Budownictwo i Architektura 24(3) 2025, 171-193

DOI: 10.35784/bud-arch.7102
Received: 17.01.2025; Revised: 23.07.2025;
Accepted: 05.09.2025; Available online: 25.09.2025

Orginal Article

Simulation-based performance evaluation of kinetic Mashrabiya for thermal comfort and energy efficiency in arid climates: A case study in Biskra, Algeria

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Abstract: In the hot, dry climate regions of Algeria, traditional buildings are constructed with cooling strategies to cope with harsh climatic conditions. The dominance of direct solar irradiance in these regions requires that building facades be well shaded, allowing for controlled solar transmittance to reduce cooling loads and minimise energy consumption. The Mashrabiya was one of the traditional shading strategies, controlling excess solar radiation and improving interior thermal comfort. Numerous studies have demonstrated that static shading can allow direct radiation to penetrate the building during overheated periods. Shading design must prevent this; however, during colder periods of the year, it is preferable to allow solar radiation to enter the building. This response can be achieved through dynamic shading systems with automated control. This research aims to evaluate the effect and performance of adaptive Mashrabiya as a kinetic sunscreen through parametric simulation, to improve indoor thermal comfort and energy efficiency. These objectives are achieved by integrating solar control with parametric Mashrabiya design to regulate solar radiation intensity and minimise cooling demand. The simulation findings, using parametric tools (Geco and Honeybee plugins for Grasshopper), showed that direct radiation was reduced by 17.9%, resulting in a 43% reduction in energy consumption, accompanied by a corresponding decrease in indoor air temperature of between 4.0°C and 4.8°C. These simulation-based results suggest promising potential for improving building performance and provide valuable insights for early-stage design.

Keywords: Mashrabiya, adaptive facades, thermal comfort, dynamic shading, solar, Grasshopper

1. Introduction

The building sector is facing significant economic, environmental, technical, and social challenges. These challenges are primarily driven by unprecedented global and regional climate change, rapid urbanisation, and excessive resource consumption. The potential responses to these challenges, and the policies to follow, will shape the present and future quality of life [1]. Over one-third of global final energy consumption and nearly 40% of total direct and indirect CO_2 emissions are attributed to the building and construction industry, highlighting the critical need to integrate sustainability strategies into building design and construction practices [2,3].

A major challenge facing construction in arid regions lies in the design of solar shading systems that can withstand the harsh climate while reducing direct solar gains and maximising daylight and views to the outside. Glazed facades enhance the visual connection between a building's interior and exterior, fostering a sense of openness. Moreover, daylight within buildings significantly impacts occupants' visual and thermal comfort, as well as their psychophysiological state [4,5]. The quality of the physical environment in offices has a significant influence on employees' behaviours, attitudes, and overall satisfaction. A positive work environment can improve job satisfaction and well-being [6].

Additionally, evidence suggests that occupants prefer working in offices that provide daylight and visual contact with the outdoors. Such an environment, free from glare and offering a comfortable temperature, has been shown to have beneficial impacts on both satisfaction and productivity [7]. However, the abundance of solar radiation in a fully glazed building may force occupants to close their shading systems and use electric lighting, resulting in insufficient daylighting in interior spaces.

These specific conditions necessitate innovative solutions that transcend conventional static building approaches. Climate-adapted building envelopes represent a paradigm shift in architectural design, characterised by their ability to dynamically respond to external environmental conditions and internal occupancy requirements [8]. These adaptive systems are positioned at the critical interface between interior and exterior environments, where they encounter continuously variable conditions, including fluctuating meteorological parameters throughout diurnal and seasonal cycles, as well as changing occupancy patterns and comfort preferences [9]. Unlike conventional building shells that maintain static properties with limited responsive capabilities, climate-adapted building envelopes leverage environmental variability to optimise performance, offering substantial potential for reducing energy demand in space air conditioning while maintaining occupant comfort [10,11]. This adaptive approach represents a fundamental departure from traditional building design philosophy, enabling structures to actively engage with their environmental context rather than merely providing passive protection against external conditions [12,13].

The static vernacular Mashrabiya, an external perforated panel made of a combination of wooden strips and screens fixed in front of a window, is used as a shading device to screen unglazed openings [14,15]. It fulfils a significant cultural and social role in Islamic architecture by serving as a functional veil that ensures privacy [16]. Beyond their functional and cultural roles, Mashrabiyas exhibit considerable morphological diversity across different regions and historical periods, reflecting local climatic conditions, cultural preferences, and available materials. These variations include differences in geometric patterns, perforation ratios, projection depths, and structural configurations [17] (Fig. 1). In Egyptian architecture, Mashrabiyas typically feature intricate geometric latticework with smaller openings and deeper projections, optimised for the intense solar radiation of the region [18,19]. Conversely, Levantine Mashrabiyas often incorporate larger openings and more linear patterns, adapted to different climatic conditions and cultural practices [20]. The diversity extends to materiality, with traditional examples utilising various wood species, including teak and local hardwoods, each contributing distinct aesthetic and performance characteristics [21].

Fig. 1. Regional architectural typologies of the traditional Mashrabiya. *Source*: [22]

The Mashrabiyas vary in their integration with the building envelope, ranging from full-height window coverings to partial screening elements, and from purely external installations to integrated cavity systems [23]. This morphological richness demonstrates the adaptive capacity of vernacular design solutions to respond to diverse environmental and cultural contexts [24]. While this shading device is well adapted to the constraints of arid regions, it does not fully meet modern needs for visual comfort due to insufficient daylighting and limited views [25,26]. Developing new, dynamic, and intelligent facades inspired by historical shading devices such as the Mashrabiya, which balance indoor thermal comfort and energy efficiency, remains a significant challenge for researchers and designers seeking to achieve modern sustainability goals alongside a high quality of life.

The present research addresses this challenge by investigating how traditional Mashrabiya principles can be transformed into dynamic, responsive shading systems that meet contemporary building performance requirements. The main objective is to evaluate the effect and performance of adaptive Mashrabiya as a kinetic sunscreen in the context of improving indoor thermal comfort and energy efficiency. These objectives are achieved by controlling the intensity of solar radiation and reducing cooling demand in an office building located in the hot, arid regions of Algeria, ultimately contributing to the design of more efficient adaptive facades that mitigate overheated periods.

