

SHADING THE GLASS FAÇADE: TEXTILE MEMBRANE STRATEGIES FOR EARLY-STAGE DESIGN FOR OFFICE BUILDING ENERGY- EFFICIENCY IN HOT-HUMID CLIMATES

PROTECCIÓN DE LA FACHADA DE VIDRIO: ESTRATEGIAS DE MEMBRANAS TEXTILES PARA EL DISEÑO EN ETAPAS TEMPRANAS PARA LA EFICIENCIA ENERGÉTICA DE EDIFICIOS DE OFICINAS EN CLIMAS CÁLIDOS Y HÚMEDOS

SOMBREAMENTO DE FACHADAS DE VIDRO: ESTRATÉGIAS COM MEMBRANAS TÊXTEIS PARA O PROJETO INICIAL DE EFICIÊNCIA ENERGÉTICA EM EDIFÍCIOS DE ESCRITÓRIOS EM CLIMAS QUENTES E ÚMIDOS

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ABSTRACT

In India's hot and humid climate, the prevalence of fully glazed multi-story (FGM) office structures results in higher energy use, primarily due to solar heat ingress through their extensive glass surfaces. While external shading is a well-known solution, designers often lack clarity on which shading type and, specifically, which material performs best during the critical early design stages. This study employs a simulation-based comparative framework to evaluate the integration of sustainable textile membranes across three distinct shading configurations: fixed solar screen, fixed diagrid, and dynamic shading. Using a representative, fully glazed, multi-storied office building model located in Chennai, the research employed Autodesk Revit for modeling, E-Quest for energy analysis, and Dynamo for parametric setup to conduct a multi-objective analysis. The procedures involved quantifying annual cooling loads to assess thermal performance, measuring Useful Daylight Illuminance (UDI) to evaluate visual comfort, and performing an Initial investment cost of the integrated shading devices to determine the economic payback period for each system compared to a non-shaded base case. Comparative analysis demonstrates the potential for considerable energy savings across all options. However, findings revealed pronounced disparities and contradictory trends between thermal and visual performance. Notably, the fixed solar screen emerged as the most effective solution, balancing energy reduction with economic viability. The study concludes that material-driven simulations are essential in the early design phase to enable well-informed choices that align sustainability with building performance.

Keywords

energy saving, fully glazed façade, textile membrane shading, dynamic shading, day lighting, hot and humid

RESUMEN

En el clima cálido y húmedo de la India, la prevalencia de edificios de oficinas de varios pisos totalmente acristalados (FGM, por sus siglas en inglés) conduce a un mayor consumo energético, principalmente debido a la ganancia de calor solar a través de sus extensas superficies de vidrio. Aunque el sombreado exterior es una solución reconocida, los diseñadores a menudo carecen de claridad sobre qué tipo de sistema de sombreado y, en particular, qué material ofrece el mejor rendimiento en las etapas críticas del diseño inicial. Este estudio emplea un marco comparativo basado en simulaciones para evaluar la integración de membranas textiles sostenibles en tres configuraciones de sombreado distintas: pantalla solar fija, estructura fija tipo diagrid y sombreado dinámico. Utilizando un modelo representativo de un edificio de oficinas totalmente acristalado y de varios pisos ubicado en Chennai, la investigación empleó Autodesk Revit para el modelado, eQuest para el análisis energético y Dynamo para la configuración paramétrica, con el fin de realizar un análisis multiobjetivo. Los procedimientos incluyeron la cuantificación de las cargas anuales de enfriamiento para evaluar el rendimiento térmico, la medición de la iluminancia útil de luz diurna (UDI, por su sigla en inglés) para evaluar el confort visual, y el análisis del costo inicial de inversión de los dispositivos de sombreado integrados para determinar el período de retorno económico de cada sistema en comparación con un caso base sin sombreado. El análisis comparativo demuestra el potencial de un ahorro energético considerable en todas las opciones. Sin embargo, los resultados revelaron diferencias marcadas y tendencias contradictorias entre el rendimiento térmico y visual. En particular, la pantalla solar fija se mostró como la solución más eficaz, al equilibrar la reducción de la demanda energética con la viabilidad económica. El estudio concluye que las simulaciones orientadas por materiales son esenciales en la fase inicial del diseño para permitir la toma de decisiones bien fundamentadas que alineen la sostenibilidad con el rendimiento del edificio.

Palabras clave

ahorro energético, fachada totalmente acristalada, sombreado con membrana textil, sombreado dinámico, luz diurna, cálido y húmedo

RESUMO

No clima quente e úmido da Índia, a prevalência de edifícios de escritórios de múltiplos pavimentos totalmente envidraçados (FGM, do inglês fully glazed multi-storey) acarreta um maior consumo de energia, sobretudo devido ao ganho de calor solar por meio de suas extensas superfícies de vidro. Embora o sombreado externo seja uma solução amplamente conhecida, os projetistas frequentemente carecem de clareza quanto ao tipo de sombreado e, especificamente, ao material com melhor desempenho nas fases iniciais de projeto, que são críticas. Este estudo emprega uma estrutura comparativa baseada em simulação para avaliar a incorporação de membranas têxteis sustentáveis em três configurações distintas de sombreado: tela de proteção solar fixa, malha diagonal (diagrid) fixa e sombreado dinâmico. A partir de um modelo representativo de um edifício de escritórios de múltiplos pavimentos totalmente envidraçado localizado em Chennai, a pesquisa utilizou o Autodesk Revit para a modelagem, o eQuest para a análise energética e o Dynamo para a configuração paramétrica, conduzindo uma análise multiobjetivo. Os procedimentos envolveram a quantificação das cargas anuais de resfriamento para avaliar o desempenho térmico, a medição da Iluminância Útil de Luz Natural (UDI, do inglês Useful Daylight Illuminance) para avaliar o conforto visual e o levantamento do custo de investimento inicial dos dispositivos de sombreado incorporados, a fim de determinar o período de retorno econômico de cada sistema em comparação com um caso base sem sombreado. A análise comparativa demonstra o potencial de economias de energia consideráveis em todas as alternativas. Contudo, os resultados revelaram disparidades acentuadas e tendências contraditórias entre os desempenhos térmicos e visuais. Destaca-se que a tela de proteção solar fixa mostrou-se a solução mais eficaz, equilibrando a redução do consumo de energia com a viabilidade econômica. O estudo conclui que simulações orientadas pelo material são essenciais na fase inicial de projeto para viabilizar escolhas bem fundamentadas que conciliem sustentabilidade e desempenho da edificação.

Palavras-chave

economia de energia, fachada totalmente envidraçada, sombreado por membrana têxtil, sombreado dinâmico, iluminação natural, ambiente quente e úmido.

