fig. 6. *Modeling process and research methodology*

Methodology

The previous researches often focused on investigating electrochromic (EC) glazing, double-skin facades (DSF), or shading devices separately as the primary research focus. However, this work aims to analyze, compare, and optimize the combined effect of these technologies on energy consumption, particularly in hot and arid climates. The research methodology is divided into two main parts:

Comparison study

Simulation of base case and comparison with EC glazing and dynamic double-skin facade (DDSF)

- Simulation Setup:
  - Simulate a base case office building with simple glazing windows.
  - Vary the window-to-wall ratio (WWR) from 10% to 90%.
  - Use standard glazing properties for the base case.
- Energy Performance Evaluation:
  - Conduct energy simulations for each WWR scenario.

  - Measure energy consumption for heating, cooling, and lighting.
- Comparison with EC Glazing:
  - Simulate the same office building scenarios but with EC Glazing.
  - Utilize properties listed in Table 2 for EC glazing.
  - Compare energy consumption with the base case.
- Dynamic double-skin facade (DDSF) simulation:
  - Model a dynamic double-skin facade with simple glazing on inner and outer skin.
  - Incorporate dynamic shading devices controlled by solar radiations incidents on the window and exterior air temperature.
  - Set the cavity depth to 100 cm.

Optimization

In the energy consumption optimization process, various parameters interact with each other, often presenting conflicting relationships. Galapagos, through its optimization algorithm, seeks to find a logical balance among these parameters. The optimization procedure is facilitated via the Galapagos plug-in, which requires two primary inputs to run effectively:

1. Fitness Parameter: This parameter serves as the basis for optimization, indicating whether the goal is to maximize or minimize certain criteria related to energy consumption.
2. Genomes: Six parameters are utilized within this component (referenced in Figure 6), each representing a specific property or aspect of the building design:
   - WWR south: ranges from 0.1 to 0.9, with increments of 0.3. to control the window-to-wall ratio (WWR) for the south-facing façade.
   - Window material: ranges from 0 to 2, with increments of 1, representing different window materials as detailed in Table 2.
   - Shading depth: ranges from 0 to 0.4, with increments of 0.1, which corresponds to shading depth.
   - Shading distance from glass: spans from 0 to 0.4, with increments of 0.3.
   - Shading angle: Ranges from 0 to 4, with increments of 1, corresponding to shading angles ranging from -0, 20, 45, 60, and 70 degrees, with increments of 1.
   - Shading position (interior/exterior): This parameter allows for the selection between interior and exterior shading positions.

Due to the unique environmental circumstances of the study case and the literature review results, the building conditions have been identified as follows:

Building characteristics	The base case description	Reference
Situation	Biskra, 34.80° N/ 5.73° A/82 m, Algeria	
Building orientation	180° (south)	
Plan form	Rectangular 4.55 m × 4.55 m	
Heating setpoint temperature	18°C	[46]
Cooling setpoint temperature	26°C	
Lighting setpoint for	300 lux	
Infiltration	0.0003 $m^3/(s \cdot m^2)$	[1]
Equipment charge	5 W/m^2	
Lighting charge	5 W/m^2	
Occupancy	0.2 ppl/mm^2	
Weather file	Energy plus weather file	[2]
Shading control setpoint: High exterior air temperature	26°C	[3], [47]
High solar radiation incidents on the window	500 W/m^2	
Cavity depth	100 cm	[48]
COP	2.7	[49]

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[1] ASHRAE Handbook, chapter 31: Energy Estimating and Modeling Methods; American Society of Heating, Refrigerating, and AirConditioning Engineers: Atlanta, GA, USA, 2001.

[2] EPW File. https://climate.onebuilding.or/WMO_Region_1_Africa /DZA_Algeria /index.html

[3] ISO13790, Energy performance of buildings, 2006.

Results and Discussion

The aim of this section is to evaluate the effectiveness of electrochromic (EC) glazing and dynamic double-skin façade (DDSF) systems in reducing energy consumption in office buildings located in hot, arid climates. The study was conducted by varying the window-to-wall ratio (WWR) and optimizing shading depth and angle to find the best-performing configurations.

Heating load of different façade systems according to different WWR (Figs.7,8)