2. Literature review

In response to the growing demand for sustainable architecture, adaptive shading systems have emerged as a critical focus in building performance research. Recent studies have extensively examined both static and dynamic shading strategies, particularly their impacts on thermal comfort and energy efficiency. In most cases, facades with fixed sun protection perform less effectively than dynamic screens, which have a significant influence on occupants' thermal perception [27,28]. Additionally, dynamic shading systems have been established as effective bioclimatic strategies, capable of delivering considerable energy savings while significantly enhancing indoor thermal comfort and occupant well-being [29,30].

Bagasi et al. [31] examined traditional Mashrabiya designs in hot climates, notably in historic Jeddah, Saudi Arabia, and found that opening the Mashrabiya facilitated airflow, lowering indoor temperatures by up to 2.4°C compared to closed configurations. This research highlights the critical role of the building envelope in moderating indoor temperature fluctuations in response to external conditions. Another study conducted by Taki et al. [32] examined the impact of modernising the Mashrabiya on a building's energy efficiency, cultural integrity, and religious significance in Saudi Arabia. Using dynamic thermal simulations, the study demonstrated significant improvements in thermal comfort and energy efficiency with traditional Mashrabiya, showing a 14% reduction in operative temperature, a 77.8% reduction in peak solar gain, a 5.7% decrease in monthly cooling load, and a 35.5% improvement in daylight factor. A previous study on the Shape Variable Mashrabiya (SVM) demonstrated its superior performance over conventional technologies such as selective glazing and Venetian blinds, particularly in mitigating overheating and enhancing thermal comfort, with significant quantitative benefits in both daylighting and energy savings. In addition to its thermal advantages, the SVM improved visual comfort through effective glare control, albeit with a reduced view to the outside [33]. Related research conducted by Erikson et al. [34] reinforced these findings, demonstrating that adaptive shading facades maintain Predicted Percentage of Dissatisfied (PPD) values at or below the comfort thresholds outlined by ASHRAE 55, while dynamic shading systems mitigate glare and solar heat gain without additional energy use [35].

The energy efficiency and daylighting performance of shading systems have been focal points of recent research. A comprehensive study by Chi et al. [36] on perforated solar facades (PSS) revealed a substantial 63% reduction in thermal solar energy transmittance and a 50% increase in the actual daylit area. Another study by Jamilu et al. [37] on kinetic facades consistently achieved approximately 30% energy savings in heating and cooling, outperforming static shading systems by maintaining 38–55% of workspaces within the recommended illuminance levels. Moreover, previous research examining the Mashrabiya-inspired adaptive shading system of Abu Dhabi's Al-Bahr Towers found significant reductions in solar radiation by 20% and solar heat gain by 50% [35,38]. These findings highlight the efficacy of dynamic facades in energy conservation without compromising occupant comfort [39].

Dynamic shading systems excel at optimising daylight quality alongside thermal comfort. Research conducted by Konstantzos et al. [40] indicated that automated blinds significantly increased spatial daylight autonomy (sDA 300) compared to manually operated alternatives. Another related study by Grobman [41] found improvements in useful daylight illuminance of up to 33.6% when dynamic shading strategies were employed, compared to unshaded scenarios. Previous research has also highlighted that kinetic façade designs utilising three-dimensional geometries significantly enhance both daylighting and thermal performance [42]. Seasonal evaluations by Mahmoud and Elghazi [43] further supported these findings, noting substantial improvements in visual comfort, particularly during the summer and winter periods. Additionally, research by Elzeyadi [44] demonstrated the potential of egg-crate dynamic shading configurations to substantially reduce solar thermal loads by 50–64%.

Numerous studies underscore the importance of adaptive shading in enhancing occupant well-being and comfort. For instance, dynamic shading solutions significantly increased indoor comfort levels by 13.3% to 26.9% across cooling and heating seasons [41]. Related research by Mazzetto [45] observed that external shading devices in hot and arid climates effectively intercepted solar radiation, reducing cooling loads and improving thermal comfort without increasing energy consumption. Notably, thermal discomfort decreased, with PPD indices dropping from over 80% dissatisfaction in unshaded scenarios to approximately 15% in highly shaded dynamic conditions. Additionally, achieving thermal comfort through passive strategies, including natural ventilation and optimised solar control, is influenced by both physiological and psychological occupant factors, as well as environmental parameters [46-48]. Despite these advantages, achieving balanced daylight conditions while minimising glare remains a challenge [49], emphasising the necessity for dynamically responsive adaptive shading solutions that address changing climatic conditions [42,50].

Several studies have examined the impact of shading systems on building energy performance, with dynamic facades receiving particular attention. Notably, recent research highlights their effectiveness in reducing thermal loads and overall energy consumption. A study by Naik et al. [30] investigated the energy-saving potential of solar screens, finding that they can achieve up to 60% energy savings compared to traditional screens. Moreover, perforated shading screens demonstrated a substantial reduction in thermal solar energy transmittance (63%), cooling energy (58%), and heating energy (86%), despite an increase in artificial lighting usage [36].

Additionally, for buildings located in warm and tropical climates, the use of dense dynamic screens was found to provide energy savings of 27–48%. Krarti [51] found that dynamic shading devices, particularly rotating overhangs, can significantly reduce energy consumption in office buildings by up to 39% by effectively controlling the amount of sunlight entering the building, thereby reducing the need for heating and cooling. Another publication analysed the Shape Variable Mashrabiya (SVM) design, showing that SVM is more advantageous than other technologies currently used in the Middle East for solar control, achieving energy savings of 17.2% and 9.9% compared to selective glazing and Venetian blinds, respectively [33]. In addition, a study by Batool et al. [52] investigated the use of dynamic external louvres in combination with vertical fins, resulting in electricity reductions of 20% to 38.5%. Hybrid double-skin facades studied by Shafaghat et al. [53] further supported these outcomes, showing an average decrease in HVAC-related energy demand of approximately 30%.

Previous research investigating the performance of external perforated solar screens found that these screens reduced energy consumption by 25% to 35% in several cities between 14°N and 40°N [54]. Omidfar [55] assessed external solar screens with complex geometry, finding a reduction in annual energy consumption of 35% and 42% compared to two reference cases. Lee et al. [56] compared the lighting energy consumption between traditional static and dynamic shading systems, observing an energy savings difference of 5% to 11%. Another related study conducted by Hammad et al. [57] showed energy savings of 5% to 14%. Comparative studies on external louvres and crate shading systems under different climatic conditions revealed a reduction of 8.9% to 20% in energy consumption, especially during the hot seasons [58]. It was concluded that dynamic shading facades generally exhibited the best performance in terms of total energy demand. Current energy-efficient design strategies and technologies for building envelopes have resulted in significant energy savings [59].