List of Abbreviations

AES: Annual energy saving per sqmt of office floor area for space cooling
 ASE: Annual sun exposure
 API: Application programming interface.
 BIM: Building information model
 DOE-2: USA Department of Energy software for energy use.
 ECBC 17: Energy Conservation Building Code, Version 2017
 EEM: Energy-efficient measures in E-Quest.
 ESD: Exterior shading device
 FGM: Fully glazed multi-storied.
 GRIHA V19: Green rating for integrated Habitat assessment, version 2019
 HVAC: Heating, ventilation, and cooling
 IIC: Initial investment cost per m² of office area
 IT: Information technology
 LEED: Leadership in energy and environmental design
 P & C: Polygon clipping methods
 PTFE: Polytetrafluoroethylene
 PES: Polyester yarns
 PVC: Polyvinyl Chloride
 SCL: Space cooling load
 SHGC: Solar heat gain coefficient.
 TNEB: Tamil Nadu Electricity Board.
 UDI: Useful daylight Illuminance
 USD: United States Dollar
 VLT: Visual light transmittance
 WWR: Window-to-Wall Ratio

INTRODUCTION

Commercial buildings with fully glazed exteriors maximize natural light and contemporary aesthetics but consume more than double the energy of their international counterparts in India due to a lack of climate responsiveness (Naturak Resources Defense Council [NRDC] & Administrative Staff College of India [ASCI], 2014). In Chennai's hot and humid climate (13.0827 N, 80.2707 E), daytime temperatures require year-round, constant air conditioning. Implementing effective exterior shading based on orientation can significantly reduce cooling loads in these highly glazed facades (Chi et al., 2018), proving far more efficient than internal blinds (Arumugam & Ramalingam, 2024). Crucially, 80% of a building's lifecycle energy performance is determined during the early design stage, making the initial integration of material-specific glazing and shading data vital (Hwang & Chen, 2022; Bhatia et al., 2024). Among the alternatives, architectural textile membranes allow for structurally viable, cost-effective, and complex freeform geometries. They protect structures from UV radiation and harsh weather (São João, Carvalho, & Figueiro, 2016) while their lightness, transparency, and high solar reflectivity minimize solar heat absorption (Tian et al., 2020).

In tropical regions, adaptive sun shading balances visual and thermal efficiency across all seasons. Designing these smart, dynamic systems requires complex cross-disciplinary engineering (Al-Masrani & Al-Obaidi, 2019), as exemplified by Abu Dhabi's Al-Bahar Towers, which

use folding, translucent PTFE fabric umbrellas inspired by traditional Mashrabiya. However, current knowledge regarding façade textile membranes remains fragmented, with applications concentrated in the Middle East and rarely implemented in the tropics. This study looks to fill that gap by comparing a solar screen, a diagrid, and a dynamic shading system—all with the latest textile fabric membrane—to determine the highest energy efficiency, optimal visual comfort, and most cost-effective initial investment for fully glazed multi-story office structures in Chennai.

TEXTILE MEMBRANES FOR FAÇADE SOLAR SHADING

Membrane materials are increasingly popular for their aesthetic appeal and practical use as ultra-lightweight wrapping envelopes or façade cladding in building retrofits (Al-Masrani & Al-Obaidi, 2019). These membranes offer environmental efficiency, organic design, high adaptability, semi-transparency, rapid installation, and minimal upkeep. Made by coating high-performance synthetic fibrous structures with novel polymers, these composites exhibit exceptional durability, hydrophobicity, flame/UV resistance, load-bearing capacity, and tear resistance (Nurazzi et al., 2021).

Commonly used for solar protection and architectural envelopes, these diverse mesh designs maintain two-way visibility and create artistic effects on glass structures (Procaccini et al., 2024). They typically consist of woven Polyester (PES) threads coated with polyvinyl chloride (PVC) or glass fiber strands covered with polytetrafluoroethylene (PTFE) or silicone. Available in various hues, strengths, and customizable prints, these fabric screens provide cost-effective, high-performing thermal insulation (Comitti et al., 2024). Glass/PTFE membranes are the most durable, often lasting over 30 years due to weather resistance (Wang et al., 2022), whereas PVC membranes are less resilient, lasting 10–15 years under high UV exposure (São João, Carvalho, & Figueiro, 2016). Ongoing research is supported by TensiNet (n.d.) and the COST Action TU 1303 initiative (Mollaert et al., 2017).

Serge Ferrari developed Frontside View 381 (Serge Ferrari group, n.d.b), a recyclable PVC-coated PES yarn membrane. It has been used for aesthetics and climate control in renovations like the Hotel Oasis and the 2008 Westraven Building modernization in Utrecht. Lightweight and translucent, these membranes are integrated into kinetic facades to dynamically respond to solar altitude. While available in India, it is primarily used for aesthetics rather than energy efficiency. However, in warmer climates, Frontside View 381 significantly reduces solar heat gain and energy consumption (Ciampi et al., 2022).

This study utilizes Serge Ferrari's Frontside View 381 for both fixed and dynamic shading systems. Existing literature

confirms that dynamic shading has not been evaluated against fixed systems (like diagrid fins and screens) in hot and humid climates. Furthermore, while exterior shading materials significantly affect the performance of highly glazed façades, there is limited data on how dynamic, diagrid, or screen shading influences the energy and daylight performance of glazed buildings in hot and humid climates like Chennai.

METHODOLOGY

This study employs a simulation-based, parametric workflow to evaluate external shading systems for a Fully Glazed Multi-storied (FGM) office building in Chennai's hot-humid climate. The methodology integrates energy analysis, daylight simulation, and computational modeling within a unified digital environment for comparative evaluation.

- **Base Model Development**

A representative fully glazed office building was modeled in Autodesk Revit based on typical contemporary office typologies (standard floor plates, glazing ratios, occupancy schedules, and material properties). The unshaded building serves as the reference base case. Chennai's Energy Plus Weather (EPW) data was integrated to accurately simulate local solar radiation, temperature, and humidity levels.

- **Shading System Modeling**

Three external shading typologies were applied to the base façade geometry:

- Diagrid fins (angled structural members)
- Solar screen system (perforated textile membranes parallel to the façade)
- Dynamic shading system (movable kinetic panels with adjustable opening ratios)

To isolate the effects of geometry and operational behavior, all three systems used the same Serge Ferrari Frontside View 381 textile membrane.

- **Parametric Control using Dynamo**

The dynamic shading configurations were developed parametrically using Dynamo (n.d.) within Revit. Custom scripts calculated solar vectors based on façade orientation, date, and time, enabling the kinetic panels to adjust their opening ratios dynamically in response to real-time solar exposure.

- **Energy Simulation**

Thermal performance was analyzed using E-Quest. The Revit model was exported and calibrated with identical operational parameters (HVAC setups, occupancy schedules, lighting loads, and glazing characteristics). Annual cooling energy consumption for each system was compared against the base case to calculate the percentage reduction in cooling demand.

