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ENHANCING ENERGY CONSUMPTION IN EGYPT WITHIN ADAPTIVE FACADE TECHNIQUES

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ABSTRACT

Building facades play a pivotal role in influencing energy efficiency and indoor comfort. In the pursuit of sustainable building practices, this research investigates the implementation of adaptive facade technologies in office buildings within the hot-dry climate of Cairo, Egypt. The study aims to assess the efficiency of adaptive facade techniques, such as thermochromic, photochromic, gasochromic, and electrochromic glazing, in mitigating energy consumption. Through simulations of various glazing types, the research yielded a substantial reduction in energy consumption, ranging from 20% to 28%. This reduction was accompanied by a noteworthy decrease in carbon emissions. These findings underscore the potential of adaptive facades to enhance building performance and sustainability within hot-dry climates. The study contributes valuable insights for architects seeking eco-friendly solutions in energy-efficient building design. By harnessing the power of adaptive facades, we can reduce energy consumption and environmental impact while providing a more comfortable and sustainable built environment, especially in regions with challenging climates like Cairo, Egypt.

KEYWORDS: Energy Consumption, Adaptive Facades, Switchable Glazing, and Office Buildings

تعزيز استهلاك الطاقة في مصر من خلال تقنيات الواجهة التكيفية

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الملخص

تلعب واجهات المباني دورًا محوريًا في التأثير على كفاءة الطاقة والراحة الداخلية. سعيًا وراء ممارسات البناء المستدامة، يبحث هذا البحث في تنفيذ تقنيات الواجهات التكيفية في المباني الإدارية في ظل المناخ الحار الجاف في القاهرة، مصر. تهدف الدراسة إلى تقييم كفاءة تقنيات الواجهات التكيفية، مثل الزجاج الحراري، والفوتوكروميك، والجازوكروميك، والزجاج الكهربائي، في تخفيف استهلاك الطاقة. ومن خلال محاكاة أنواع الزجاج المختلفة، أسفر البحث عن انخفاض كبير في استهلاك الطاقة، يتراوح من 20% إلى 28%. ورافق هذا التخفيض انخفاض ملحوظ في انبعاثات الكربون. تؤكد هذه النتائج على قدرة الواجهات التكيفية على تعزيز أداء المبنى واستدامته في المناخات الحارة الجافة. تساهم الدراسة برؤى قيمة للمهندسين المعماريين الذين يبحثون عن حلول صديقة للبيئة في تصميم المباني الموفرة للطاقة. ومن خلال تسخير قوة الواجهات التكيفية، يمكننا تقليل استهلاك الطاقة والأثر البيئي مع توفير بيئة بناء أكثر راحة واستدامة، خاصة في المناطق ذات المناخات الصعبة مثل القاهرة، مصر.

الكلمات المفتاحية : استهلاك الطاقه ، الواجهات التكيفيه ، الزجاج القابل للتحول و المباني الإدارية.

1. INTRODUCTION

The building facade assumes a prominent role as a pivotal interface demarcating the interior and exterior environments. The facade must be thoughtfully designed to provide a tangible boundary to the building, ensuring privacy and shielding inhabitants from adverse external influences [1]. Notably, these architectural elements play an indispensable role in shaping a building's aesthetics and character, while also serving as conduits for natural light and ventilation. The ramifications of facades extend to the energy consumption of a structure, as they commonly function as the primary juncture between the internal and external domains, thus affording them control over aspects like heat regulation, ventilation, and natural illumination. Various factors come into play wherein the building facade exerts influence on energy consumption, encompassing considerations such as insulation, glazing, shading mechanisms, natural ventilation strategies, and daylighting [2, 3].

The prospects of sustainable building practices are influenced by multifaceted challenges. Primarily, from a social perspective, there exists an imperative to attain a heightened level of user well-being and indoor environmental quality. Simultaneously, from an environmental standpoint, there is a pressing need to curtail building energy consumption and mitigate the environmental repercussions associated with buildings [4, 5]. Numerous innovative concepts and technologies for building envelopes have been proffered as solutions to enhance indoor comfort conditions while concurrently diminishing environmental impacts across the lifecycle of structures [6]. Particularly noteworthy is the growing attention devoted to the amalgamation of passive and active design technologies within the building envelope, an area of burgeoning interest within the research and development community [7, 8].

Owing to the swiftly evolving dynamics governing the interaction between humans and the built environment, the advent of adaptable architecture has emerged as a response to this paradigm shift. Consequently, a profusion of new facade typologies is burgeoning and evolving within our technologically advancing society. These emerging paradigms proffer practical and efficient architectural solutions tailored to unique and previously unexplored applications, harmonizing with the demands of contemporary adaptive, dynamic, flexible, and ever-evolving activities [9].

Objectives

The research aim is to investigate the opportunities of reducing energy consumption through some techniques of adaptive facades, in office buildings, and in hot-dry climate zones in Egypt, and Cairo. Also, encourages architects to make the decision to use this technique in buildings through the positive results in reducing the annual energy consumption. It could be achieved through the following objectives.