Despite extensive research on adaptive shading systems and their benefits for energy efficiency and thermal comfort, significant gaps remain, particularly regarding the application of adaptive facades in hot, arid climates and their integration with vernacular design principles. Few studies have explored the performance of Mashrabiya-inspired dynamic systems using comprehensive simulations that address thermal, daylighting, and energy metrics in office environments. Moreover, the complex geometry of such systems poses modelling challenges, often limiting their representation in existing simulation tools. This research addresses these gaps by evaluating a kinetic Mashrabiya system specifically designed for Algeria's climatic context, aiming to enhance thermal comfort and reduce cooling loads. The findings aim to inform design strategies that balance energy efficiency, occupant well-being, and cultural relevance in understudied regions.

3. Methodology

A parametric study was conducted on an existing office building in Biskra, a city in southeastern Algeria (latitude 34.48° N, longitude 5.44° E, elevation 81 m). The climate is extremely hot during summer, with short, cold winters. The average temperature in July, the hottest month, is 34.4°C, with occasional peaks of 46°C. The average monthly relative humidity ranges from 16.78% to 70.1%. Solar radiation is intense, with direct solar radiation reaching up to 768 W/m² in July [60] (Fig. 2). Winds are generally weak, with an annual average of 4.4 m/s, blowing south and southwest in summer and north to northeast during colder periods [61].

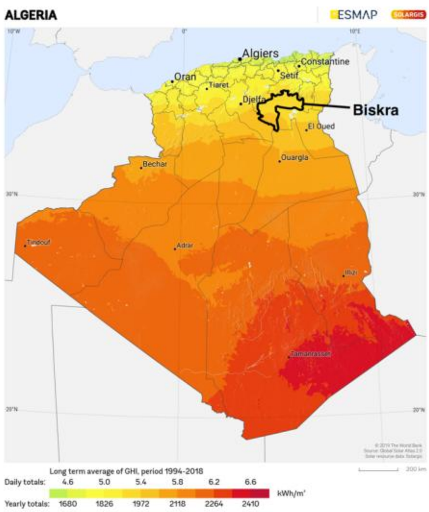


Fig. 2. Global horizontal irradiation map of Algeria and location of the case study: Biskra. *Source*: [62]

The simulations in this study were performed using Grasshopper, an algorithmic editor for Rhino's 3D modelling tool, with a plug-in called Geco, which provides a link to Autodesk Ecotect [63]. Geco enables Ecotect to import geometry from Rhinoceros and analyse building performance, including thermal values, solar radiation, and energy use. This allows users to conduct conceptual design and mass modelling within Rhinoceros, offering real-time visualisation of design alterations and supporting quicker, better-informed decisions [64].

The study was divided into two consecutive phases. The first stage focused on evaluating thermal and visual comfort performance, direct solar radiation, and solar heat gains throughout the year for the base case scenario (a building without adaptive shading). The second stage involved designing an adaptive shading facade device with a kinetic hexagonal base pattern to achieve suitable indoor thermal comfort (Fig. 3).

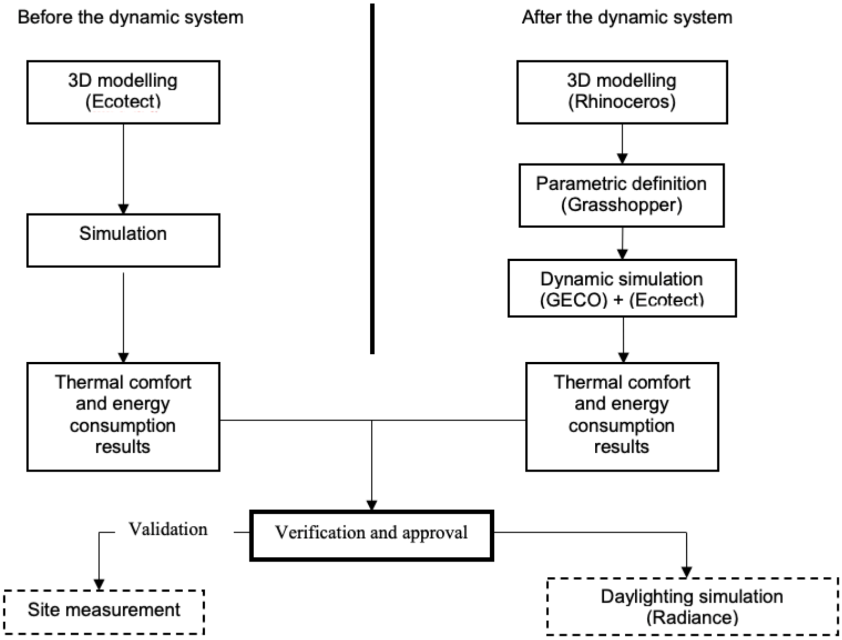


Fig. 3. Workflow diagram illustrating the development process. *Source*: Authors' own study

To optimise daylighting performance, semi-transparent PV modules are used as the panel material for the entire facade. This simulation process enables the selection of the best design among various options. It helps visualise how kinetic facade systems combined with PV modules interact with indoor spaces and predicts their performance early in the design process.

3.1. The case study

This study uses a virtual model of a typical office building illustrated in Fig. 4, featuring 60% curtain walls on the exterior facades. The building has a surface area of 859 m² and consists of four floors. The interior activities are divided into 58 workspaces. Regarding thermal properties, the external wall has a thermal transmittance (U-value) of 1.090 W/m²K, while the curtain walls are equipped with double-glazed units with a Solar Heat Gain Coefficient (SHGC) of 0.81. The office building is fully air-conditioned, except for the circulation spaces, which are naturally ventilated, with a cooling set-point temperature of 27°C and an efficiency of 95%. The focus of this phase of the simulation was to estimate indoor air temperature, direct solar radiation, and heat gains.

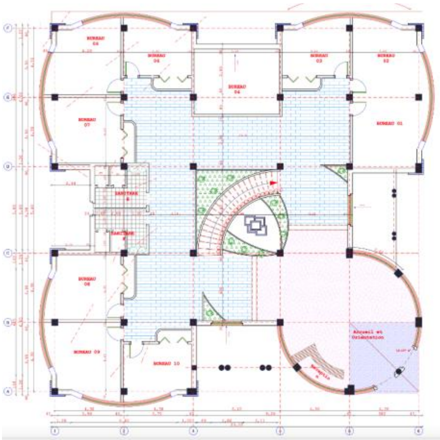


Fig. 4. a) Case study volume facing south-west, b) Typical floor plan of the office building. *Source*: Authors' own study

The simulations were performed with consideration of internal conditions to describe the energy gains occurring within the building. These include occupancy periods, with the building assumed to be fully occupied from Sunday to Thursday, between 8 am and 5 pm, with significant sensible and latent occupant gains, air infiltration, natural ventilation, and lighting gains. However, the energy consumption of appliances was not taken into account. The indoor conditions of the building can be controlled through parametric and real-time scenarios, applicable to different facades. For the assessment of thermal comfort and to calculate the overheating zone, the adaptive comfort standard in ASHRAE 55–2010 was adopted, intended for office buildings [65], where the comfort limit for the city of Biskra ranges between 22.9°C and 26.9°C. The principal architectural and thermal conditions are presented in Table 1.