- **Daylight Analysis**

Visual comfort and indoor daylight availability were assessed using Autodesk Insight, specifically measuring Useful Daylight Illuminance (UDI). This step ensured that minimizing solar heat gain did not inadvertently compromise necessary indoor daylight penetration.

- **Economic Evaluation & Comparative Framework**

Initial investment costs (fabrication, material, and installation) were estimated for each system. Payback periods were then calculated using the simulated annual energy cost savings to assess long-term financial feasibility. To ensure a fair comparison, all simulations used identical boundary conditions and analysis periods, isolating geometry and system behavior as the primary performance variables.

Overall, the methodology combines parametric modeling, performance simulation, and economic analysis to provide a comprehensive evaluation of shading strategies. The integration of tools such as Revit, Dynamo, E-Quest, and Insight enables a replicable and scalable workflow for early-stage design optimization in climate-responsive architecture. The overall methodology flowchart is shown in Figure 1.

RESEARCH CONTEXT

Climatic Context of Chennai, India

Chennai, situated at 13.0827°N latitude and 80.2707°E longitude, has a warm, muggy climate. The city's position on the thermal equator and coastline prevents drastic seasonal temperature fluctuations. The warmest period occurs from late May to early June, with peak temperatures ranging from 37 to 41 °C. January is the coolest time, with temperatures ranging from 19 to 25 °C.

The selected specimen shading membrane

Frontview 381-3109, manufactured by Serge Ferrari group (n.d.a), is a premium PVC-coated polyester fabric with an open structure that is pre-tensioned during coating (S. A. Industries BEC, 2014). Table 1 presents a summary of the manufacturer's technical specifications. The available data on transmission and reflection are based on measurements taken at normal incidence, without considering other angles.

Simulation tools

This study uses swift, straightforward simulation tools during the initial design phase to identify the optimal shading solution. The workflow employs E-quest for energy modeling alongside Revit + Dynamo for geometric construction, illumination analysis, and shadow/incident angle calculations.

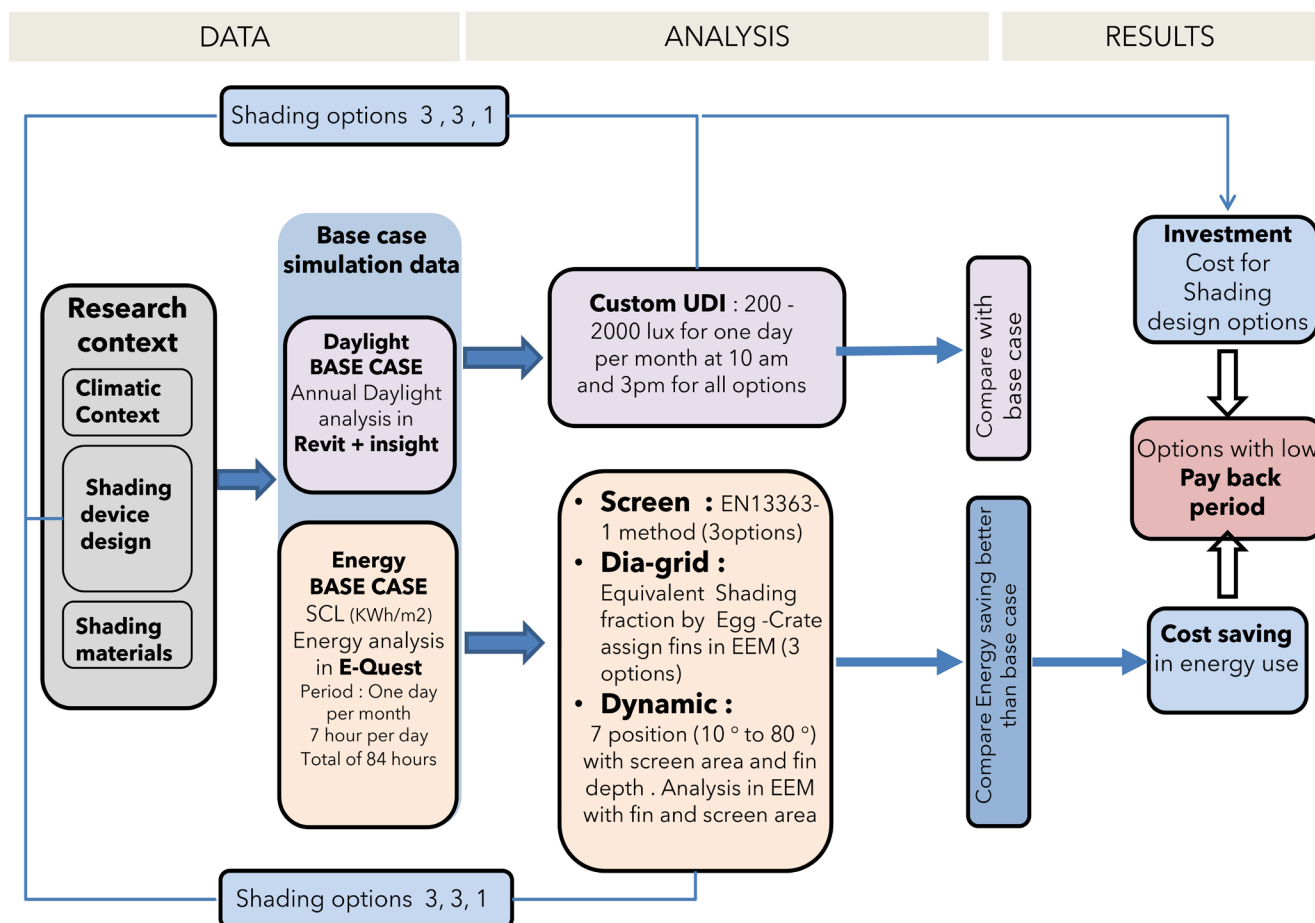


Figure 1. The methodology flow chart. Source: Preparation by the Authors.

Material property	Value / specifications	Image of application	Image of sample
Color	Ash - Blond - 381-3109		
Material	P.V.C. coated polyester		
Yarn	1100 Dtex PET HT		
Weight	600 grams / m ²		
Thickness	1.1 mm		
Tensile Strength (wrap/weft)	330/330 daN/5cm		
Tear resistance (wrap/ weft)	65/65 daN/5cm		
Temperature resistance	- 30 °C to 70 °C		
Flame retardancy	Euroclass B-s2, do/EN 13501-1		
Thermal transmission (Ts) %	29		
Thermal reflection (Rs) %	36		
Thermal Absorption (As) %	35		
Visual transmission (Tv) %	29		

Table 1. Technical specification of Front View 381-3109. Source: Serge Ferrari group, (n.d.b)

- **E-Quest:** Derived from DOE-2, this user-oriented software provides hourly dynamic heat characteristics to analyze building envelope heat transfer, delivering professional-grade results with minimal input (Barozzi et al., 2016). It incorporates Energy Efficiency Measures (EEM) as a sub-simulation of the base model. This study uses the Detailed Design Wizard to calculate the Space Cooling Load (SCL)—the hourly and annual cooling energy (kWh) removed from the cooling coil—which represents a major energy use in hot climates like Chennai.
- **Revit + Insight:** Revit establishes the building geometry, while Insight functions as an integrated plug-in for daylight simulation based on the defined geometry, spaces, location, and components.
- **Dynamo:** Operating as a visual programming application within Revit, Dynamo uses a node-based computational method to encode the design workflow. In this study, shading device geometry is imported into Dynamo to calculate the shading fraction (the percentage of the glazed panel shaded) at specific times and orientations.