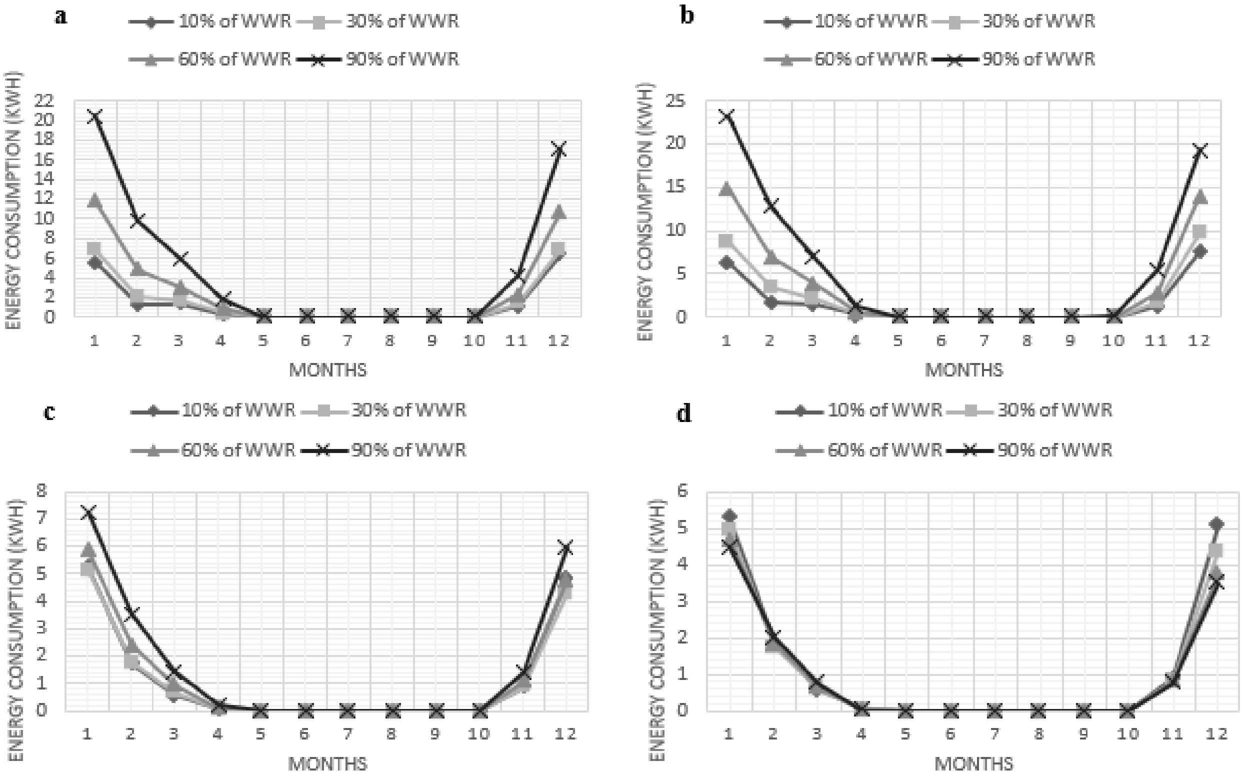

Fig. 7. *Heating energy consumption of different façade systems according to different WWR in kWh.* **a.** *simple glazing,* **b.** *EC glazing,* **c.** *DDSF 20 cm shading depth + 45° shading angle /INT: double low-E air /EXT: simple glazing,* **d.** *DDSF 20 cm shading depth + 45° shading angle /INT: double low-E vacuum/EXT: simple glazing*

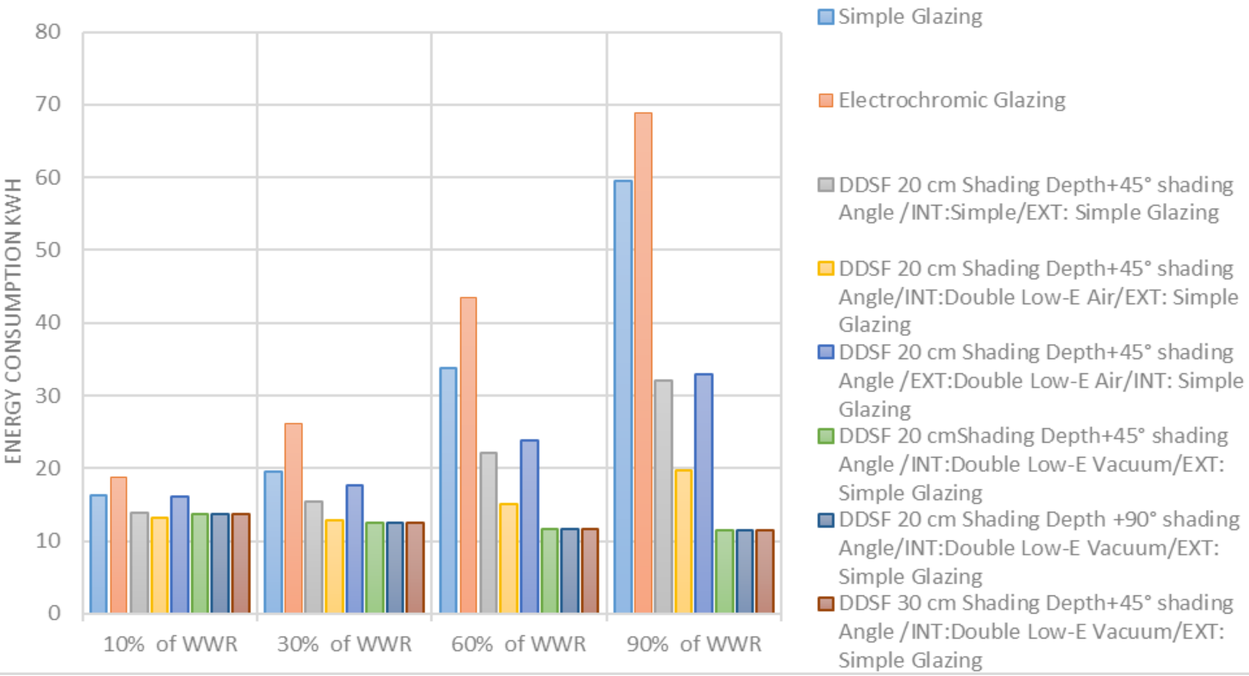

Fig. 8. *Energy heating loads of different façade systems according to different WWR in kWh*