- Study and analysis of the different techniques of the adaptive facades, their components, and their characteristics.
- Investigating the techniques that have the significant effect of reducing energy consumption and improving thermal comfort.
- Determining the appropriate techniques of adaptive facades that can be applied in a hot-dry climate, in Egypt.

Research Problem

One of the main issues in Egypt is the significant imbalance between rising energy consumption and the available resources [10]. Previous research has shown that buildings in hot, arid climates, especially office buildings, have poor energy performance. These buildings consume a substantial amount of energy for cooling, ventilation, and air conditioning, resulting in high electricity costs and increased carbon dioxide emissions, harming the environment. Urgent changes are needed in the building sector to reduce energy use and improve overall efficiency and well-being. The primary architectural challenge is achieving thermal comfort for occupants while reducing energy consumption. The design of the building facade assumes a pivotal role in addressing energy conservation and diminishing cooling loads [2, 3].

Research Methodology

The research methodology comprises two phases. The initial phase is theoretical, encompassing data collection and analysis. The subsequent phase involves practical aspects, often referred to as the simulation phase, which is structured into three steps. In the first step, essential inputs are identified, including the climate template, model specifications, and the specifications pertaining to adaptive facade techniques. The second step entails the execution of simulation processes for each adaptive facade technique separately, systematically analyzing their performance. Ultimately, the third step includes the outcomes of the simulation processes, as shown in **Fig. 1.**

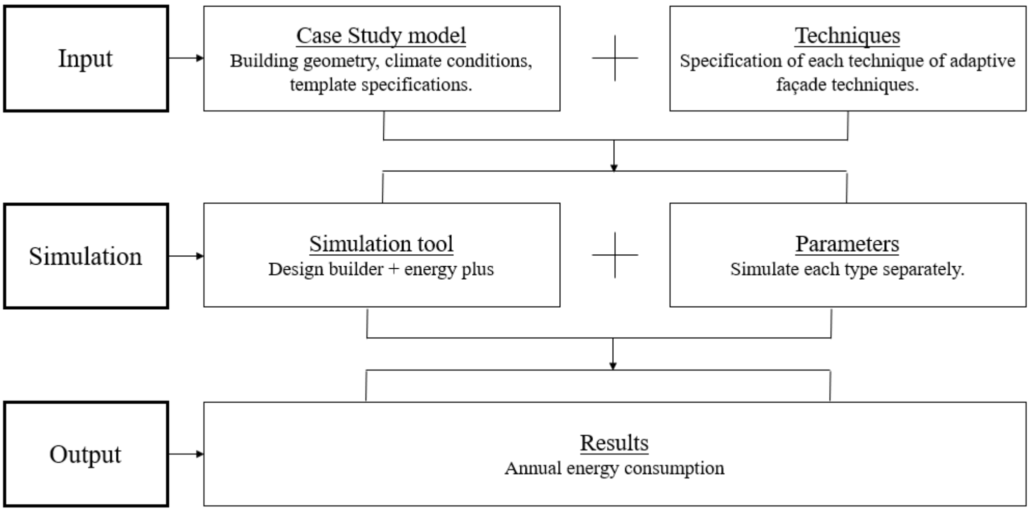


Fig.1. Simulation steps.

2. ADAPTIVE FCADADE DEFINITION

Adaptive facades, defined by the European COST Action TU1403, are building exteriors designed to meet three key performance criteria: energy efficiency, occupant comfort, and environmental impact reduction [11]. These facades can adapt to changing environmental conditions, such as daily cycles, seasons, and short-term weather fluctuations. They are multifunctional systems that modify their functions over time to enhance overall building performance. Adaptive facades save energy by responding to weather conditions and prioritizing occupant comfort based on occupants' needs and preferences [12].

3. THE NEED OF ADAPTATION

The building facade not only plays a significant role in a building's aesthetics but also serves as a vital barrier between the interior and exterior environments. It is exposed to unpredictable weather conditions, such as extreme temperatures, wind, precipitation, and solar radiation, which directly impact the comfort of occupants indoors. The design of an adaptive facade, as illustrated in **Fig.2**, necessitates specific environmental considerations [13].

Despite substantial external climate variations, the indoor comfort requirements of occupants remain relatively stable. Therefore, building envelopes must possess adaptability to address short-term weather fluctuations, daily cycles, and seasonal patterns. The effectiveness of adaptive systems relies on their ability to balance occupant dynamics with external environmental conditions [11]. Furthermore, adaptive facades significantly contribute to energy conservation by adjusting their components to respond to external conditions, either passively or actively [13].