DESIGN OF THE SHADING DEVICES

FIXED SOLAR SCREENS

Perforated screens offer visual benefits for minimalist design over projecting fins or louvers. Their effectiveness depends on material, perforation ratio, depth, geometry, and location, with traditional architectural elements further enhancing thermal comfort in hot climates (Alhmoud & Alhmoud, 2024). This study positions a flat screen 20 cm from the glazing plane. The base curtain panel measures 4 m × 2 m, with a floor height of 4 m. The screen covers the top and bottom of the panel, leaving a central viewing gap. The screen area is varied across three configurations: 60%, 80%, and 100% (Figure 2).

FIXED DIAGRID FINS

Diagrids, which emerged in modern steel construction around 2003, use diagonal bracing on framed outer supports (Brake, 2011). This diagonal egg-crate shading system effectively manages daylight harvesting, glare control, and exterior views. This research employs a 4 m × 4 m grid positioned 20 cm from the glazed panel, with fin depths of 400, 500, and 600 mm. Diagonal fins are placed at floor levels and at the center of the panel grid (Figure 3).

DYNAMIC SHADING DEVICE

Dynamic shading systems enhance occupant comfort by adapting to real-time environmental conditions (Sorooshnia et al., 2023). Kinetic rotation and folding mechanisms can reduce cooling and lighting energy

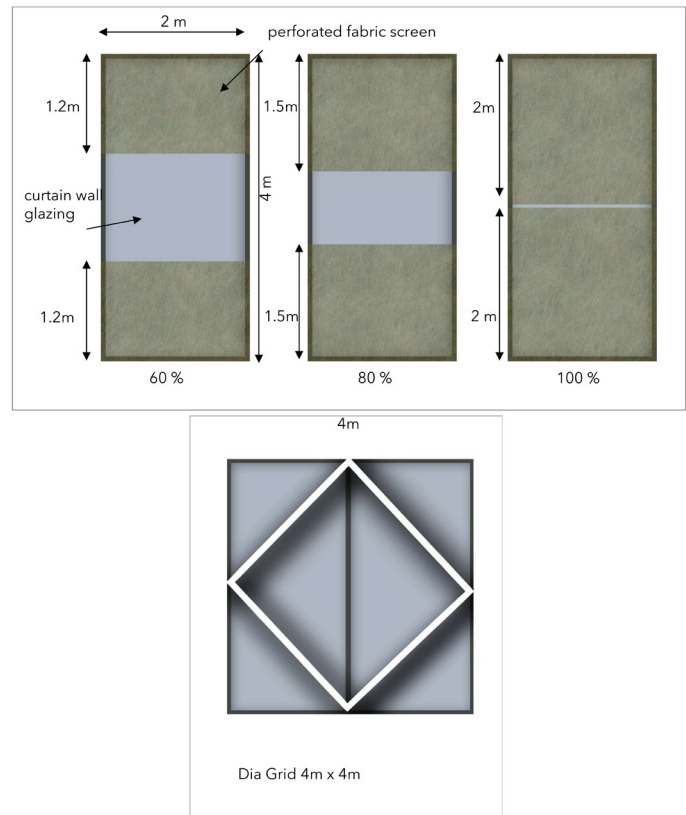


Figure 2. Solar screen options: 60%, 80%, and 100% of the glazing panel area & Diagrid front view. Source: Preparation by the Authors.

demands by 19%–24% in tropical regions (Shi, Tablada & Wang, 2020). This study uses a dynamic solar screen with perforations and an umbrella-type folding mechanism. Operated by a central pneumatic piston, the device extends or retracts in a manner similar to the Al-Bahr Tower system. The 4 m × 4 m panel contains four diagonal arms that fold across seven stages (Figure 3). Modeled via a pattern-based curtain panel family in Revit, the system opens or closes by adjusting the central axis height. The seven operational stages range from 20° to 80° at 10° intervals

ENERGY PERFORMANCE

Annual energy simulations were performed using a standard single-story open-plan office model, consistent with those employed in prior research (Thalfeldt, Kurnitski & Voll, 2015). All three types of shading devices are applied only to East, West, and South orientations. This research did not consider the angle of the fins, the thermal properties of the shading material, or the solar transmittance through the shading material.

ANALYSIS PERIOD

- One day per month: The dates used for simulation are one day per month, the 21st day of every month

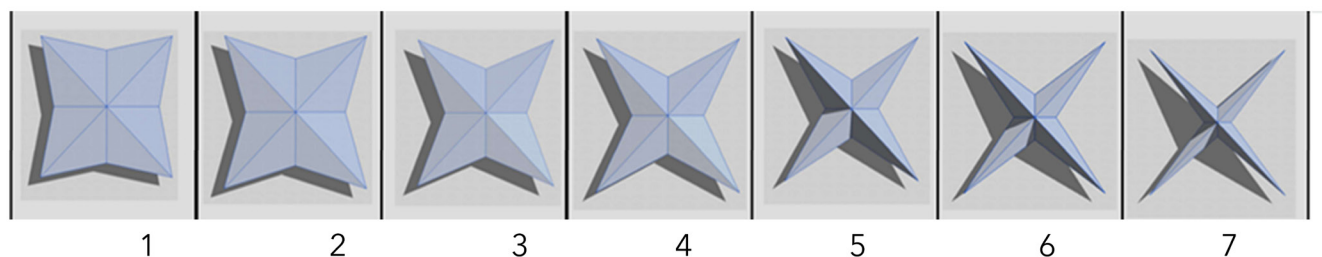


Figure 3. Image of the dynamic shading geometry and 7 folding stages. Source: Preparation by the Authors.

(Coakley, Raftery, & Keane, 2014). As the dynamic shading is based on hourly data, it would be complex to take all days of the year as the analysis days. Data from one day per month is compiled to produce the annual results.

- Shading Analysis Hours: For the influence of the shading design on the energy, this is taken from 10 am to 4 pm, as it is the peak hours for solar radiation on the façade plane.

The covers 12 days at 7 hours per day, totaling 84 hours out of the 2880 daytime hours.