Cooling load of different façade systems according to different WWR (Figs. 9,10)

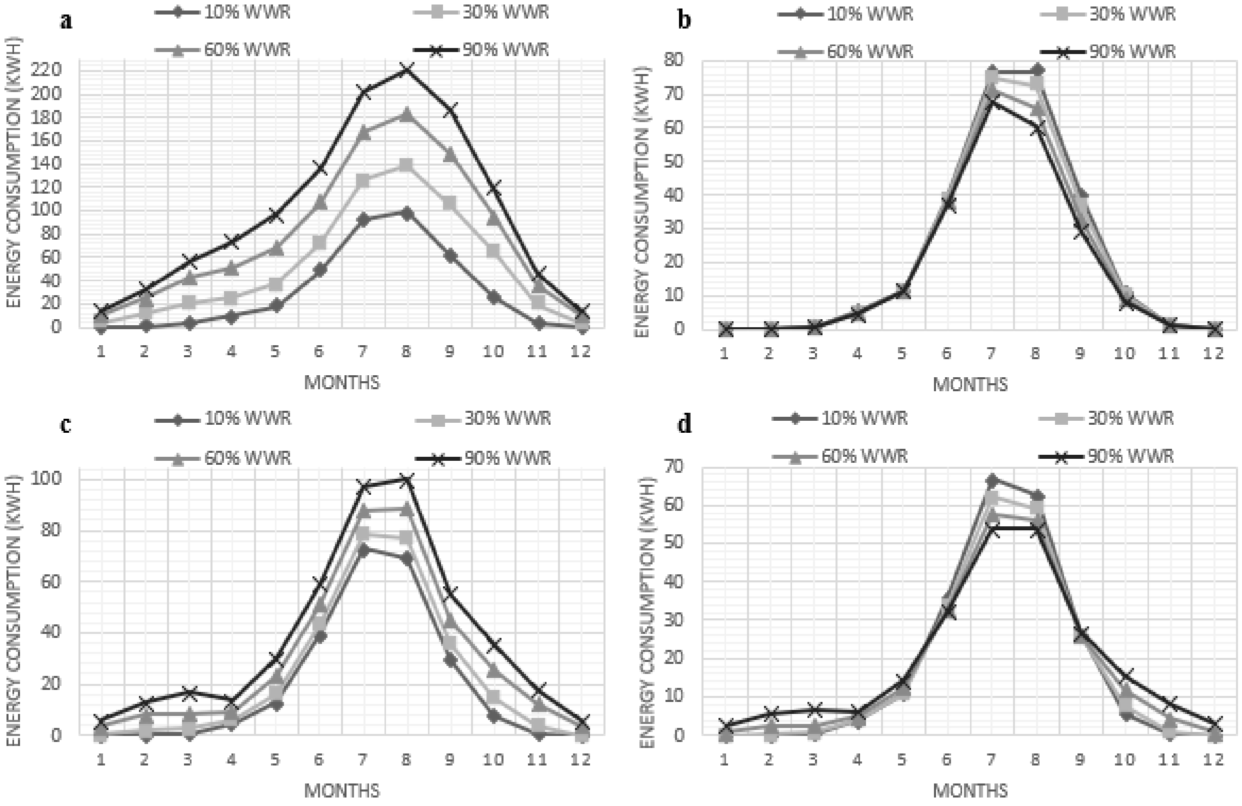

Fig. 9. *Cooling energy consumption of different façade systems according to different WWR in kWh.* **a.** *simple glazing,* **b.** *EC glazing,* **c.** *DDSF 20 cm shading depth + 45° shading angle/INT: double low-E air /EXT: simple glazing,* **d.** *DDSF 20 cm shading depth + 45° shading angle /INT: double low-E vacuum/EXT: simple glazing*