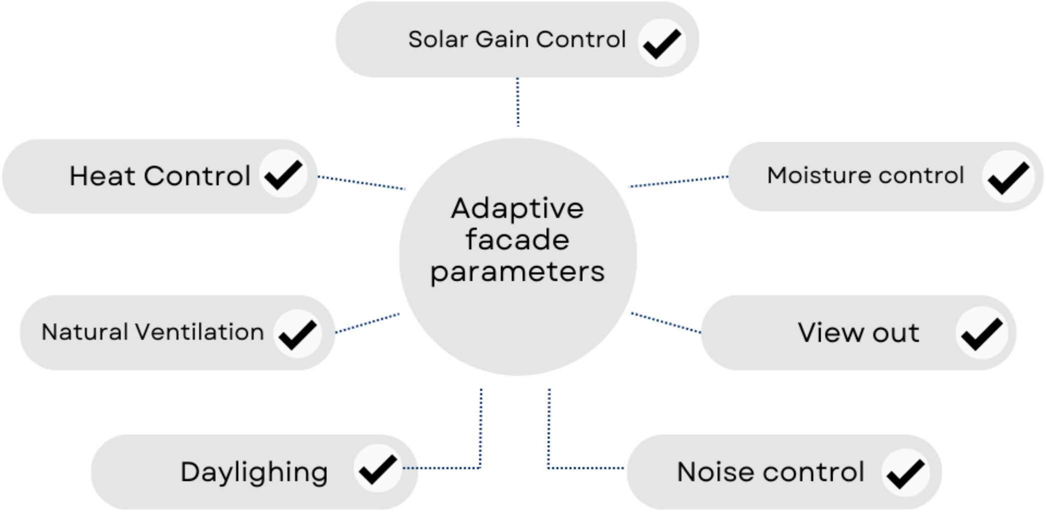


Fig. 2. Adaptive facades parameters, source: author based on [15].

4. ADAPTIVE FACADES FEATURES

These adaptive façade features efficiently contribute to the building's energy balance, reducing the demand for air conditioning devices and, as a result, reducing energy consumption. Some more specific Features of adaptive facades such as energy performance, control strategy, sensing, thermal comfort, visual comfort, integration with the building, flexibility, aesthetics, cost efficiency, and user interaction [14 -16], as shown in **Fig. 3**.

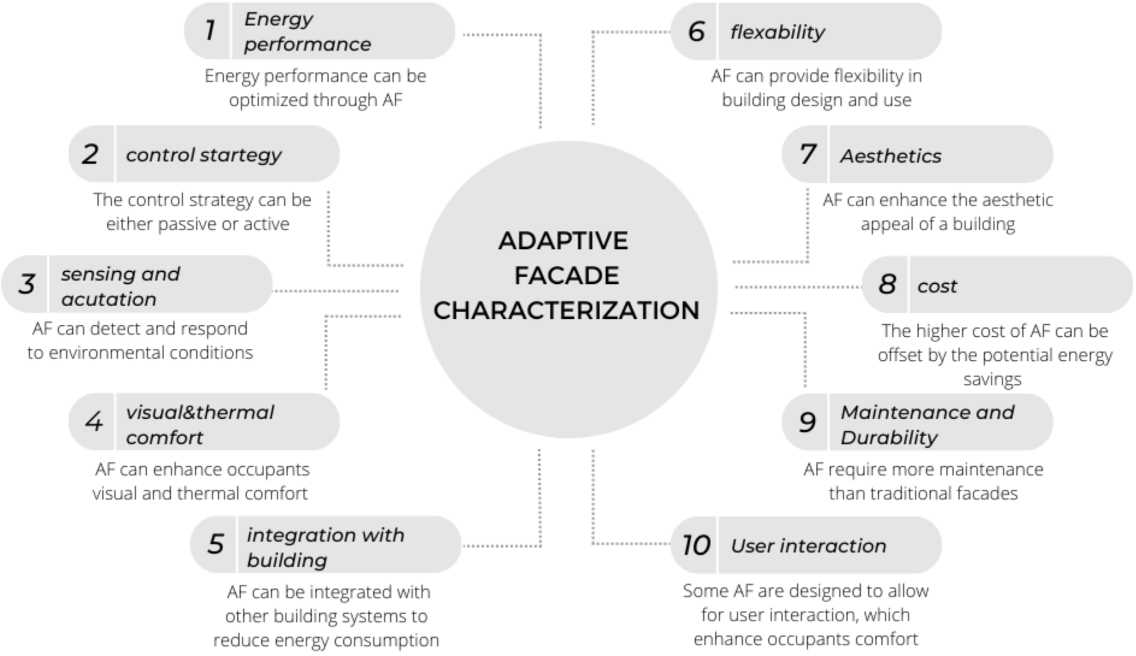


Fig. 3. Adaptive facades features, source: author based on [14].

5. ADAPTIVE FACADES TECHNOLOGIES

Based on the expertise in each technology’s market requirements, adaptive facade technologies can be classified into four distinct categories: switchable windows, dynamic shading devices, solar active facades, and active ventilative facades, as shown in Table 1 [17].

Switchable windows: are designed to enhance indoor comfort and energy efficiency by adjusting their optical properties to control solar gains and daylight. They are available in different stages of development [17].

Dynamic shading devices: including technologies like louvers, Venetian blinds, and glass flirts, have proven to be highly effective in enhancing the indoor environment of buildings. They serve a triple purpose by improving thermal comfort, reducing energy consumption, and preventing glare[18].