Material properties for envelope components, including glazing, insulation, and thermal mass, were assigned based on typical values for office buildings in Biskra, Algeria, and aligned with local construction standards. These properties – such as thermal conductivity, specific heat capacity, and density – were integrated into the simulation model.

Table 1. Characteristics parameters of the tested case study. *Source*: Authors' own study

Space Parameters	Value	Unit
Number of floors	4	Levels
Dimensions	23 x 23 x13.94	m
Wall thickness (Ext)	0.30	m
Wall thickness (Int)	0.15 m	m
U-Value	1.090	W/(m^2.K)
	Curtain Walls Parameters	
Glass type	Double Glazing	
Visible light Transmittance	92	%
SHGC	0.81	
	Model surface visible reflectance	
Wall	50	%
Floor	20	%
Ceiling	80	%
Mashrabiya (White Paint)	80	%

	Internal Conditions	
Comfort zone limit	22.9 – 26.9	°C
Relative humidity	60%	
Occupancy	0.1	people/m^2
Fresh Air	12.5	L/s/person
Equipment's loads	12	W/m^2
Lighting loads	10.6	W/m^2
Lighting levels	300	Lux
	Radiance Parameters	
Ambient bounces	8	
Ambient division	25000	
Ambient sampling	4096	
Ambient resolution	512	

3.2. Dynamic shading configurations

To optimise indoor thermal comfort, a dynamic shading system was proposed and added to the office building facades. It is essentially based on a triangular modular system inspired by the traditional Mashrabiya shading device and imitates the dynamic facade designed by the studio Aedas in London for the "Al Bahar Towers" project in Abu Dhabi [66]. To ensure a continuous response to the solar trajectory, an algorithmic definition was developed using a parametric tool and applied to the three glazed facades – south, east, and west – of the building (Fig. 5). Each facade has its own specific motion programme, which is gradually closed according to a percentage determined by orientation and sun exposure. This approach enables control of solar radiation levels and calculation of shading element sizes for sun control in response to environmental changes.

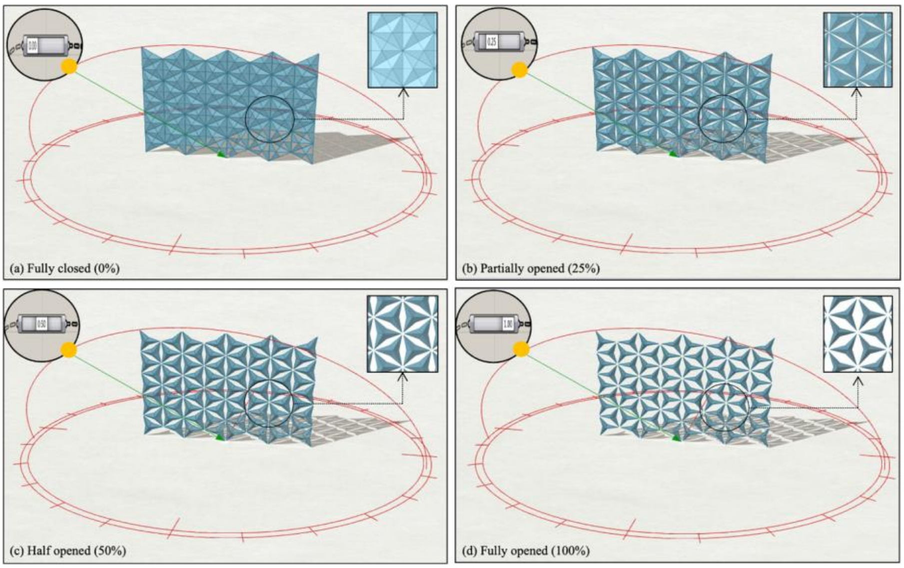


Fig. 5. Dynamic shading system elements with different opening variations (0%, 25%, 50%, and 100%). *Source*: Authors' own study

At this stage, dynamic simulations were conducted using Geco, a plug-in for Grasshopper and Rhinoceros modelling software. After importing the Grasshopper inputs – building geometry, dynamic shading device, and the configuration of the different thermal zones – Ecotect was used to perform the thermal and energy simulations, and the results were exported back to Grasshopper (Fig. 6). Real-time and typical meteorological year (TMY3) weather files for Biskra were used to ensure representative local climate conditions, imported via the Geco plug-in to support accurate solar radiation, temperature, and humidity data for the simulations.

Annual daylighting simulations of the kinetic Mashrabiya were conducted to assess the facade's performance under varying sunlight conditions. The simulations used the Ladybug/Honeybee 1.8.0 plug-in in combination with the Radiance daylight simulation engine. Radiance, a validated ray-tracing tool, is well suited for analysing complex spatial configurations and provides precise control over material properties related to light reflection and transmission [67]. Radiance simulation parameters are presented in Tab. 1.

Daylighting tests were performed on a workplane positioned 0.80 m above the floor, using a grid spacing of 0.25 m × 0.25 m. A total of 576 virtual sensors were deployed across three typical workspaces, each measuring 7 m × 7 m with a height of 3 m, located on the east, south, and west facades. Each workspace featured a single daylight source: a full-height glazed curtain wall protected by the proposed kinetic Mashrabiya.

The study employed the Useful Daylight Illuminance (UDI) metric to evaluate daylight quality. UDI quantifies the percentage of time that daylight levels fall within the 300–3000 lux range during occupied periods, which is considered beneficial for occupants [68,69]. Through this metric, the space area is categorised as follows: UDI Low (UDI < 300 lux), UDI (300 lux < UDI < 3000 lux), and UDI High (UDI > 3000 lux). Additionally, Daylight Glare Probability (DGP) was used to assess visual discomfort caused by glare in interior spaces [70]. Glare Autonomy (GA), another time-based metric simulated in this study, measures the percentage of occupied hours during which DGP remains below a defined threshold (e.g., DGP ≤ 0.35), indicating how often a space remains free from discomfort glare throughout a typical year [71].