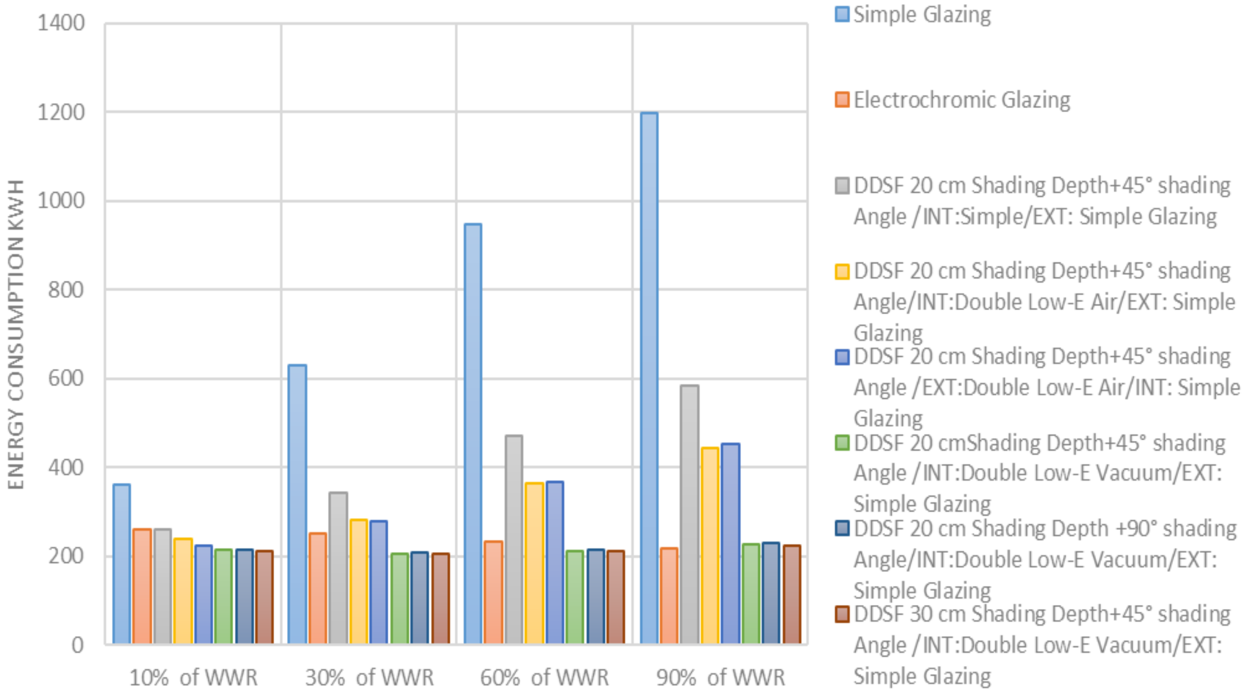

Fig. 10. *Energy cooling loads of different façade systems according to different WWR in kWh*

Lighting load of different façade systems according to different WWR (Figs.11,12)