BASE CASE ENERGY MODEL

Based on prior research findings, a shading element is necessary for a typical story in Chennai, where the glazed surface area exceeds 25% of the office floor area (Chockalingam, 2021). The base-case model is created in E-Quest with more than 25% of the office's glazing area. The office building is a rectangular block measuring 30m x 45m, with the longer side facing east/west, and 60 meters in height. The building was created with 15 floors, with a floor-to-floor height of 4m. Simulation was run in the floor-multiplier mode for the mid-floors (between the ground and top floors). The total built area is 13,500 m², and the total fully air-conditioned office area is 10,800 m². Each standard floor has 1350 m², with 1080 m² of office area on each floor, four zones per orientation, and a non-air-conditioned core area in the center, as shown in Figure 4.

The following are the assumptions for the energy analysis based on default data and from case studies (Chockalingam, 2021):

- Location & Climate : Chennai & weather data*. E.P.W. file.
- Project North : True North
- Office space planning/activity zones : 50% Open office plan with 25 % cubicles, 10% corridors, 5% lobby, and 10% utilities.
- Floor-to-floor height : 4 meters
- Floor to false ceiling height : 3 meters
- Zoning pattern : perimeter and core
- A/C Zones : office area is 80% air-conditioned, and 20% core area as non- A/C
- Occupancy rate : 12.5 persons per m²
- Occupancy hours : 9 am to 6 pm & 6 days a week.
- Walls : 150mm A.A. block with no insulation.
- Glazing : single grey-tinted clear 6mm thick in an aluminum framework
- Glazing no 1205 as per DOE glass Library with SHGC : 0.59
- Visual transmittance : 0.43
- WWR % : 95 % in all orientations.

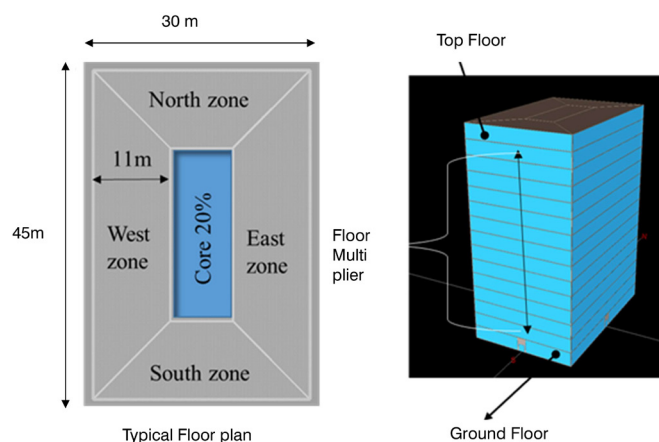


Figure 4: Base case model in E-Quest. Source: Preparation by the Authors.

- Window size : 2m x 4m.
- Lighting load : 1 watt / m²
- Power load : 2 watts/m²
- Cooling set point : 23.3 °C
- HAVC Type : VAV with a chilled water system per floor.
- Supply air temperature : 12 °C
- Relative Humidity (RH) : 50 %
- Latent Heat gain per person : 58 W
- Sensible heat gain per person : 73W

The energy base-case model is created using a detail design wizard to obtain hourly SCL and EUI results. The simulated results for each hour of the day produce a total of 3,000 hours (9 am to 6 pm, 6 days a week, with SCL density of 96.5 kWh/m² and EUI of 219 kWh/m²).

ENERGY ANALYSIS FOR SOLAR FABRIC SCREEN

EN 13363-1 offers a straightforward approach to revising the SHGC of façade glazing. Laboratory findings demonstrate a reduction in SHGC for specific glazing types when paired with particular solar screens. In E-quest, Energy-Efficient Measure (EEM) façade components are created by incorporating an additional glazing type with

Description	Value	Units
Stg (solar transmittance of glazing)	0.46	
St (solar transmittance of fabric)	0.29	
g (SHGC of glass)	0.59	
Sa (solar absorbance of fabric)	0.35	
Ug - U factor of glazing	1.19	w/m2
G	1.14	w/m2
G2	10	w/m2
G1	5	w/m2
g tot	0.23	
Glazing no. equal to gtot	1403	

Table 2. The EN 13363-1 method for the selected glazing and the revised SHGC value as per the equations. Source: Preparation by the authors.

a lower SHGC value, as determined by the EN13363-1 method (Carletti, Sciarpi, & Pierangioli, 2014). To determine the adjusted SHGC for the chosen single-tinted glass from the DOE glass library, specifically no 1205 (SHGC = 0.59) (Lawrence Berkeley National Laboratory – James J. Hirsch & Associates, 2009), Equation 1 and Equation 2 must be used.

$$g_{tot} = S_{tg} + S_a(G/G_2) + St((1 - g)G/G_1)$$

(Equation 1)

Where g_{tot} is the revised SHGC by adding an exterior screen over the glazing, S_{tg} is the Solar transmittance of the glazing, S_t is the solar transmittance value of the screen, S_a is the solar absorbance of the screen, G_1 and G_2 are fixed values defined by the standards, g is the SHGC of the glazing, and G is derived from equation 2.

$$G = (1/U_g) + (1/G_1) + (1/G_2)$$

(Equation 2)

Where U_g is the U-value of the glazing. The area of the solar screen is revised in the base-case model to include another type of glass with an SHGC of 0.23, as per the DOE glass library no. 1405. In the EEM of the E-Quest base case model, the window glazing is replaced with a solar screen (60% screen area), as shown in Figure 2. The 84 hours for the analysis period are compared with the base case in Table 2.

ENERGY ANALYSIS FOR THE DIAGRID SHADING DEVICE

In E-Quest, complex fins like the diagonal egg crate cannot be created. Hence, we have created equivalent

horizontal and vertical fins based on the shadow fraction of the diagrid fins. The Dynamo script is used to calculate the shadow area using the P & C method (Murta, 2015) for the Diagrid, as shown in Figure 2, and the equivalent egg-crate fin's depth, as shown in Table 3. In E-Quest, we create window shading using the table and run EEM to get the space cooling energy use.

ENERGY ANALYSIS FOR THE DYNAMIC SHADING DEVICE

The dynamic shading device combines fins and a screen that transforms its shape according to the sun's angle. The Dynamo script calculates the shading panels' sun angle and the corresponding open angle. To simplify, only 7 positions were taken, ranging from 10 ° to 80 ° in 10 ° intervals. Using the geometric calculations from the elevations, we can determine the screen area and fin depth for each step, as shown in Table 5. The calculations for this information are performed over the 84-hour analysis timeframe. For each hour, the base case model is updated with revised specific fin depth and screen area as an EEM simulation. Subsequently, the results from 84 EEM simulations are aggregated and evaluated against the base case for the identical analysis period. Energy savings exceed those with no shading for all types of shading devices, as shown in Figure 6.

