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PUZZLEGLAZE: A USER-DRIVEN WINDOW SYSTEM TO MAXIMIZE USER COMFORT

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ABSTRACT

Not everyone can afford an air conditioning system for their home, thus requiring a manual flexible window system that helps household stay comfortable without using expensive automated systems. This study aims to conceptualize, design and evaluate a low cost, user driven window system where access to mechanical cooling is limited. This study proposes a window system which works like a puzzle named as PuzzleGlaze, with a 3×3 grid of panels in which four panels of clear glass, four panels with sun-film-coated glass, and a ventilation void. Each panel has a lock-and-key mechanism that lets it slide sideways and up and down, so users can adjust the window panel position depending on the sun angle at different times of the day. This exploratory design research based on a physical model prototype evaluates performance of the proposed system for heat, daylight and glare by digital simulation comparative study against a fully clear glass window and a fixed sun film window. The findings show that PuzzleGlaze reduces glare, improves user control of natural light, and uses less film material, making it both practical and cost-effective. This study suggests that simple, hands-on design solutions can offer flexible and sustainable ways to respond to changing sunlight in urban buildings.

Keywords: *Adaptive window system; Interactive facade systems; Lock-and-key panel mechanism; Low-tech facade innovation; User-centric daylight control.*

1. INTRODUCTION

Creating a comfortable indoor environment and reducing heat without compromising light are important aspects in our day-to-day life. But in cities like Pune, where sunlight can be strong and direct, it often creates problems of glare and heat gain. This makes indoor spaces uncomfortable and forces people to depend on artificial cooling or heavy shading, which can feel uncomfortable and can create disturbance and making it expensive. Most conventional solutions, like fixed sun films or static shading devices, don't change with the sun also cause darkness when applied to the whole window. Once installed, they either block too much light or too little, leaving users with limited control. This is where the idea of PuzzleGlaze came into the picture. Inspired by the logic of a puzzle, the system uses a grid of nine small panels, four of clear glass, four with sun film, and one left open for air movement. These panels can move up and down and also sideways through lock and key mechanism i.e. tongue and groove joint where the groove acts as a channel for the panels to slide. This makes the window flexible, interactive, and less wasteful, since sun film is only used where it really matters. For this research, a

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physical prototype of 1:2 scale named PuzzleGlaze was created and tested under simulated sunlight conditions that mimic Pune's sun path and also simulations are carried out on Revit and Grasshopper-Honeybee software. This study aims to show how adaptive window systems like PuzzleGlaze can be used to control daylight, heat and glare, while also giving users more control over their indoor environment.

2. LITERATURE REVIEW

Figure 1 maps insights drawn from the literature study where various discourses in window systems have been categorized based on mode of operation and energy usage. While the passive facades are on the left extreme where the systems are static and non-responsive but are cost effective and built solutions in most of the cases; on the right extreme lies the Kinetic facade which are dynamic and responsive. Research on Kinetic facades shows that they save energy, give better daylight and comfort by responding dynamically to environmental conditions, but a very few real-life examples are seen (Hosseini et al., 2019). Adaptive facades also move or react to weather to cut glare and heat and work best when designed for local climate and user needs (Juaristi et al., 2018a). Parametric studies of sun-responsive facade skins have further demonstrated that such systems can significantly improve daylighting performance and visual comfort when their geometry is tuned to local solar conditions (Tabadkani et al., 2018).