Solar active facades: encompass technologies designed to manage solar radiation and excessive daylight effectively. their impact extends to thermal comfort, energy consumption, and visual comfort. the performance of these technologies is intricately linked to how materials react to sun radiation and temperature functions, influencing their chemical, physical, and biological properties[17].

Active ventilated facades: utilize ventilation, employing two methods. the first method involves managing airflow within the façade cavity, while the second focuses on regulating the airflow entering the building. these approaches are instrumental in improving thermal comfort within the building and reducing overall energy consumption [17].

The focus of the practical part of this research will be on the switchable windows category.

Table 1. Adaptive facades techniques, classified into four categories, source: author based on [17].

Adaptive facades techniques		
Switchable glazing	Passive	-Thermochromic glazing -Photochromic
	Active	-Electrochromic device -Nanocrystal in-glass composites window -Gasochromic window -Suspended particles devices -Liquid crystals -Electrokinetic pixels windows -Elastomer-deformation tunable window -Liquid infill tunable window
Dynamic shading devices	Active	-Conventional dynamic shading devices (Venetian blinds ,Louvers and Glass frits) -Kinetic dynamic shading devices (Parametric geometries and Foldable origamis)
	Hybrid	-Systems base on Biomimetics -elastomer-deformation tunable window
		Dynamic photovoltaic shading devices
Solar active facade	Double skin facade	-Ventilation mode (-No ventilation, Natural (Hybrid) and Mechanical (Hybrid)) -Airflow path (Buffer zone, Indoor air curtain , Outdoor air curtain, Air supply and Air exhaust) -Geometry of the cavity (Box-window, Corridor, Shaft-box and Multi- storey)
	Green	-Green roofs Vertical greenery system
		Static photovoltaic panels
		Phase change materials (PCM)
Active ventilated facade	Closed cavity façade (CCF) (With pressurized system and With mechanical ventilation)	
	Automated operable windows	
	Actively ventilated double-skin façades	

5.1. Switchable Glazing

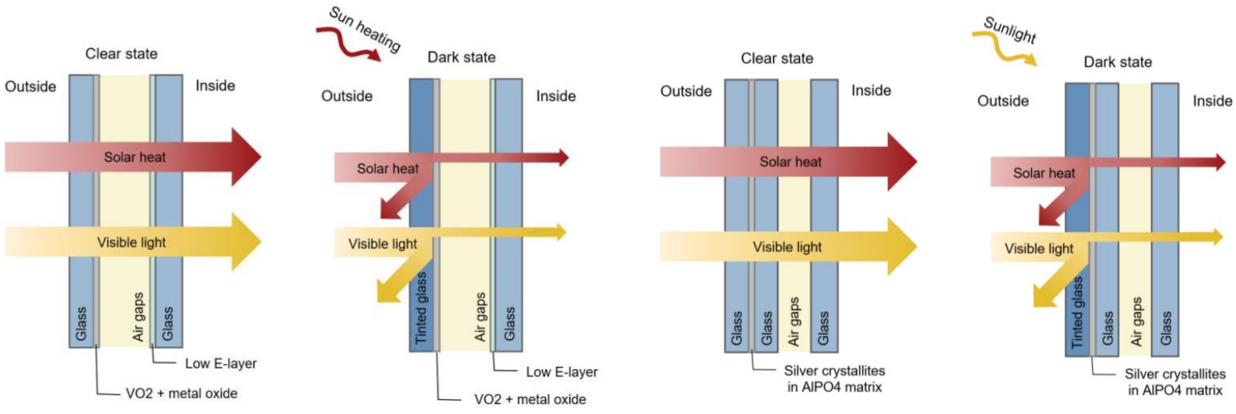
Switchable windows have the capability to modify their optical properties, allowing them to control the solar gains and daylight within interior spaces by either reflecting or absorbing them, as indicated [19]. The primary goal of these windows is to improve the thermal comfort of indoor spaces while simultaneously reducing the building's energy consumption through effective solar radiation control.

5.1.1. Thermochromic window

Thermochromic windows, depending on external temperature conditions, possess the ability to regulate and modify the transmission of solar heat and light. This control is achieved through a change in their color, shifting from a clear to a dark state [20]. These windows incorporate a metal oxide, particularly vanadium oxide (VO_2), positioned between two glass layers. When the temperature reaches a specific threshold, the material undergoes a transformation, exhibiting a metallic color and becoming reflective to infrared radiation. Consequently, during the summer, these windows effectively manage the solar energy entering the building, leading to a reduction in the energy required for cooling, as shown in **Fig. 4A** [21].

5.1.2. Photochromic window

Photochromic windows, akin to thermochromic glazing, operate with a comparable principle. However, they distinguish themselves in their ability to regulate and adjust the transmission of solar heat and light based on solar radiation rather than temperature variations [20]. These windows feature a photochromic layer, typically composed of silver crystallites enclosed within an $AlPO_4$ or borosilicate matrix. The color of the tinted glass is determined by the size of the silver crystallites, as shown in **Fig. 4B** [22].