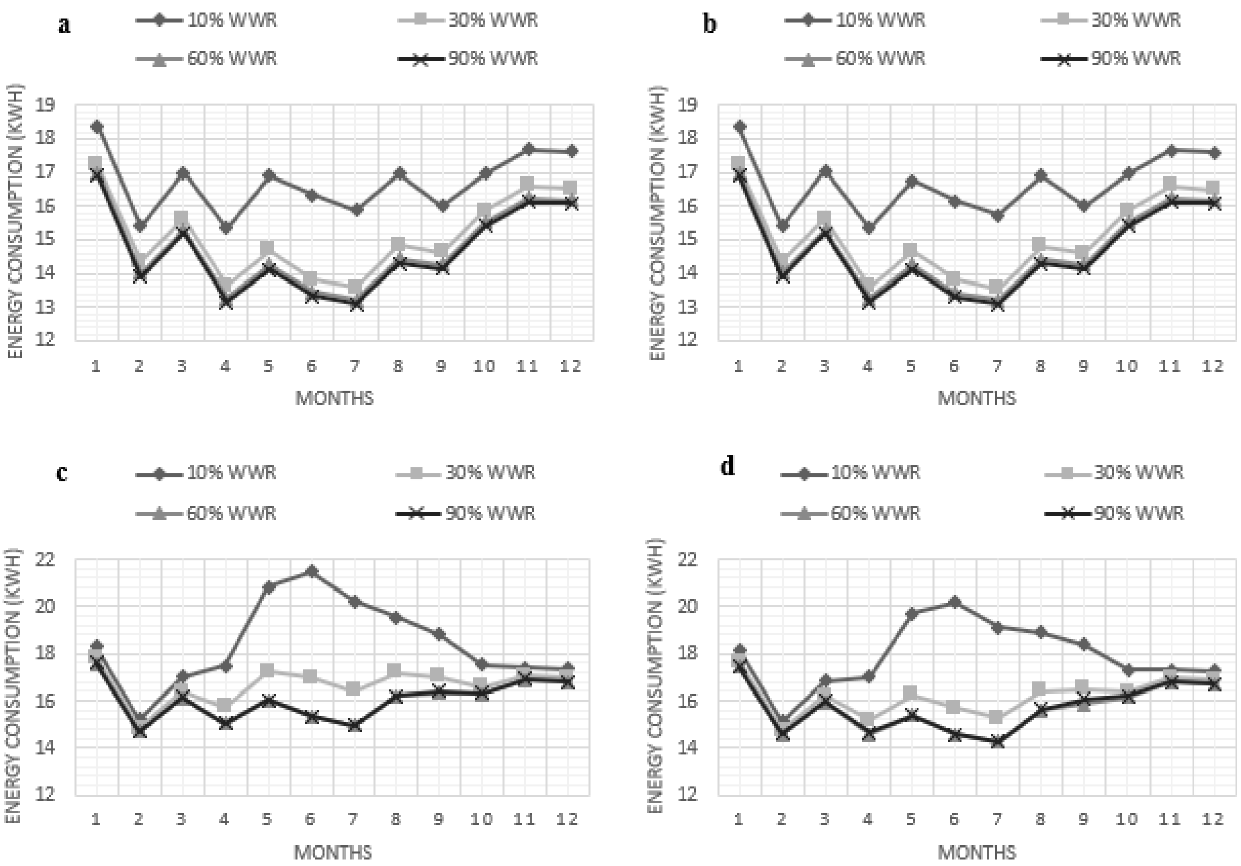

Fig. 11. *Lighting energy consumption of different façade systems according to different WWR in kWh.* **a.** *simple glazing*, **b.** *EC glazing*, **c.** *DDSF 20 cm shading depth + 45° shading angle/INT: double low-E air /EXT: simple glazing*, **d.** *DDSF 20 cm shading depth + 45° shading angle /INT: double low-E vacuum/EXT: simple glazing*

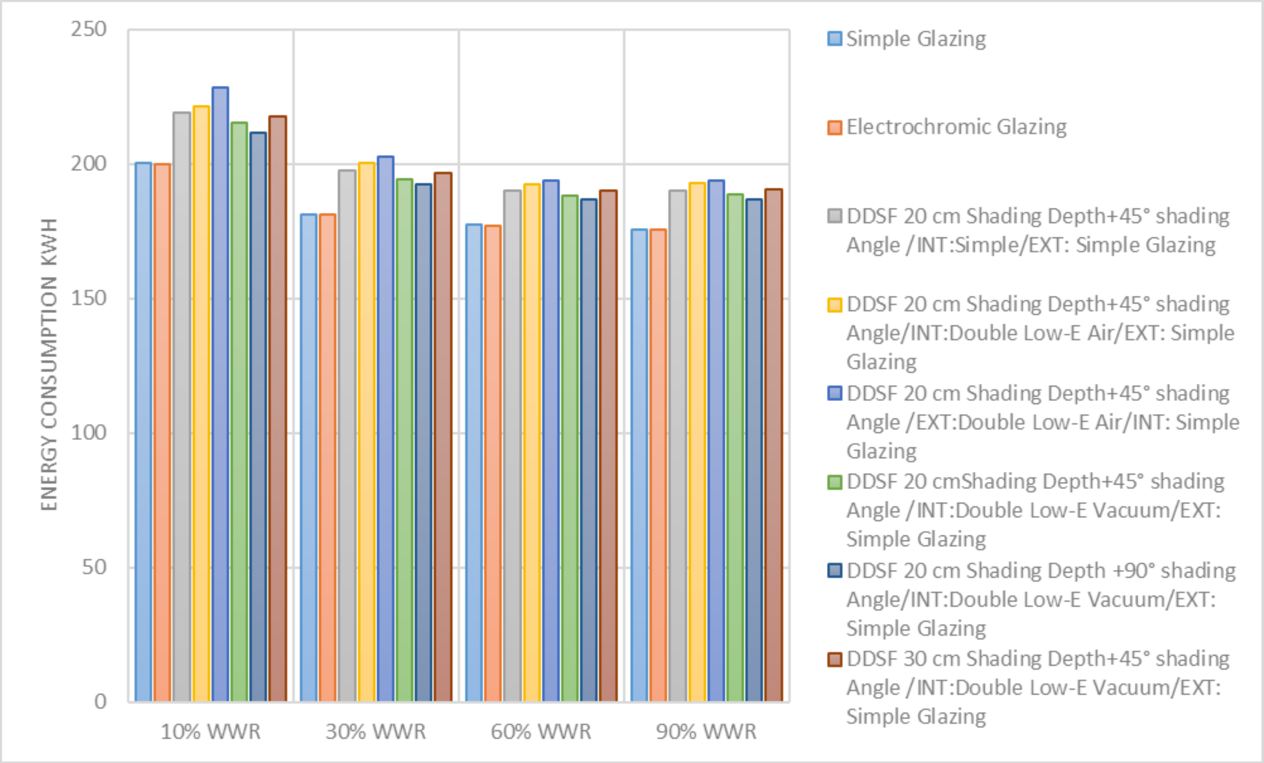

Fig. 12. *Lighting loads of different façade systems according to different WWR in kWh*

Overall energy consumption of different façade systems according to different WWR (Fig.13)