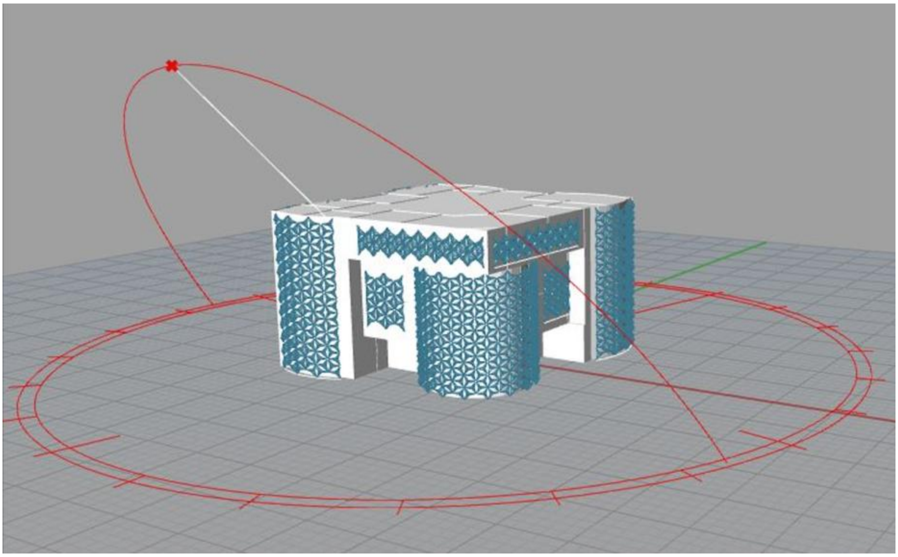


Fig. 6. Office building geometry imported into Rhinoceros software. *Source*: Authors' own study

4. Results and discussion

This section presents the simulation outcomes assessing the thermal and visual performance of the proposed kinetic Mashrabiya. The results compare the base case with the adaptive shading configurations across different orientations. Key indicators include solar radiation, indoor temperatures, energy consumption, UDI, and glare metrics.

The base case evaluation revealed high incident direct solar radiation, solar heat gains, and indoor air temperatures, all of which exceed the comfortable range and are associated with high energy consumption due to cooling demand. This can be attributed to the office building’s high window-to-wall ratio, which exceeds 60%, with no shading protection during the overheated period.

4.1. Incident solar radiation

The initial results indicate that the planar profile of the building facades, devoid of recesses or natural shading elements, results in exceptionally high levels of direct solar radiation. During the overheated period from 21 May to 21 August, the facades experienced a maximum average daily solar radiation level of 3200 Wh/m². This substantial solar heat gain can be attributed to the lack of architectural features that could mitigate the incident radiation. Consequently, this design flaw results in uniform exposure to solar radiation across large glazed areas, which in turn can lead to significant internal thermal discomfort for building occupants (Fig. 7).

The integration of dynamic shading devices proved effective in reducing direct solar radiation on the building’s facades. After installation, the levels of direct solar radiation decreased significantly, falling within the range of 400 to 1000 Wh/m² (Fig. 8b). This represents a 35% reduction in direct solar radiation. Such a notable decrease highlights the effectiveness of dynamic shading systems in reducing solar heat gain and enhancing the energy efficiency of buildings, especially in hot and dry climates. These findings align with those of Figliola et al. [72], who found that using a dynamic solar protection mechanism can substantially reduce the amount of direct radiation received by a vertical exterior surface. For example, the dynamic facades installed on the Al-Bahr Towers are expected to decrease solar radiation entering the building by 20%, demonstrating significant potential for improving energy performance [38].

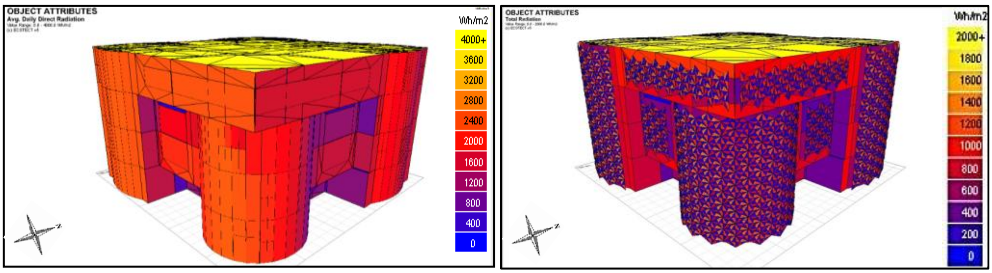
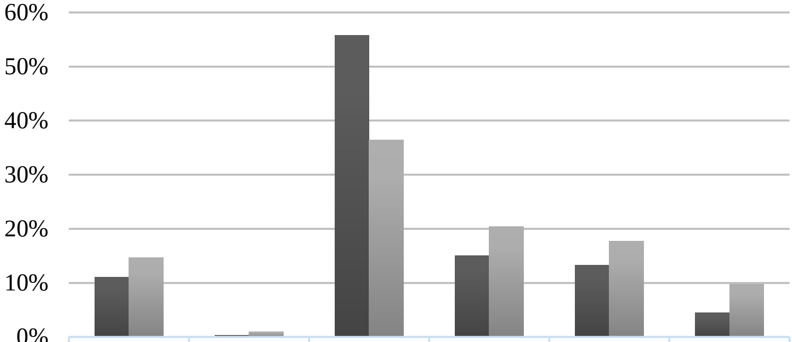


Fig. 7. (a) Daily mean incident direct solar radiation for the base case; (b) Daily mean incident direct solar radiation with dynamic shading applied. *Source*: Authors' own study

4.2. Passive solar gains

The simulation results provide a comprehensive analysis of the various external and internal heat exchanges in the studied office building. As shown in Fig. 8, the base case scenario indicates that direct solar gains are the primary source of passive heat gains, accounting for 55.8% of the total. This is followed by gains from ventilation (15%), internal sources (13.3%), and conduction (11.1%). The substantial contribution from direct solar gains highlights the significant impact of solar radiation on the building's thermal environment. This study primarily focused on direct solar gains due to their considerable contribution to passive gains and their direct connection to the proposed shading devices. Other factors, such as ventilation, internal gains, and conduction, were considered less critical in this context and therefore were not the primary focus of the analysis.