(B) (A)

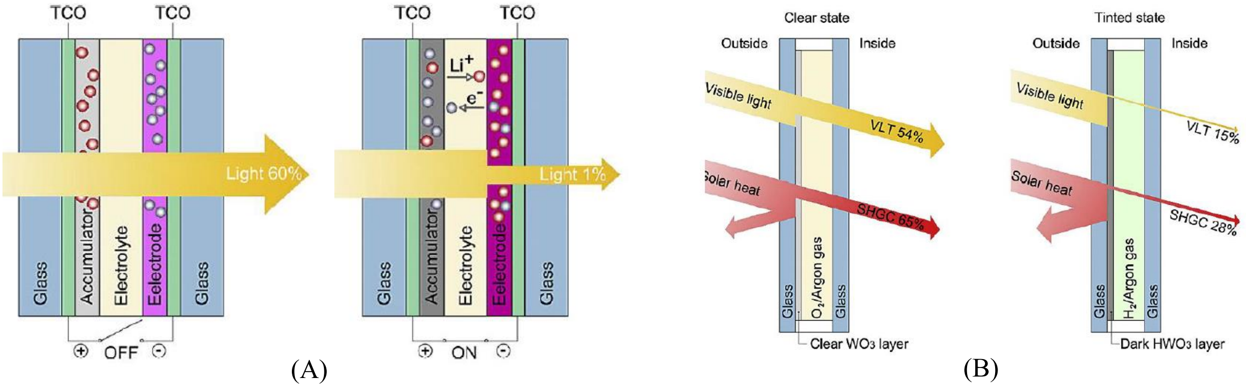
Fig. 4. (A) Thermochromic glzing operation, source: [21], (A) Photochromic glzing operation, source: [22].

5.1.3. Electrochromic window

Electrochromic windows respond to external electrical stimuli by transitioning from a clear to a dark state through oxidation or reduction reactions. This transformation effectively regulates and reduces the solar heat entering the building. These windows consist of five layers. The layers arrangement is as follows; transparent conductive oxide for the outside layer, electron accumulation layer which performs as a counter electrode, ion conductor layer or electrolyte, electrode layer, and finally transparent conductive oxide for the outside layer [23], as shown in **Fig. 5A.**

5.1.4. Gasochromic window

Gasochromic windows typically consist of a gas-sensitive layer, often made of materials like tungsten oxide (WO3) or similar compounds. When this layer is exposed to certain gases, such as hydrogen (H2), it undergoes a chemical reaction that causes it to change from a clear or transparent state to a dark or opaque state. This is useful for improving energy efficiency and occupant comfort in buildings [19,24], as shown in **Fig. 5B** .



(A) (B)

Fig. 5. (A) Electrochromic glzing operation scheme, source: [21] , (B) Gasochromic glzing operation, source: [19,21].

6. CASE STUDY

The base case involves an office building located in New Cairo, Egypt **Fig. 6**. This building features an open floor plan with a single core and is occupied by many people who work long hours. These conditions offer significant opportunities to decrease energy usage and improve thermal comfort by using switchable glazing.

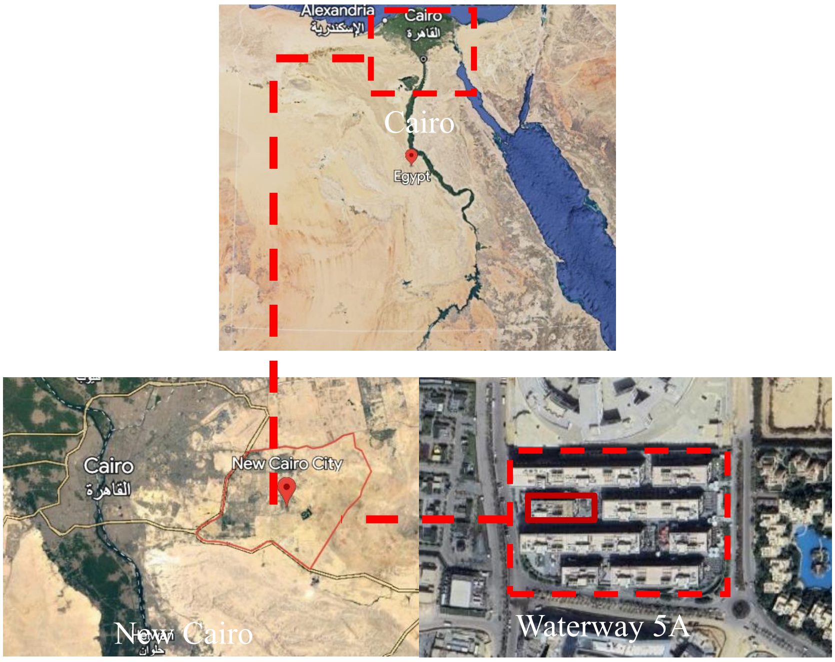


Fig.6. Case study location, source :author based on [25].