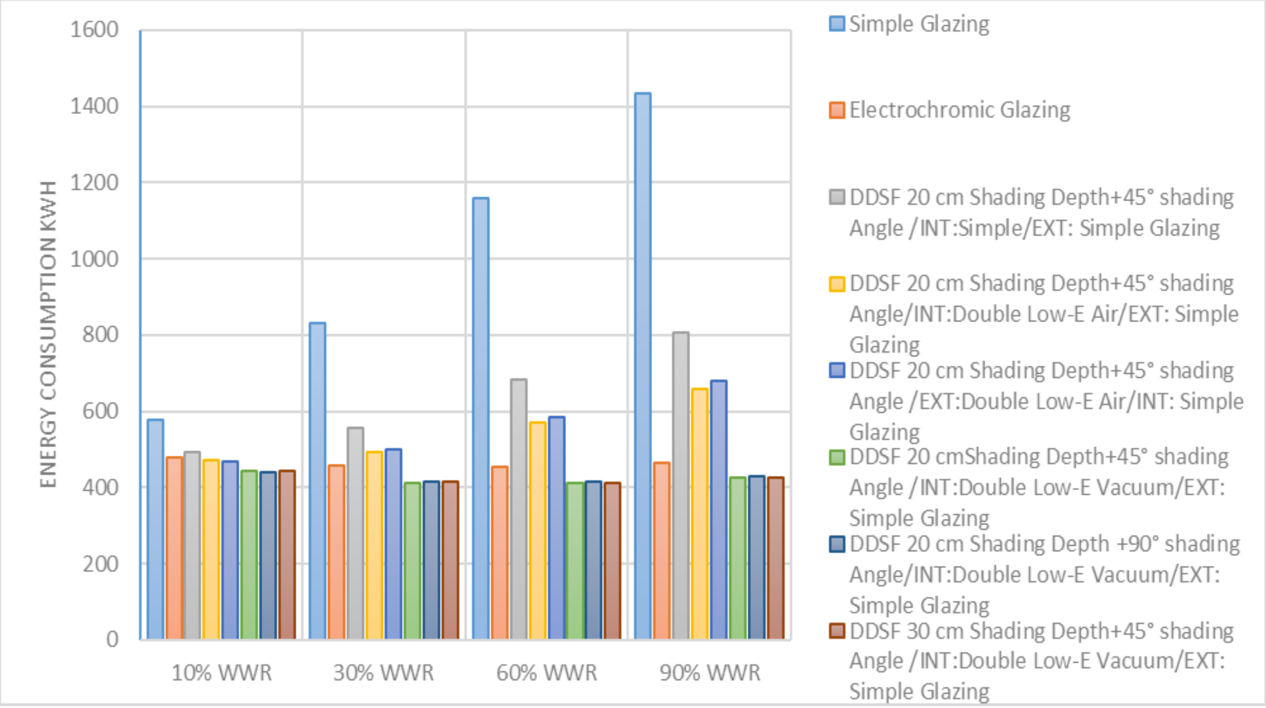

Fig. 13. *Overall energy consumption of different façade systems according to different WWR in kWh*

The results show that an increase in the window-to-wall ratio (WWR) correlates with higher energy consumption in the majority of the study cases, and this is because of the large amount of direct irradiation penetrating the building space. On the other hand, Figures 11 and 12 indicate that the decrease of energy consumption required for lighting is related to the increase of window-to-wall ratio WWR due to the important amount of sunlight entering the space.

Electrochromic (EC) Glazing

As shown in Figures 8,10,12, EC glazing consistently outperforms standard glazing across all WWR scenarios. For example, at a 90% WWR, the EC glazing reduces energy consumption for cooling by 67.65% compared to the base case (Table 3). This is primarily due to the EC glazing's ability to dynamically adjust its solar heat gain coefficient (SHGC) and visible light transmittance (Tvis), allowing it to block unwanted solar heat during the hot months while still providing natural daylight. In practical terms, this technology is particularly beneficial for large office buildings with expansive glass facades, as it can significantly reduce cooling loads during peak summer months in arid environments.

Dynamic double-skin façade (DDSF)

As demonstrated in Figures 8,10,12, when the DDSF system is optimized with a shading depth of 20 cm and an angle of 45°, it shows even more significant energy savings, particularly at higher WWR levels. For instance, at a 90% WWR, the DDSF system reduces overall energy consumption by 70.32% compared to the base case (Table 3). This is because the air cavity between the two layers of glazing acts as an insulating buffer, preventing heat transfer into the building while allowing for natural ventilation. The shading devices integrated into the DDSF system further reduce solar heat gain by blocking direct sunlight, especially during midday when solar radiation is highest.

The study demonstrates that the shading angle of 45° was optimal in blocking unwanted solar heat without obstructing too much daylight. Increasing the shading angle to 90° had a negligible effect on energy savings, suggesting that 45° provides the best balance between solar protection and natural lighting.

Comparison Between EC Glazing and DDSF

As indicated in Figure 13, while EC glazing offers significant energy savings, the DDSF system shows greater potential in climates with extreme solar exposure. The combination of dynamic shading and natural ventilation in the DDSF system not only reduces cooling loads but also improves thermal comfort within the building. However, EC glazing has the added advantage of better visual comfort, as it allows occupants to maintain a connection with the outside environment even when the windows are fully tinted.

These findings suggest that in hot, arid climates, the use of dynamic façade systems such as EC glazing and DDSF can drastically reduce the energy demand of office buildings, contributing to more sustainable architectural designs. The DDSF system, in particular, proves to be highly effective at large WWR levels, making it an ideal choice for modern office buildings where aesthetics and energy efficiency are both priorities.