	Conduction	Indirect solar	Direct solar	ventilation	Internal gains	Inter-zonal gains
Base case	11,10%	0,30%	55,80%	15%	13,30%	4,50%
Dynamic Shading	14,70%	1%	36,40%	20,40%	17,70%	9,80%

Fig. 8. Annual passive building gains analysis. *Source*: Authors' own study

This imbalance in heat gains leads to internal thermal discomfort, particularly during the summer months. The high levels of direct solar gains necessitate increased use of air conditioning to maintain a comfortable indoor climate, resulting in substantial electricity consumption. The implementation of a dynamic shading system represents a notable improvement in managing these heat exchanges. The system effectively reduces direct solar gains by 19.4%, lowering them to 36.4% of the total annual gains. This reduction is crucial as it directly addresses the primary source of thermal discomfort and high cooling energy demand. These conclusions align with the findings of Hoffmann et al. [73], which confirmed that dynamic solar shading systems, adjusting to different solar angles throughout the day and across seasons, reduce solar heat gains during the summer months while optimising exterior views.

4.3. Thermal comfort

The analysis presented in Tab. 2 shows a significant extension of the overheating zone throughout the summer period, spanning from May to September, during which only 629 hours were spent in indoor comfort. The implementation of the dynamic shading Mashrabiya led to a notable improvement in thermal comfort during working hours. Annual comfort conditions increased from 21.3% to 38%, indicating more hours within the optimal temperature range of 22.9°C–26.9°C. This enhancement was especially evident in the transitional months of April, May, and October. Additionally, the percentage of overheated hours decreased from 56.5% to 34.2%, reflecting improved solar control during peak radiation periods. Conversely, the occurrence of sub-comfort thermal conditions associated with low indoor temperatures increased from 22.2% to 27.8%, suggesting better heat retention or moderated solar gains in cooler months. The most significant improvement occurred in April, when comfort hours rose from 22.2% to 77.8%.

Notably, the implementation of dynamic shading devices resulted in a maximum moderate air temperature of 38°C, representing a decrease of 4.0°C to 4.8°C from the initial indoor air temperatures observed in the case study. Additionally, the month of April was entirely free from overheating, resulting in 360 hours of work without the need for air conditioning.

Table 2. Percentages of thermal conditions based on annual working hours. *Source*: Authors' own study

Month /Condition	Base Case (No Shading)			Dynamic Shading		
	Cold (%)	Comfort (%)	Hot (%)	Cold (%)	Comfort (%)	Hot (%)
Jan	100.0%	0.0%	0.0%	100.0%	0.0%	0.0%
Feb	88.9%	11.1%	0.0%	88.9%	11.1%	0.0%
Mar	33.3%	44.4%	22.2%	55.6%	44.4%	0.0%
Apr	0.0%	22.2%	77.8%	22.2%	77.8%	0.0%
May	0.0%	11.1%	88.9%	0.0%	44.4%	55.6%
Jun	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%
Jul	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%
Aug	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%
Sep	0.0%	0.0%	100.0%	0.0%	22.2%	88.9%
Oct	0.0%	11.1%	88.9%	0.0%	55.6%	44.4%
Nov	44.4%	44.4%	11.1%	44.4%	55.6%	0.0%
Dec	100.0%	0.0%	0.0%	100.0%	0.0%	0.0%
Annual	22.2%	21.3%	56.5%	27.8%	38.0%	34.2%

These results are consistent with those of Sherif et al. [54], who examined external perforated solar screens and found them highly effective in enhancing thermal comfort, particularly in cities between 14°N and 40°N latitude, and Giovannini et al. [33], who investigated an innovative shading device, the Shape Variable Mashrabiya (SVM), which significantly reduced overheating and improved thermal comfort more effectively than selective glazing and Venetian blinds. Nevertheless, our findings exceeded those reported by Bagasi et al. [74], who highlighted the significance of the building envelope in reducing indoor temperature variations through the use of traditional Mashrabiya in historic Jeddah, Saudi Arabia. Their results showed indoor temperature reductions ranging between 2.1°C and 4.2°C, compared to 9.4°C to 16°C outdoors.

4.4. Daylighting simulation results

The results shown in Tab. 3 and Fig. 9 indicate that dynamic shading Mashrabiya can substantially enhance the availability of useful daylight across all facade orientations. For the east facade, the simulated UDI area increased from 43.0% in the base case to 57.78% with dynamic shading, marking a 34.4% improvement. On the south facade, UDI rose from 41.0%

to 58.32%, representing a 17.32% increase. The west facade, which had the highest base UDI at 46.0%, also experienced a notable rise to 58.30% after implementing dynamic shading, corresponding to a 26.7% increase.

Simulations also show that the UDI Low area, which indicates non-daylit spaces, increased across all orientations with dynamic shading. The UDI Low area on the east facade rose from 27.0% to 36.43%, on the south facade from 27.0% to 36.35%, and on the west facade from 27.0% to 39.15%. This suggests a trade-off, as the modelled improvements in overall useful daylight come with a moderate increase in spaces lacking sufficient daylight.

Table 3. Annual results of daylighting simulations. *Source*: Authors' own study

	Cases	UDI area (%)	UDI High area (%)	UDI Low area (%)	Glare Autonomy area (%)
Ea	Base Case	43.00	30.00	27.00	70.00
	Dynamic Shading	57.78	5.78	36.43	92.61
So	Base Case	41.00	31.00	27.00	62.00
	Dynamic Shading	58.32	5.32	36.35	90.35
W	Base Case	46.00	26.00	27.00	69.00
	Dynamic Shading	58.30	2.55	39.15	93.90

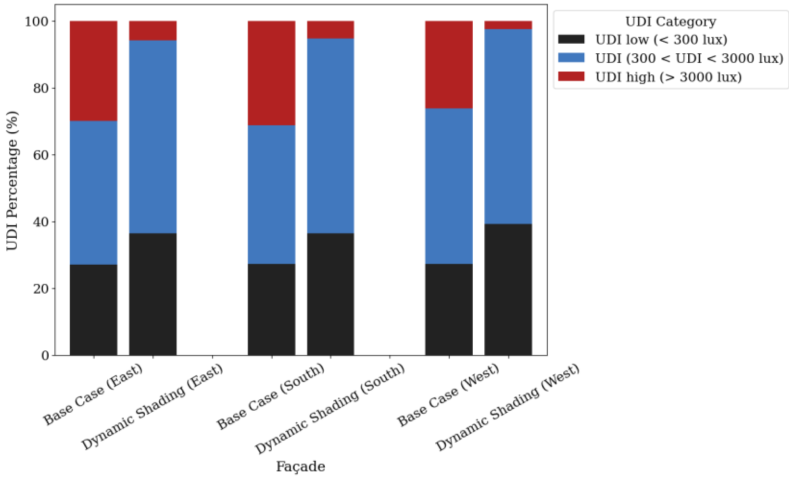


Fig. 9. Useful daylight illuminance (UDI) distribution across facades. *Source*: Authors' own study

Nevertheless, the results show that overall daylight performance becomes consistent across all facades, with simulated UDI values reaching about 58% after applying dynamic shading. These findings highlight the potential of dynamic shading strategies to deliver more uniform and optimal daylight conditions for various orientations, leading to a more even distribution of daylight throughout the space.