6.1. Weather Data

The Cairo region falls under the Bwh climate classification according to the Köppen system, signifying a hot and arid climate. Summers are hot and dry with temperatures reaching up to 45°C, and the area experiences continuous sunshine throughout the year [26]. Data from Cairo_ ETMY indicates that the average annual air temperature in Cairo is 22°C. August records the highest annual mean air temperature, reaching 35°C, while January exhibits the lowest annual mean air temperature at 10°C. (This information is based on data from Cairo International Airport.) [27].

6.2. Case Study Description

The base case involves an office building with a total area of 893 square meters **Fig. 7**. This building is divided into two main zones: the office area and the service area. It comprises a basement floor and extends to five floors above ground level. The building features a curtain wall façade, and the third floor is selected as the reference point for the base case. Considering the office building type in this case study, the operational schedule is defined as five working days per week, from 8:00 a.m. to 4:00 p.m., with an occupancy density of 4.5 square meters per person.

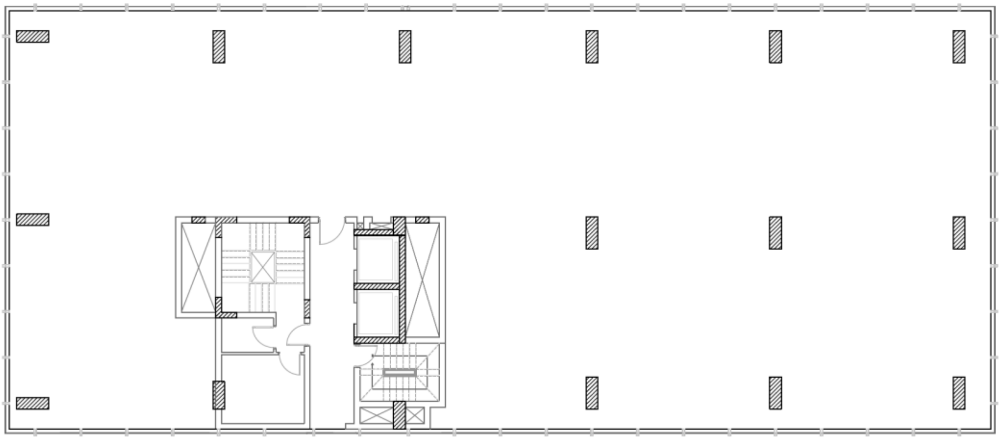


Fig. 7. Case study plan, source: author.

6.3. Simulation Methodology

The aim of this simulation is to analyze the impact of employing various switchable glazing types on the annual energy consumption of the case study building. After establishing the base case, the simulation process involves two phases. The first phase employs conventional window glazing, while the second phase employs different types of switchable glazing, which fall under the category of adaptive facades. Each type of switchable glazing will be individually simulated in this second phase.

6.3.1. Simulation process depending on conventional windows

In this phase, conventional and standard window glazing components typically employed in the construction of office buildings in Egypt will be utilized. The chosen glazing type is double glazing, consisting of 6mm glass, a 12mm air gap, and another 6mm glass. The properties of the glazing material are detailed in **Table 2** [17,19, 23].

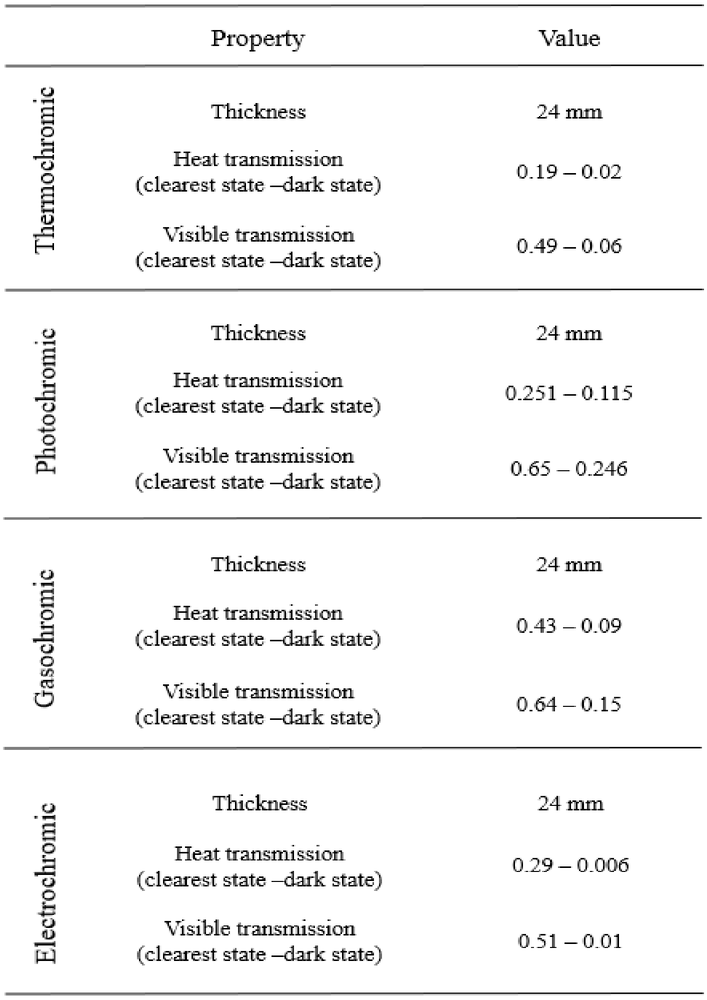
Table 2. Specifications of used glass in the base case, source: author based on [17, 9, 23].