As illustrated in Table 4, the computed incidental angle is shown for each hour and orientation on March 21st. Based on this, the dynamic device steps were assigned, and their equivalent WWR % and fin depth were assigned in the EEM runs. For example, at stage one, WWR % is 20, and the fin depth from the shadow area calculation is 400mm, no. 2, as shown in Table 5. And for stage 7, WWR is 80% with a fin depth of 200 mm (no. 2), as shown in Table 4. The Sun's path, the Sun vector, and the incident angle of the dynamic panel calculation

DIAGRID 4m x 4m	Hour	Orientation	Diagrid SF %			Equivalent Fin SF %		
			600	500	400	800	660	520
21 st March	11 am	East	55	47	37	52	44	33
	3 pm	West	42	35	28	40	34	25
	11 am	South	72	60	48	74	62	46
	3 pm	South	72	60	48	82	69	51
21 st June	11 am	East	70	59	47	49	41	31
	3 pm	West	49	41	33	35	30	22
21 st September	11 am	East	65	54	43	61	52	38
	3 pm	West	37	31	25	35	29	22
	11 am	South	73	61	49	71	66	44
	3 pm	South	73	61	49	88	74	55
21 st December	11 am	East	55	46	37	69	58	43
	3 pm	West	37	31	25	45	38	28
	11 am	South	27	22	18	29	24	18
	3 pm	South	24	20	16	32	27	20
TOTAL			751	628	503	762	648	476
Average			53.6	44.9	35.9	54.4	46.3	34.0

Table 3. Table of equivalent H.F. and V.F. depth as per SF% of the Diagrid options. Source: Preparation by the authors.

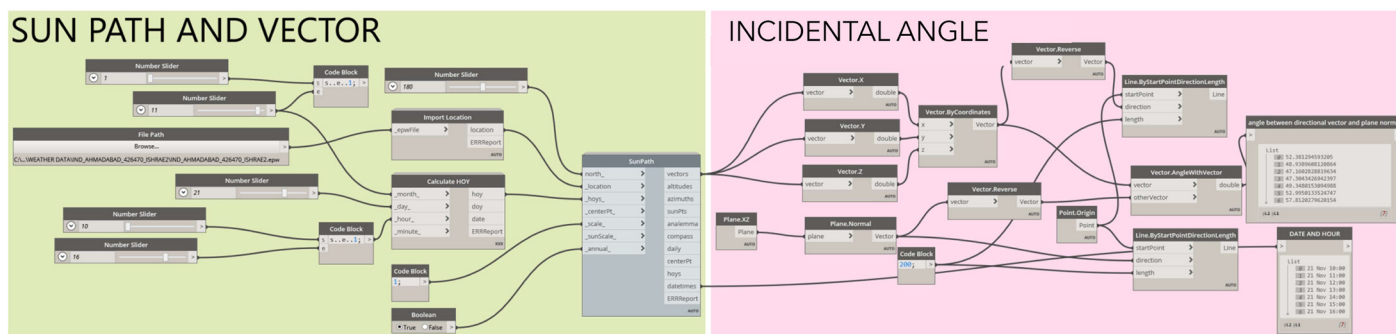


Figure 5. Sun path, sun vector, and the incidental angle of the dynamic panel calculation script in Dynamo. Source: Preparation by the authors.

21 st March - orientation	Hour - Dynamic device step number						
	10am	11am	12pm	1pm	2pm	3pm	4pm
East/ West	42	27	0	4	19	24	49
South	17	21	23	23	22	19	15
East/ West	5	3	1	1	2	3	5
South	2	3	3	3	3	2	2

Table 4. Incidental angle on March 21st and its dynamic shading device step no for each hour and orientation. Source: Preparation by the authors.

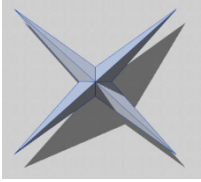
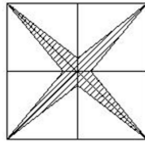
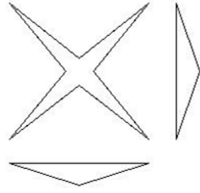
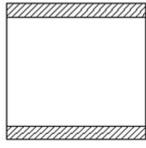
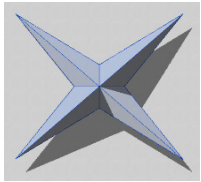
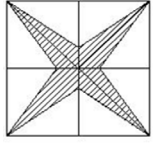
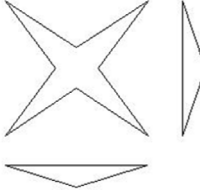
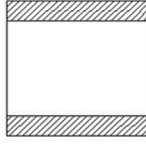
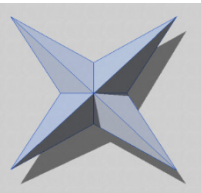
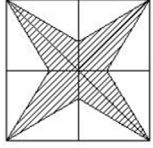
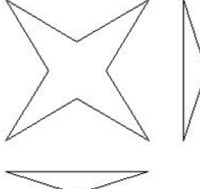
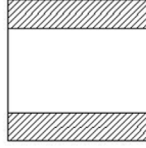
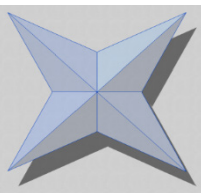
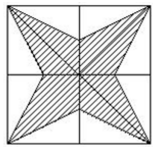
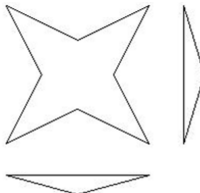
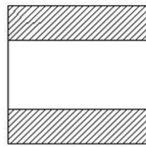
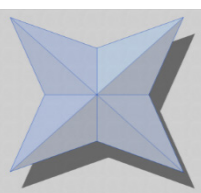
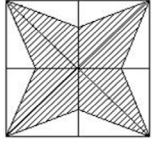
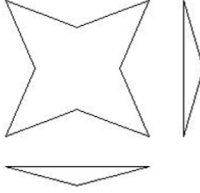
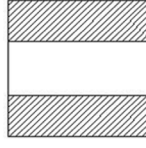
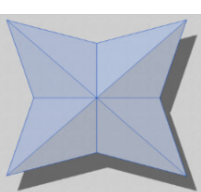
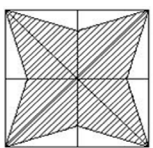
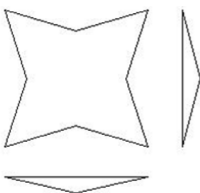
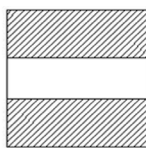
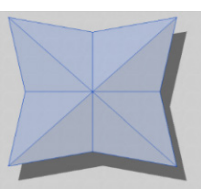
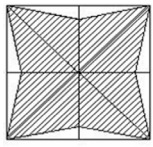
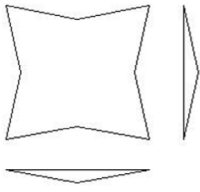
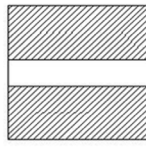
Stage	Image	Description	Values	Plan view	View of the fin area	View of the screen area
1		Stage	8	 80%		
		WWR	20%			
		Projection	650			
		G2	400 x 2			
		HF/VF dep	375			
2		Stage	7	 70%		
		WWR	30%			
		Projection	630			
		G2	600 x 2			
		HF/VF dep	315			
3		Stage	6	 60%		
		WWR	40%			
		Projection	610			
		G2	800 x 2			
		HF/VF dep	305			
4		Stage	5	 50%		
		WWR	50%			
		Projection	575			
		G2	1000 x 2			
		HF/VF dep	287			
5		Stage	4	 40%		
		WWR	60%			
		Projection	532			
		G2	1200 x 2			
		HF/VF dep	266			
6		Stage	3	 30%		
		WWR	70%			
		Projection	475			
		G2	1400 x 2			
		HF/VF dep	237			
7		Stage	2	 20%		
		WWR	80%			
		Projection	400			
		G2	1600 x 2			
		HF/VF dep	200			