Compared to previous researches, which showed energy savings up to 59% in [31], 48% in [36], and 34.3% in [39] with static double-skin facades, the optimized DDSF system in this study achieved up to 70.32% energy savings. This improvement can be attributed to the integration of advanced shading systems and the use of low-E vacuum glazing in the inner skin, which significantly reduced thermal transmission and improved overall building performance.

Overall, the study highlights the potential of EC glazing and DDSF systems in reducing energy consumption in arid climates, with DDSF offering the highest energy savings at higher WWR levels. These results underscore the importance of selecting the right façade system based on specific climatic conditions and building requirements.

Table 3. Overall energy saving compared to glazing reference in percentage **(%)**

Overall energy saving compared to glazing reference in percentage **(%)**				
	10% of WWR	30% of WWR	60% of WWR	90% of WWR
Simple glazing				
Electrochromic glazing	17.02	44.81	60.78	67.65
DDSF 20 cm shading depth + 45° shading angle / INT: simple / EXT: simple glazing	14.72	33.12	40.95	43.80
DDSF 20 cm shading depth + 45° shading angle / INT: double low-E air / EXT: simple glazing	18.17	40.51	50.68	54.17
DDSF 20 cm shading depth + 45° shading angle / EXT: double low-E air / INT: simple glazing	18.90	39.77	49.44	52.66
DDSF 20 cm shading depth +45° shading angle / INT: double low-E vacuum / EXT: simple glazing	23.50	50.33	64.54	70.32
DDSF 20 cm shading depth + 90° shading angle / INT: double low-E vacuum / EXT: simple glazing	23.90	50.19	64.31	70.10
DDSF 30 cm shading depth + 45° shading angle / INT: double low-E vacuum / EXT: simple glazing	23.20	50.13	64.44	70.25

In the previous results, the strategy variables were limited in some parameters, such as shading depth and shading angle. To understand more about the link between energy consumption and DDSF parameters and find the best configuration, a multi-objective optimization (MOO) via Galapagos is developed, and the results are shown in Figures 14,15.

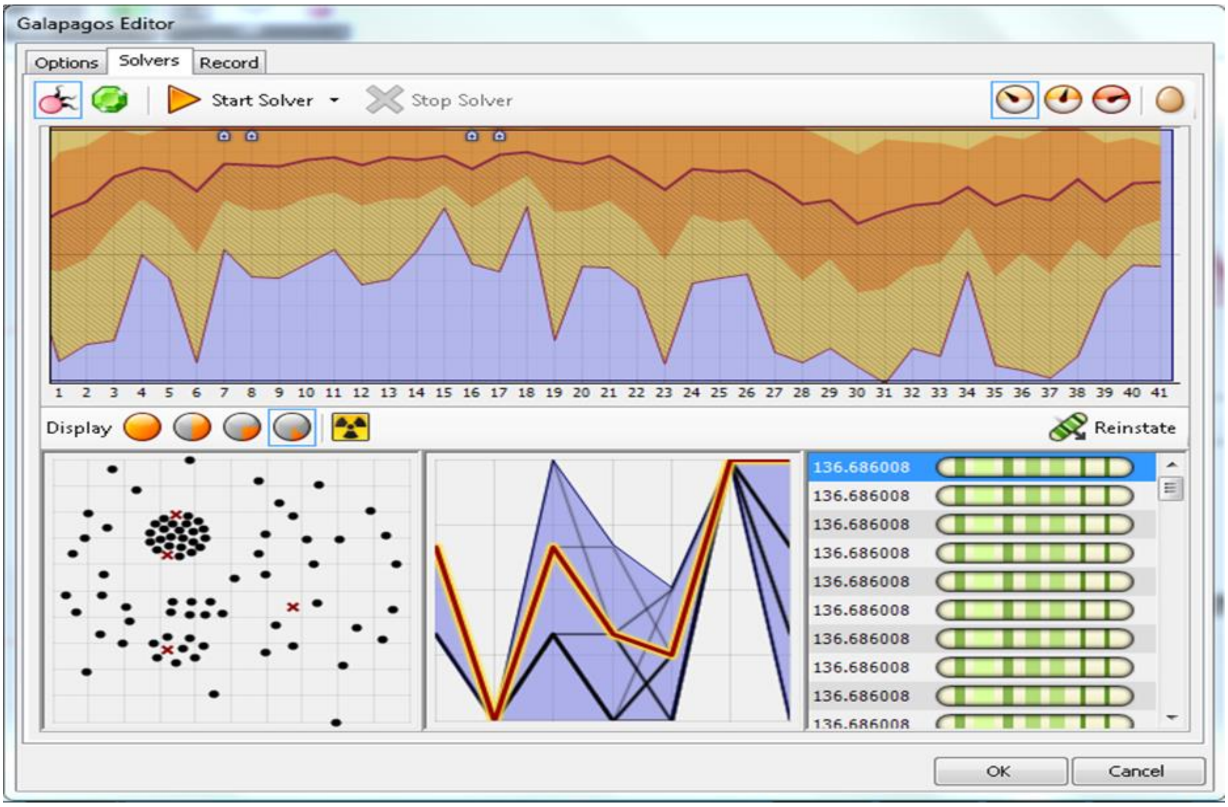

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Fig. 14. *Multi-objective optimization process via Galapagos plugin*