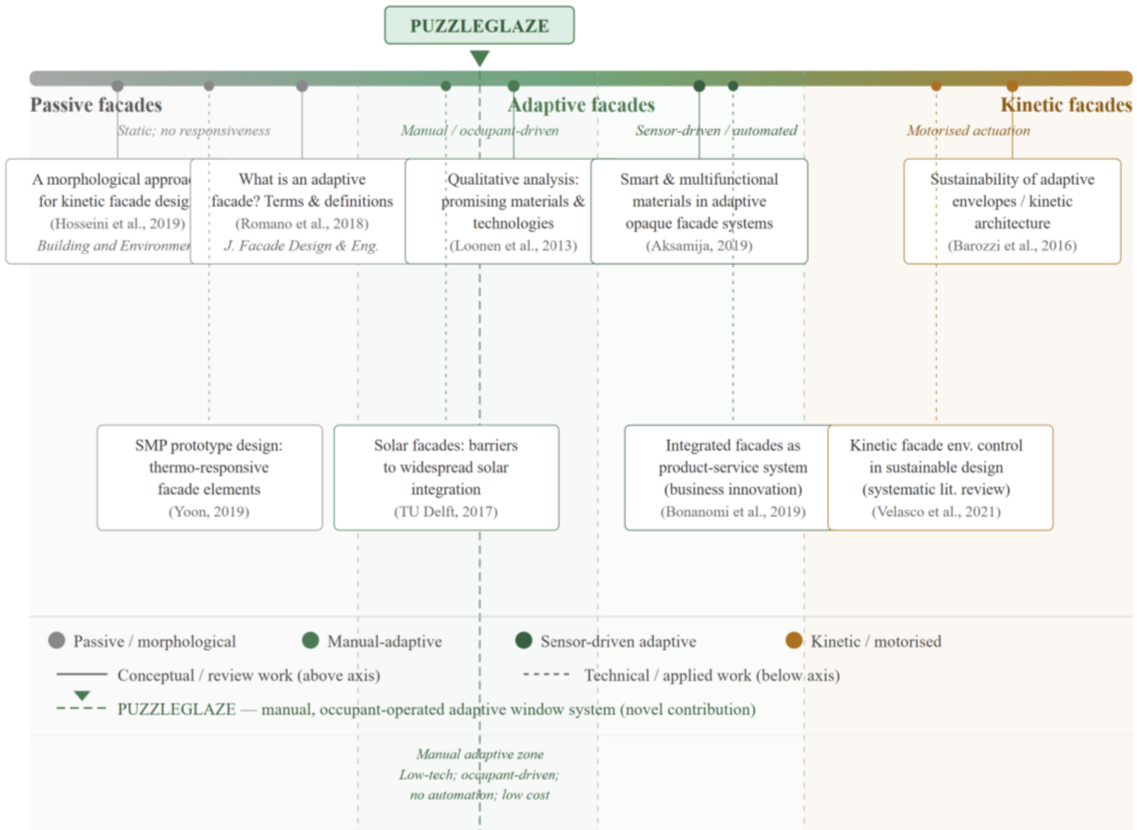

Figure 1: Facade design research spectrum: From passive to kinetic facades, situating PuzzleGlaze within the manual-adaptive zone

However, to install, operate and maintain such kinetic and adaptive facades a system is required which might be overwhelming for a layperson. As a product if such facades can be rented or serviced, such advanced designs would become more affordable and universal (Azcárate-Aguerre et al., 2018). Solar facades do have a potential for universal use but are seen as too costly and slow to adopt (Prieto et al., 2017). Adaptive facades in real projects reduce cooling needs, but most rely on expensive tech; simpler solutions are missing (Barozzi et al., 2016). However, adaptive facades do act like building skins, adjusting to climate and people (Romano et al., 2018), but use of smart materials, sensors-based technologies have become expensive limiting household adoption; thus, highlighting a need for low-cost and simple design solution (Juaristi et al., 2018b). Research also highlighted limitations of kinetic and adaptive facades, which says since it is automated and expensive it is not preferred in households (Hosseini et al., 2019; Juaristi et al., 2018a). This identified a clear research gap that a window system is required that can be manually operated by the user making it user-centric and cheaper, improving indoor thermal comfort and also ensuring sustainable operation and maintenance.

PuzzleGlaze addresses this gap as a novel contribution as a cost-effective solution at the intersection of adaptive façade designs and low-tech driven solutions. The system doesn't require automation, sensors and nor specialist installation. Thus, PuzzleGlaze system situates itself within the adaptive façade spectrum – between the static passive systems and motorised dynamic facades – this study responds to the call in the literature for a simpler and more accessible solution for residential buildings (Barozzi et al., 2016; Hosseini et al., 2019). Simulations were conducted to evaluate performance, focusing on daylight distribution, glare reduction, and solar heat gain, following standard metrics for indoor environmental quality (Hosseini et al., 2019; Juaristi et al., 2018a).

3. DATA AND METHOD

This research adopts an exploratory design approach (Groat & Wang, 2013) to evaluate the performance of a partially glazed, adjustable window system referred to as PuzzleGlaze – using sun films for glare control and daylight optimization. The methodology involves three sequential stages- (1) conceptual design, (2) physical prototype construction and observation, and (3) digital simulation to validate PuzzleGlaze performance under user-adjusted puzzle. For simulation study, the window system is evaluated within the Pune India (18.52°N, 73.85°E) context which is categorized as hot semi-arid climate (Köppen climate classification BSh) characterised by high solar radiation, prolonged periods of intense direct sunlight, and limited cloud cover during summer months.