Table 5: The 7 steps of the dynamic shading device and its respective fin depth and percentage of screen area for E-Quest E.E.M. runs. Source: Preparation by the authors.

script in Dynamo are shown in Figure 5.

OBSERVATIONS

1. The energy saved by the solar screen is the highest for the shading devices, followed by the Dynamic and the Diagrid options, as shown in Figure 6
2. The solar screen's energy saving of 60% of the glazed area is almost equal to the dynamic shading at 50% of the glazed area, as shown in Figure 6
3. The increased energy saving is greater with the screen area than with the Diagrid fin depth, as shown in Figure 6.

DAYLIGHT PERFORMANCE

Annual daylight analyses were conducted using an open-plan office model for each shading device type. The visual and optical properties of the fabric were specified in the Revit model, with a visible light transmittance (VLT) of 29%. Daylight analysis was conducted using the Insight plugin Lighting Analysis for Revit. The Useful Daylight Illuminance (UDI) was employed as the metric; the analysis was performed on the 21st day of each month (García-Martín et al., 2025), as dynamic shading uses hourly data. Shading performance was evaluated at 10 am and 3 pm (Ahmed, 2021)—10 am for the east, 3 pm for the west, and both times for the south orientations. The analysis adhered to a threshold range of 200-2000 lux per ECBC (NRDC & ASCI, 2017), encompassing 24 hours of the total 2880 occupancy hours.

BASE CASE DAYLIGHTING MODEL

The base-case geometry was developed in Revit, incorporating shading-device options for each floor. The simulation assumptions are as follows:

- No window coverings or interior partitions are present.
- Reflectivity is set at 80% for ceilings, 20% for floors, and 50% for walls
- Glazing is specified as no 1205 from the D.O.E. glass library, with a visual transmittance of 0.43
- The analysis plane is positioned at 0.8 meters, with a grid size of 0.6 x 0.6 meters
- Analyses are conducted at 10 am and 3 pm
- The shading fabric has a visual light transmittance (VLT) of 0.29 and an optical reflectance of 30%
- The sky component is based on annual weather data from Chennai

Twelve analyses are conducted one day per month at 10 am and 3 pm, with the results averaged and presented in Figure 7.

OBSERVATIONS

1. The Diagrid configuration demonstrates superior performance, as shown in Figure 7.

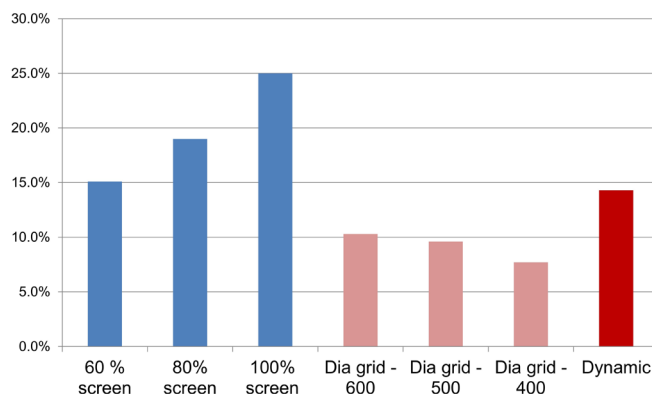


Figure 6. Energy-saving is better than no shading at all with the types of shading devices. Source: Preparation by the authors.

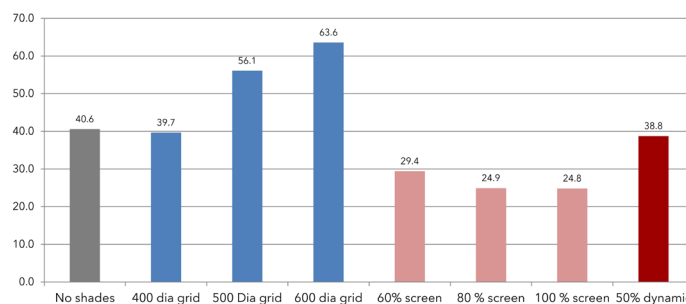


Figure 7. Daylight analysis by a custom range of 200-2000 lux for the percentage of the usable floor area at 9 am and 3 pm. Source: Preparation by the authors.

2. The solar screen performs below the no-shade baseline, while dynamic shading achieves results equivalent to the no-shade condition as shown in Figure 7.
3. Shading effectively controls glare above the 2000 lux threshold, outperforming the no-shade scenario as shown in Figure 7.

PAYBACK PERIOD

The payback period is an efficient method for evaluating the economic feasibility of solutions at the initial design stages (Malatji et al., 2013; Chidiac et al., 2011). It represents the time needed for an initiative to recover its initial investment through cost reductions. This research shows that only energy conservation for space cooling exceeds the baseline scenario. The payback period calculation accounts for the shading device's initial investment cost, as determined by the case study data and Equation 3.

$$P_b = IIC - O_{fa} / AES - O_{fa}$$

(Equation 3)

Shading device options	cost per panel	ICC for one floor in the east, west, and south facades, area of 600 m ²	ICC cost per office floor area in R/ m ²	ASE per m ² of office area kWh/ m ² /year	Payback period in years
400 Diagrid	36250	978750	725	63.2	11.48
500 Diagrid	41650	1124550	833	78.7	10.58
600 Diagrid	46600	1258200	932	84.5	11.03
60% screen	20800	561600	416	123.9	3.36
80 % screen	26400	712800	528	155.8	3.39
100 % screen	32000	864000	640	205.1	3.12
Dynamic	98000	2646000	1960	117.3	16.71

Table 6: Cost of shading panel in USD with installation and other costs per m² of office floor, and its energy-saving cost.
Source: Preparation by the authors.