In terms of glare risk, represented by the UDI High area, dynamic shading was highly effective: the east facade saw an 80.7% reduction (from 30.0% to 5.78%), the south facade dropped by 82.8% (from 31.0% to 5.32%), and the west facade by 90.2% (from 26.0% to 2.55%). These reductions indicate that dynamic shading dramatically decreases the risk of excessive daylight, particularly on the west facade.

These findings are consistent with previous studies, confirming the effectiveness of dynamic shading systems in improving daylight performance. Comparable to the 33.6–50% increases in useful daylight area reported by Brzezicki and Chi et al. [36,75], our analysis found UDI improvements ranging from 26.7% to 42.2% across all facades. While earlier research emphasised both energy efficiency and daylight optimisation, our findings specifically demonstrate significant enhancements in daylight distribution, with simulated UDI values converging at approximately 58% following the implementation of dynamic shading.

4.5. Glare autonomy analysis

Assessing glare risk is particularly important in office spaces, where visual comfort directly influences occupant productivity and well-being. The initial results show that the base case Glare Autonomy values for the three different workspaces ranged from 62.0% (south) to 70.0% (east), with the west facade at 69.0%, reflecting moderate glare control under standard conditions. Dynamic shading systems substantially improved these results, increasing glare protection to 92.6% (east, +32.3%), 90.4% (south, +45.7%), and 93.9% (west, +36.1%). The most notable improvement occurred in the south facade, which initially performed the poorest but achieved comparable results to the other orientations with dynamic shading (Fig. 10).

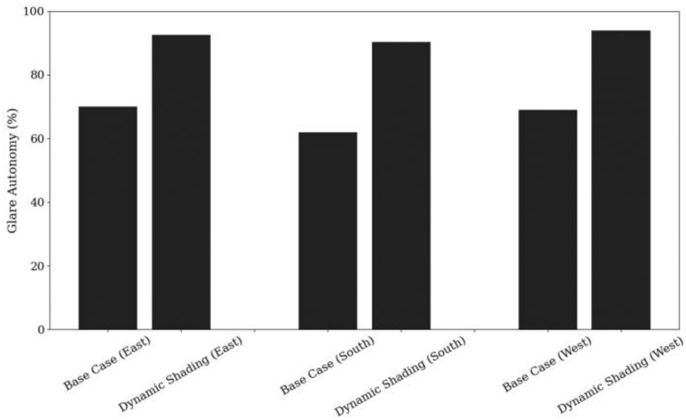


Fig. 10. Glare utonomy (GA) across facades. *Source*: Authors' own study

The west facade maintained its strong performance, reaching a final value of 93.9%, which demonstrates particularly effective glare mitigation for afternoon sun conditions. These consistent improvements across all orientations confirm that dynamic shading provides reliable glare reduction while preserving daylight access, making it particularly valuable for buildings with varied solar exposures. The system's ability to elevate even the lowest-performing facade (south) to over 90% glare autonomy underscores its effectiveness as a comprehensive solution for visual comfort.

4.6. Annual energy savings results

The total annual energy savings resulting from the use of dynamic shading facades compared to the base case are illustrated in Fig. 11. Prior to the integration of the shading system, the building exhibited substantial energy consumption, primarily driven by cooling loads during the summer months. The highest cooling demand was recorded in the hottest period of the year, with energy use rising sharply in early April and peaking at 22,955 kWh in July and August. Following this peak, consumption declined steadily to approximately 2,000 kWh by early November. The adoption of the dynamic shading system resulted in a significant reduction in energy use – up to 43% – with consumption dropping to 10,488 kWh and 10,729 kWh in July and August, respectively, and reaching minimum values of 1,336 kWh in February and 2,080 kWh in November. Despite a seasonal increase in energy use during the winter months, overall consumption remained moderate, underscoring the system's effectiveness in enhancing the building's energy efficiency.

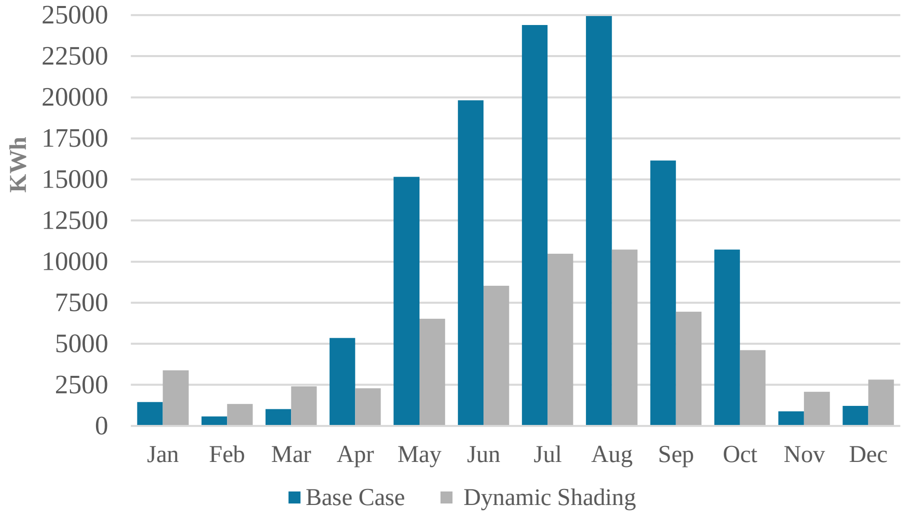


Fig. 11. Comparison of annual energy consumption. *Source*: Authors' own study

After evaluating the total energy consumption across the case study, we simulated the Energy Use Intensity (EUI) for three distinct workspaces located on the east, south, and west facades to assess the performance of the dynamic Mashrabiya system. On the east facade, cooling energy consumption decreased significantly from 193.3 kWh/m² in the base case to 108.1 kWh/m² with dynamic shading – a reduction of approximately 44%. Heating demand increased slightly from 6.9 to 12.1 kWh/m², and lighting energy rose from 4.7 to 6.4 kWh/m². A similar trend was observed on the south facade, where cooling demand dropped from 172.7 to 97.3 kWh/m² (44% reduction), while heating and lighting increased from 0.3 to 8.3 kWh/m² and from 4.7 to 6.7 kWh/m², respectively. On the west facade, cooling demand declined from 186.7 to 99.8 kWh/m² (a 47% reduction), accompanied by modest increases in heating and lighting (Fig. 12).