3.1 CONCEPTUAL DESIGN OF PUZZLEGLAZE

The foundation of this study is the development of a modular window system inspired by the logic of a puzzle. The window is divided into a 3×3 grid consisting of nine equal-sized panels. The sunfilm panels and clear glass panels are in 50-50 ratio so that it is easy to apply or have a grid pattern in which 4 panels are made of clear glass, 4 panels are glass panels with sunfilm, and one panel is left void with a jali for ventilation. These panels can be moved up and down or sideways with the help of lock and key mechanism which is basically tongue and groove joint in which the tongue part having extruded edge can move in the groove or channel of the same size. This configuration or mechanism allows the panels to be manually adjusted sliding or rotating them based on the changing position of the sun throughout the day. Such as if the sun is at higher angle the sunfilm panels can be moved upwards so that it reduces glare and heat coming inside the room, if the sun angle is at lower horizon the sunfilm panels can be moved downwards and heat coming inside can be reduced, in such way it is very user - centric that the individual can decide how much heat can be entered and adjust it accordingly. Also, these panels are in grid so are aesthetically appealing and also the pattern can go on changing as per the individual's choice, so different patterns can be seen throughout the day.

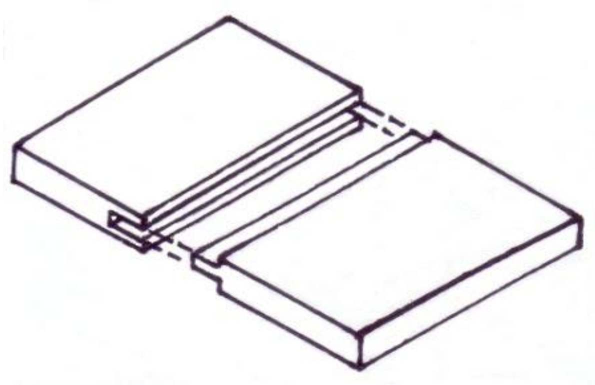

Figure 2: Tongue and groove joint mechanism in which groove acts as a channel

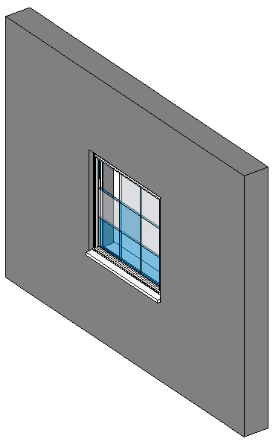

Figure 3: Window panel design with 9 panels, four with sunfilm and 4 as clear glass and corner is void for ventilation.

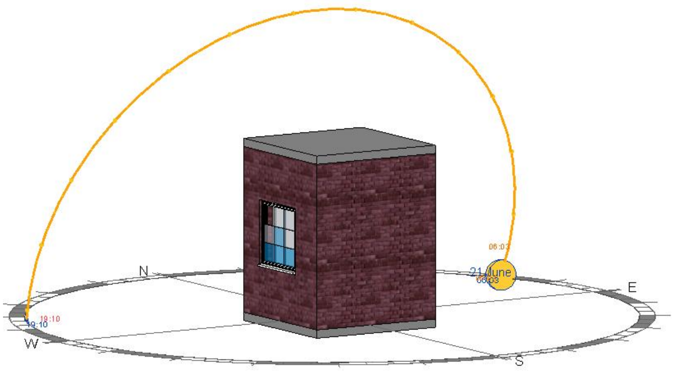

Figure 4: The digital Revit software model room with the prototype window placed to the west side as heat gain is more towards west.

3.2 PHYSICAL PROTOTYPE CONSTRUCTION AND OBSERVATION

The prototype was built at a scale of 1:2, considering a standard window opening of 1200mm x 1200mm as shown in Figure 5. The window system is divided into 9 equal parts each measuring 400mm X 400mm at 1:1 scale. The scaled prototype panel measured 200mm X 200mm which was fabricated using acrylic sheet which was used as a substitute to glass for the ease of demonstration at lower cost. The material prototype development cost was around INR1200 (USD 14). The tongue and groove joint to facilitate the sliding mechanism was created as shown in Figure 5 with each panel having extruded tongue profiles along two adjacent sides and groove channels along the remaining two sides. The window frame is similarly provided with groove channels along the inner edges allowing smooth sliding mechanism.