Where Pb = Payback period, IIC-Ofa = initial investment cost per sqmt of office floor area for the retrofit options, AES-Ofa = annual energy saving per sqmt of office floor area for space cooling. The initial investment costs were based on the Indian national average trade prices and Chennai building practitioners. The shading device costs per m² of façade area (Table 6) use a \$1 = ₹78 conversion rate (IRS, 2022). This cost, multiplied by the façade area and divided by the office area, gives the IIC per option. Using the TNEB commercial rate of Rs. 8.5/kWh (Tamil Nadu Electricity Regulatory Commission [TNERC], 2017), annual space cooling energy savings per m² are calculated. Figure 8 shows the payback period for all options based on energy savings and investment costs.

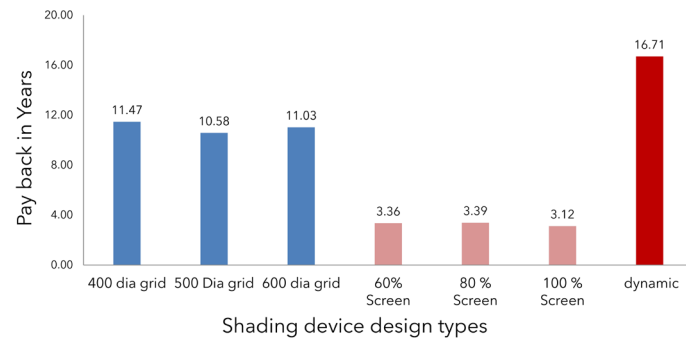


Figure 8. Payback period in years for all the selected shading device types. Source: Preparation by the authors.

RESULTS AND DISCUSSION

The findings indicate that the efficacy of external shading systems in hot-humid climates is influenced not solely by the presence of shading but also by the interplay among material properties, geometric configuration, and operational behavior. Previous research has underscored the environmental advantages of textile membranes, notably their lightweight nature, high solar reflectance, adaptability, and semi-transparent characteristics (Al-Masrani & Al-Obaidi, 2019; Nurazzi et al., 2021). This study advances understanding by quantitatively comparing fixed solar screens, dynamic shading systems, and diagrid shading, using the same Serge Ferrari Frontside View 381 membrane material in the climatic context of Chennai. By maintaining material consistency, the study isolates the impact of shading typology and system behavior on cooling-energy performance.

Among the three typologies examined, the solar screen system achieved the most significant reduction in cooling energy demand, approximately 25%. This finding corroborates earlier research by Ciampi et al. (2022), which identified Frontside View 381 fabric shades as highly effective in mitigating solar heat gain in warm climates. However, this study advances the literature by demonstrating that membrane performance is enhanced when integrated with a continuous, uniformly distributed screen geometry. The results also align with Kirimtat & Manioğlu (2024), who contend that static perforated skins can surpass more complex adaptive systems in tropical latitudes due to their consistent protection against high-angle solar radiation. Thus, the study suggests that in hot-humid climates, climatic responsiveness and geometric stability may be more influential than technological sophistication. Furthermore, the relatively low cost and

shorter payback period enhance the feasibility of fixed shading systems for large-scale commercial applications.

The material-based simulation approach also highlights the importance of the textile membrane's high solar reflectance in minimizing surface heat absorption compared to conventional high-thermal-mass materials such as concrete or aluminum. However, because all three shading systems employed the same membrane material, the variation in energy performance is primarily attributable to differences in geometric configuration and system behavior. This demonstrates that façade form should be understood as an active environmental parameter rather than merely an aesthetic decision.

The dynamic shading system achieved a moderate reduction in cooling energy consumption, approximately 15%. Existing literature frequently highlights the adaptability and responsiveness of kinetic façades and textile-based movable systems (Gonçalves et al., 2024). However, the present findings indicate that adaptive capability does not necessarily equate to enhanced energy efficiency in tropical climates. Although the system effectively responded to changing solar conditions, its overall performance was inferior to that of the fixed screen due to inconsistent shading coverage and increased operational complexity. This finding addresses a significant gap identified in the literature review, in which dynamic membrane shading systems had not previously been evaluated relative to fixed systems in hot-humid climates.

Conversely, the diagrid shading system achieved energy savings of less than 10%, indicating that increased openness and visual permeability may reduce thermal performance. While previous research has emphasized the aesthetic and visual potential of textile façades (Procaccini et al., 2024), the present study elucidates the trade-off between daylight access, outward visibility, and cooling-load reduction. Although less thermally effective, the system facilitates greater daylight penetration and outward views, aligning with architectural priorities regarding occupant experience and spatial quality (Sawyer et al., 2022). Overall, the study suggests that fixed solar screen systems offer the most balanced solution for hot-humid office buildings by integrating thermal efficiency, economic feasibility, and indoor environmental quality. More importantly, the findings advance climate-responsive façade research by challenging the assumption that complex adaptive technologies invariably surpass passive design strategies.

CONCLUSION

This study emphasizes the essential role of incorporating shading system design at the initial

stages of architectural development, particularly for fully glazed, air-conditioned office buildings in hot-humid climates such as Chennai. The findings indicate that early-stage decisions significantly impact cooling energy demand, underscoring the necessity for performance-driven design approaches rather than post-design optimization. By employing a parametric computational framework, the research systematically assessed multiple external shading strategies using textile membrane materials. Among the evaluated options, the perforated solar screen positioned parallel to the glazed façade proved to be the most effective solution, offering an optimal balance between energy efficiency, daylight performance, and economic feasibility. In contrast, while dynamic shading systems provide adaptive control, their high initial capital cost, system complexity, and extended payback periods limit their practical applicability in developing economies such as India.

The study contributes to the field by introducing a material-based simulation methodology that enables consistent comparisons across different shading typologies using the same textile membrane material. This approach isolates the influence of geometry and system behavior, thereby providing clearer insights into performance outcomes. The results confirm that well-designed solar shading can significantly reduce energy consumption while maintaining adequate daylighting and visual comfort, all with relatively low investment costs. However, the scope of this research is limited to specific textile membrane materials, three façade orientations, and three shading device types, with a primary focus on controlling direct solar radiation on glazed surfaces. Future research should expand this framework to include a wider range of materials, alternative geometrical configurations, additional climatic variables, and integrated performance parameters such as ventilation and embodied energy. Overall, the study highlights the substantial potential of textile membrane façade systems as a sustainable and cost-effective strategy for reducing building energy consumption. It establishes a foundation for further exploration of membrane-based shading solutions, contributing to the advancement of climate-responsive and performance-driven architectural design.

AUTHOR CONTRIBUTION CRediT

Conceptualization: C.C.; Data Curation: C.C.; Formal Analysis: C.C.; Investigation: C.C.; Methodology: C.C.; Project Administration: C.C.; Resources: A.M.; Software: C.C.; Supervision: C.C.; Validation: A.M.; Visualization: A.M.; Writing – Original Draft: A.S.K.S.; Writing – Review & Editing: N.M.; Writing – Revision & Editing: M.N.

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