	Property	Value
Clear glazing	Thickness	24
	Heat transmission	0.89612
	Light transmission	0.91339

6.3.2. Simulation process using switchable windows

This process involves simulating four distinct types of switchable glazing, belonging to the category of adaptive facades. Each type is simulated separately, and the specific properties of the switchable glazing are detailed in **Table 3**. Additionally, LED lighting was incorporated [21- 23].

Table 3. Specifications of Switchable glazing types, source: author based on [21-23].



	Property	Value
Thermochromic	Thickness	24 mm
	Heat transmission (clearest state –dark state)	0.19 – 0.02
	Visible transmission (clearest state –dark state)	0.49 – 0.06
Photochromic	Thickness	24 mm
	Heat transmission (clearest state –dark state)	0.251 – 0.115
	Visible transmission (clearest state –dark state)	0.65 – 0.246
Gasochromic	Thickness	24 mm
	Heat transmission (clearest state –dark state)	0.43 – 0.09
	Visible transmission (clearest state –dark state)	0.64 – 0.15
Electrochromic	Thickness	24 mm
	Heat transmission (clearest state –dark state)	0.29 – 0.006
	Visible transmission (clearest state –dark state)	0.51 – 0.01

6.4. Simulation Results

In the results, it was observed that the annual energy consumption significantly decreased with the implementation of various types of switchable glazing. Notably, this reduction in energy consumption was accompanied by a decrease in carbon dioxide (CO_2) emissions, highlighting the environmental benefits of using these adaptive facade technologies.

Additionally, the solar gains through the exterior windows saw a notable reduction, contributing to improved thermal comfort and energy efficiency. According to the data presented in **Table 4** and **Fig. 7**, the energy consumption and CO_2 production for a single-floor office space decreased by a percentage ranging from 20% to 28%. Similarly, solar gains through the exterior windows were reduced from 79.6% to 92%.

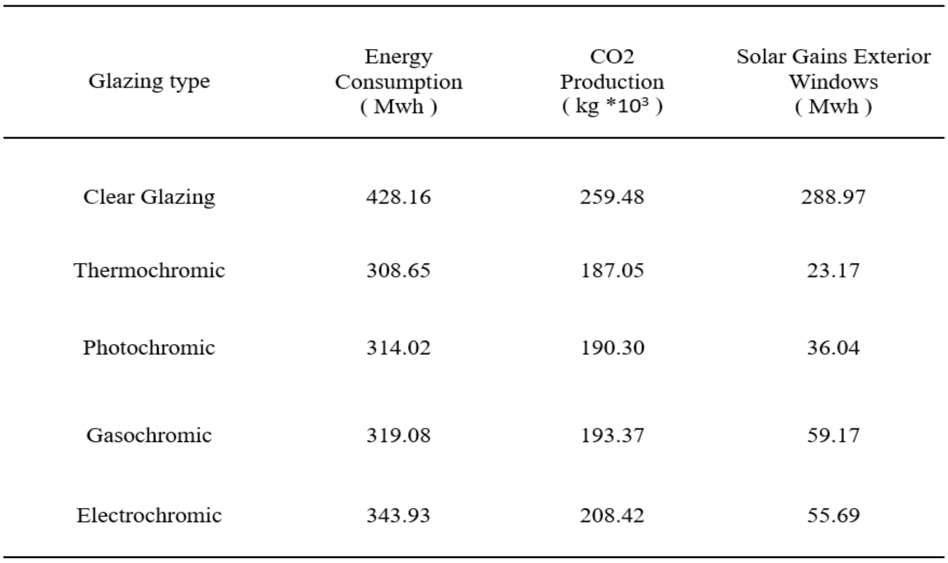
- Thermochromic Glazing (28% Reduction): The utilization of thermochromic glazing achieved a substantial 28% decrease in annual energy consumption and CO_2 emissions. This glazing type, which responds to temperature changes by darkening in hot weather and lightening in cold weather, contributed to a 92% reduction in solar gains from exterior windows.
- Photochromic Glazing (26.7% Reduction): The installation of photochromic glazing led to a noteworthy 26.7% reduction in annual energy consumption and CO_2 emissions. It also resulted

in an 87.5% reduction in solar gains through exterior windows. Photochromic glazing adapts to sunlight exposure, reducing glare and cooling demand.

- Gasochromic Glazing (25.5% Reduction): The use of gasochromic glazing led to a 25.5% reduction in annual energy consumption and CO_2 emissions. It was associated with a 79.6% reduction in solar gains through exterior windows. Gasochromic materials react to specific gases, making them advantageous for maintaining indoor comfort and reducing heating and cooling energy demands.
- Electrochromic Glazing (20% Reduction): Implementing electrochromic glazing resulted in a 20% decrease in energy consumption and CO_2 emissions. It also led to an 80.7% reduction in solar gains through exterior windows. Electrochromic glazing can adjust its tint based on temperature changes, thereby regulating incoming sunlight and heat.