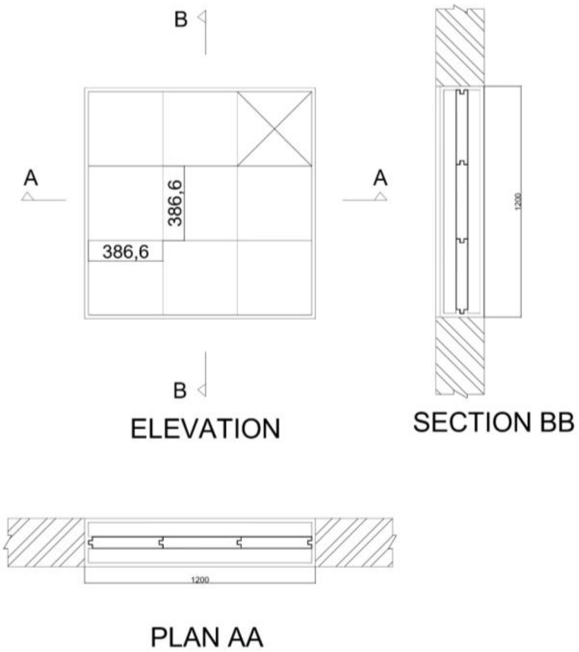

Figure 5: Technical drawings of PuzzleGlaze prototype, a nine- panel window

The prototype model consisted of a transparent acrylic sheet of 3mm cut to a panel size of 200mm X200mm at 1:2 scale (see Figure 6) and 3 panels pasted together by an adhesive making effective thickness 9mm thick (see Figure 7) in such a way that it creates tongue and groove by cutting the sides or the middle part, representing standard glass. Sun film is applied to designated panels i.e. four panels. A single panel left open to simulate a ventilated void will have a jali or small net. The window panel mechanism is designed to allow manual adjustment to simulate how users might react to changing glare throughout the day. Each panel operates on a lock-and-key mechanism: two adjacent sides of the panel are designed with extruded parts (keys), while the other two sides have depressions (locks) (see Figure 8). The side frame of the grid is provided with corresponding slots, enabling panels to securely slide, rotate, or fit in place. This ensures both flexibility of movement and structural stability during adjustment.

Figure 6: Cutting of acrylic sheets to make nine window panels in a wood cutting machine

Figure 7: Pasting the 3 acrylic panels with an adhesive

Figure 8: Making tongue by trimming side panels and groove by trimming middle panel

To make the prototype window, the frame was made of wood to provide both strength and ease of fabrication. The frame also consisted of tongue and groove geometry so as to make panels fit into and slide easily. The window system fabricated consisted of 4 panels with sunfilm applied (see Figure 9), 4 clear glass panels and a void (Figure 10). The clear glass panels used in the PuzzleGlaze system are showing white patches due to the adhesive used while pasting three panels together, as transparent adhesive was not commercially easily available due to probable adverse reaction to health. Figure 11 shows a beam of artificial light falling onto the window system where panels with sunfilm layering are blocking the direct light. In addition to this a backside support was given to make the window stand independently which was also made of wood (see Figure 12).

Figure 9: Black are panels with sunfilm

Figure 10: A void for ventilation is at the corner

Figure 11: The striking of glare on the window panel

Figure 12: The backside window supports

3.3 DIGITAL SIMULATION TO VALIDATE PUZZLEGLAZE PERFORMANCE

3.3.1 Revit Solar Analysis

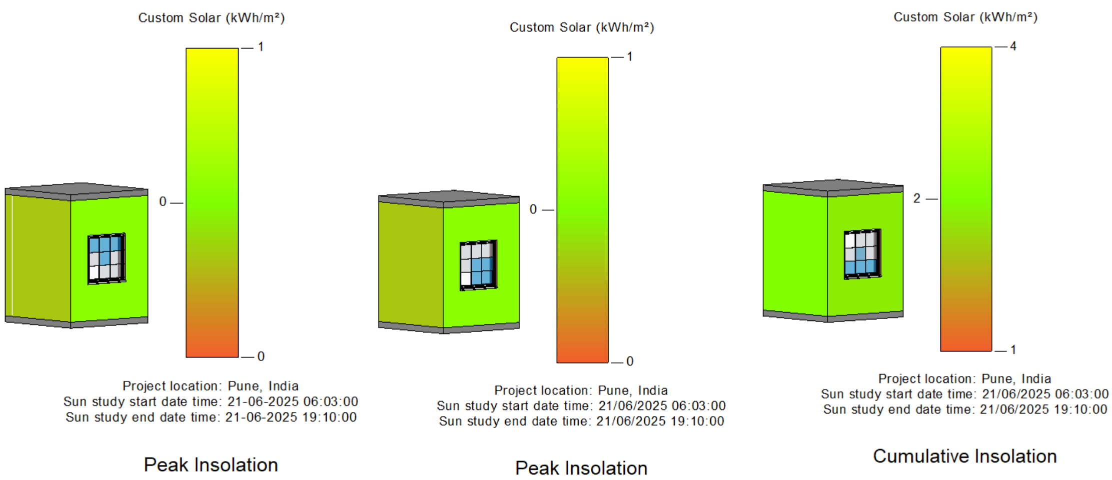

Figure 13: Simulation of Adaptive Panel Response to Solar Insolation at Different Sun Angles in Revit