Overall energy savings are primarily driven by the substantial reductions in cooling loads, which more than offset the relatively minor increases in heating and lighting demands. In terms of total EUI, the east facade saw a 38% reduction (from 204.9 to 126.6 kWh/m²), the south a 37% reduction (from 177.7 to 112.3 kWh/m²), and the west a 43% reduction (from 199.7 to 113.7 kWh/m²). These results indicate that the dynamic shading system is most effective on the west facade, followed by the east and south facades.

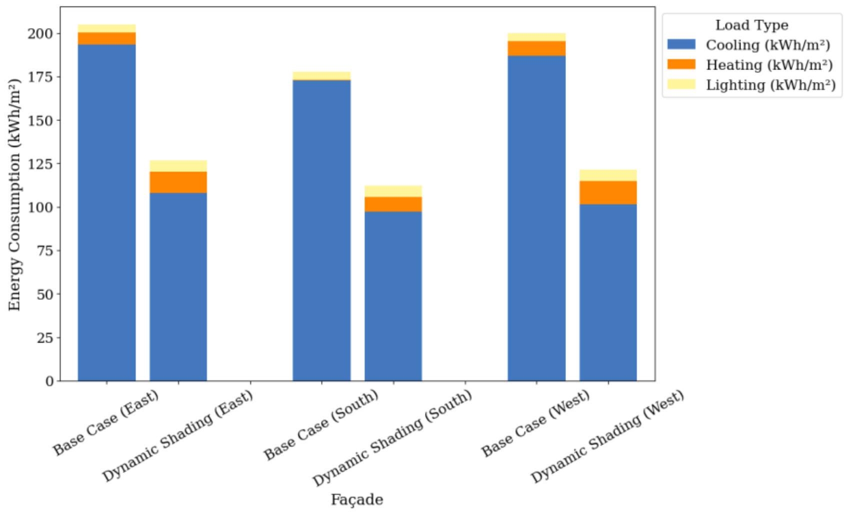


Fig. 12. Annual energy results across facades. Source: Authors' own study

Our findings demonstrate energy savings of 37–43%, primarily through reduced cooling loads, aligning closely with prior studies. Naik et al. [30] reported up to 60% savings using solar screens, while Krarti [51] found a 39% reduction with rotating overhangs. Batool et al. [52] observed 20–38.5% savings using dynamic louvres and fins, and Shafaghat et al. [53] reported 30% HVAC savings with hybrid double-skin facades. Compared to the 17.2% savings from Shape Variable Mashrabiya systems [33], our dynamic Mashrabiya demonstrates superior performance. Overall, our findings are consistent with, and in some cases exceed, the energy reductions reported in the literature, confirming the effectiveness of dynamic shading in hot climates.

5. Conclusions

For most climates, conventional building envelopes with static properties may not be an optimal solution. Adaptive building facades are considered a crucial step in improving the energy efficiency of buildings.

This paper has examined the possibilities for integrating dynamic shading facades in summer and winter, using parametric tools (Geco and Honeybee plug-ins for Grasshopper) and Ecotect for simulation modelling, proposed for improving energy performance and indoor comfort. One of the advantages of the parametric design approach using Grasshopper is its intuitive applicability to complex geometries.

Based on the presented simulation results, it was concluded that the integration of a dynamic shading device can significantly reduce direct solar radiation by 35%, leading to reduced energy consumption in the studied office building. Furthermore, quantification of the potential energy savings achievable with a daily adaptive facade showed a reduction of direct radiation by 17.9%, which translated into a 43% reduction in energy consumption, accompanied by a decrease in indoor air temperature ranging between 4.0°C and 4.8°C.

In addition to energy savings, the dynamic Mashrabiya system enhanced daylight availability, with Useful Daylight Illuminance (UDI) increasing by 17–34% across orientations. Although UDI Low (non-daylit) areas also rose moderately, lighting energy demand increased only slightly (from 4.7 to 6.4–6.7 kWh/m²), indicating a net benefit in visual comfort without significantly compromising lighting efficiency.

It is also noteworthy that this fieldwork has some limitations. The study relies on simulation tools that, while robust, cannot fully replicate real-world performance, especially in terms of occupant behaviour, dynamic weather conditions, or control system inefficiencies. Despite the application of these dynamic shading devices, which aim to minimise the overheating period by protecting the building from intense solar radiation characteristic of the dry and arid local climate, it was not possible to eliminate the entire overheating period. This limitation is due to the absence of coupling between this device and other passive or active cooling strategies. Based on the evaluation method applied, future research can further examine the differences and applicability of dynamic shading devices in various hot and dry zones of Algeria.

The findings have crucial implications for both energy efficiency and occupant comfort. High levels of direct solar radiation without adequate shading led to increased cooling loads, necessitating higher energy consumption to maintain indoor thermal comfort. In contrast, the implementation of dynamic shading devices can substantially reduce cooling energy requirements by limiting solar heat gain. This not only improves the building's energy performance but also aligns with sustainable building practices aimed at reducing carbon footprints.

Looking forward, this study will serve as a basis for optimising numerous other factors that may influence the effectiveness of dynamic facades in future work. Building on the insights gained from traditional Mashrabiya devices, we will be able to establish multi-criteria comparisons between dynamic and static shading devices on fully glazed buildings in hot and arid climates. This comparison will use the Mashrabiya concept to assess performance in conjunction with modern shading solutions. Additionally, we will evaluate the effect of orientation on the behaviour of dynamic shading devices and their impact on energy performance. Understanding how Mashrabiya orientation influences thermal comfort and energy efficiency can lead to more effective designs in hot climates. Furthermore, we aim to optimise the technical characteristics of these devices, including the selection of materials and structural types.

To address implementation challenges and validate simulation results, we are currently constructing a physical prototype of the kinetic Mashrabiya, along with a scaled test box. This will include addressing the identified limitations through: (1) occupant behaviour studies, (2) comprehensive cost-benefit analysis, and (3) durability testing of physical prototypes. This experimental setup will enable real-time performance monitoring under local climate conditions, helping to bridge the gap between simulated performance and practical application.

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