These findings highlight the considerable energy savings, CO_2 reduction, and control over solar gains achieved through the implementation of switchable glazing, emphasizing their pivotal role in enhancing building performance and sustainability.

Table 4. Simulation results, source: author



Glazing type	Energy Consumption (Mwh)	CO2 Production (kg $*10^3$)	Solar Gains Exterior Windows (Mwh)
Clear Glazing	428.16	259.48	288.97
Thermochromic	308.65	187.05	23.17
Photochromic	314.02	190.30	36.04
Gasochromic	319.08	193.37	59.17
Electrochromic	343.93	208.42	55.69

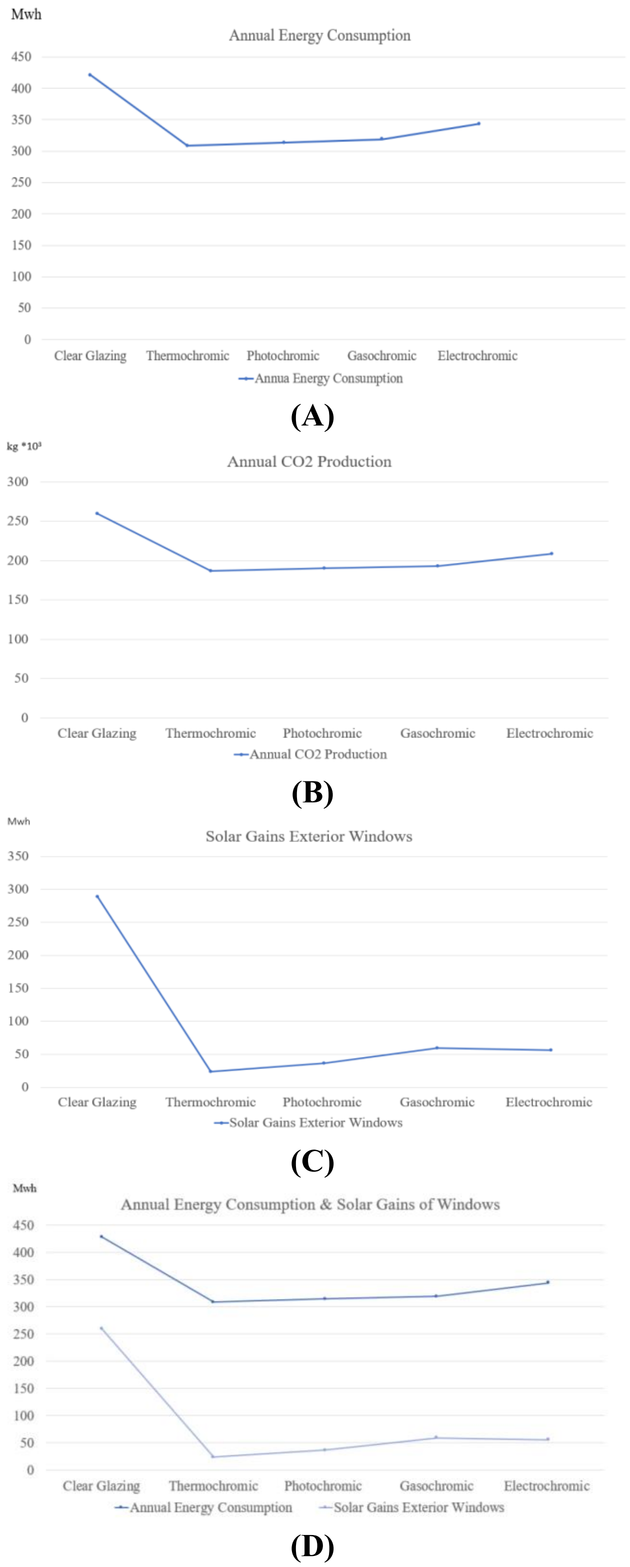


Fig. 7. Simulation results : (A) Annual energy consumption, (B) Annual CO_2 production, (C) Annual solar gains of exterior windows (D) The relation between the annual energy consumption and the annual solar gains for windows, source: author.

CONCLUSIONS

Ultimately, this research highlights the significant potential of adaptive facade techniques in reducing annual energy consumption and promoting sustainability in building design. The study found that various switchable glazing technologies, such as thermochromic, photochromic, gasochromic, and electrochromic glazing, can lead to substantial energy savings ranging from 20% to 28%. These technologies not only reduce energy consumption but also decrease solar heat gains for exterior windows, lower CO_2 production, and enhance occupant comfort and well-being.

However, the effectiveness of adaptive facade techniques can vary based on factors like climate and building materials characteristics, emphasizing the importance of tailored solutions. Overall, adaptive facade techniques offer a promising pathway toward energy-efficient buildings, making them a crucial part of our efforts to combat climate change and create a sustainable future in the built environment. Further research and innovation in this field about other techniques are essential for continued progress.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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