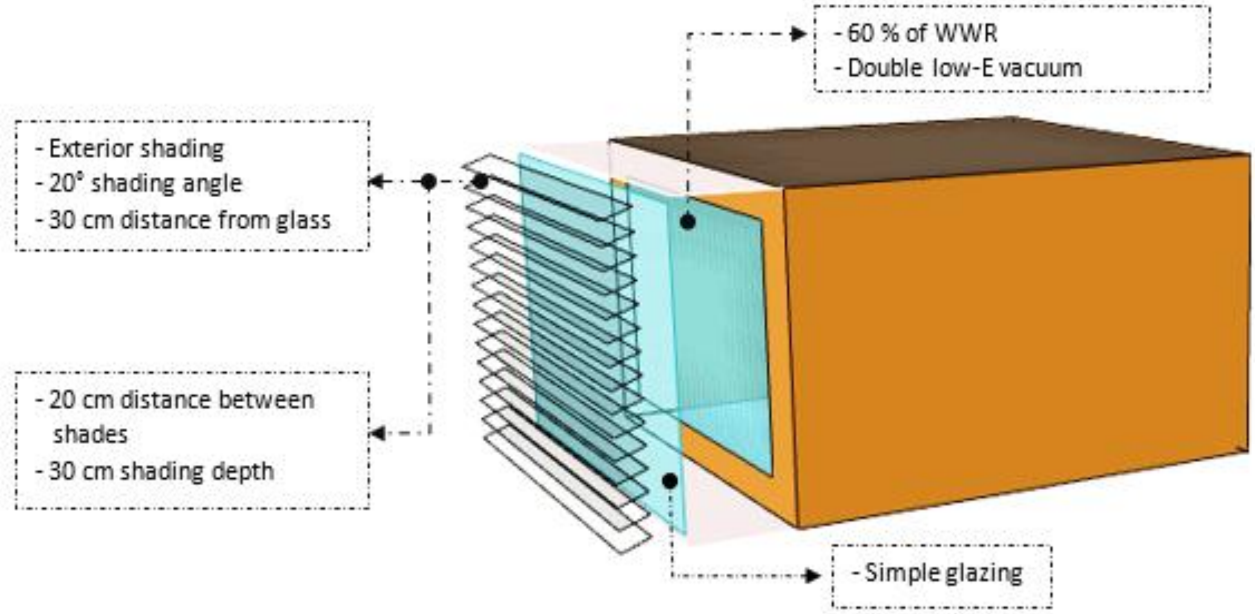

Fig. 15. *The best configuration of DDSF after multi-objective optimization*

Conclusion

The major goal of this research was to compare the feasibility of using a smart façade-electrochromic glazing system and dynamic ventilated double-skin façades (DDSFs) in office buildings in hot, arid region. Meanwhile, multi-objective optimization was developed to find the optimum configuration of DDSF in such climate conditions.

Consequently, it was found that the cooling energy load is more significant than the heating load due to the long summer period, which lasts almost seven months.

Moreover, the WWR has a considerable effect on energy consumption; an increase in the window-to-wall ratio (WWR) correlates with higher energy consumption used for heating, cooling, and lighting.

Meanwhile, it is preferred to use EC glazing in such climate conditions to reduce energy consumption. Using EC glazing as a smart active system is a good choice to reduce the direct radiation on the window. Thanks to its glazing properties such as visible light transmittance (Tvis) and solar heat gain coefficient (SHGC). The percentage between EC glazing and reference glazing in terms of saving energy in 90% of WWR is 67.65% which is a significant reduction.

This study demonstrates that smart and dynamic double-skin facades (DDSF), particularly when optimized for shading angle and depth, can result in substantial energy savings in hot, arid regions. The most efficient configuration tested reduced overall energy consumption by 70.32%, highlighting the potential for DDSF systems to play a critical role in sustainable architecture. These findings underscore the importance of integrating advanced facade technologies in regions with high solar exposure to optimize energy efficiency.

At this stage, this research is limited to the influence of DDSF on energy consumption while considering a few parameters such as shading depth, shading angle, etc. It will be more interesting for future researches to study other parameters such as cavity depth and color, shading materials, etc., and their effect on thermal and visual comfort.

Conflict of interest

The authors declare that they have no conflict of interest.

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The study was performed without financial support.

Nomenclature

EC	electrochromic
DDSF	dynamic double-skin facade
WWR	window-to-wall ratio
Low E	low emissivity
WO3	tungsten trioxide
NiO	nickel oxide
U-values	thermal transmittance
SHGC	solar heat coefficient
Tvis	visible light transmittance
COP	coefficient of performance
MOO	multi-objective optimization

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