The Figure 13 shows the solar insolation study carried out in Revit software at different sun positions, including higher, middle, and lower horizon angles. As the position of the sun changes throughout the day, the panels also adjust accordingly to control the amount of sunlight entering the space. This helps in reducing heat gain and improving indoor comfort through a simple passive design approach. The panels with sunfilm can be manually moved at the top when the sun is at higher altitude in the morning, then the panels can be moved to the middle in the afternoon, and the panels can also move to the bottom when the sun is at lower altitude in the evening.

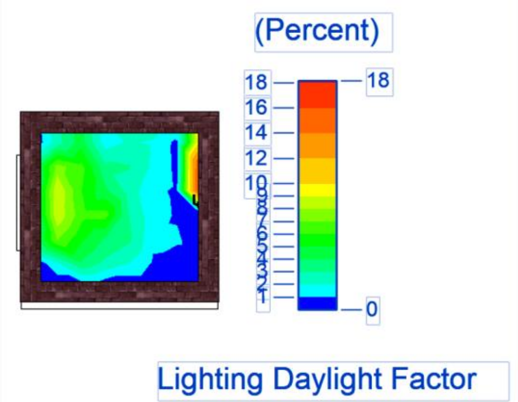

Figure 14: Daylight simulation showing the effect of sunfilm panels on indoor light control

The Figure 14 shows that direct sunlight enters the room more intensely through the clear glass surfaces. The simulation study also shows that the sunfilm panels help reduce the intensity of incoming sunlight, creating a more balanced indoor environment and improving visual and thermal comfort within the space.

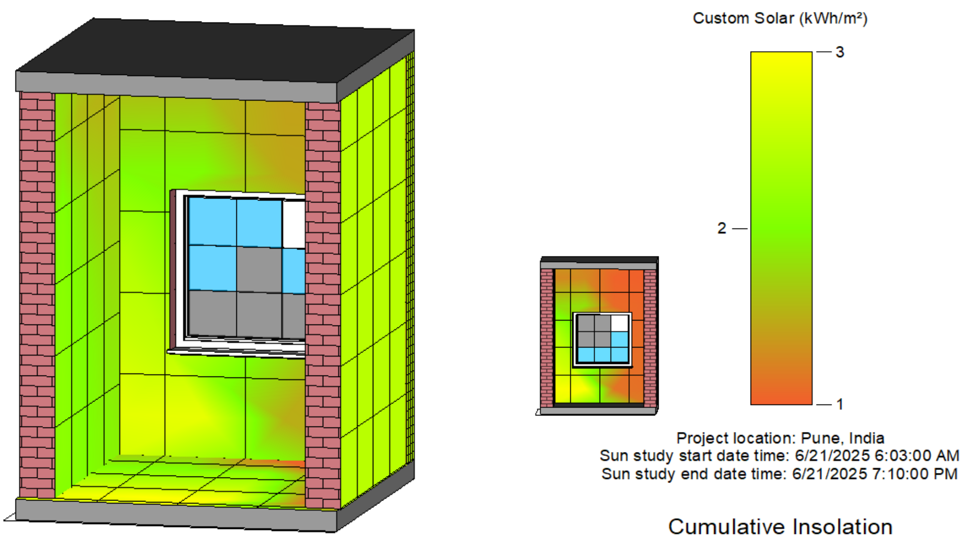

Figure 15: Comparison of solar heat gain through clear glass and sun-film-coated panels

The figure compares the solar heat gain through clear glass panels and sun-film-coated panels based on the simulation carried out in Revit software. The clear glass allows a greater amount of sunlight and heat to enter the room, creating brighter and warmer areas near the window. In contrast, the sun-film-coated panels reduce the amount of solar radiation entering the space, helping to maintain lower surface temperatures and improve indoor comfort.

3.3.2 Grasshopper-Honeybee with Radiance and OpenStudio Plugins

The prototype model was made in Rhinoceros software, in which the Daylight (Tabadkani et al., 2018) and Heat gain simulations were carried out in Grasshopper using Ladybug, Honeybee (refer Figure 22 in Annexures), Radiance, and Open studio plugins by making a manual script of components referring to various resources available on the internet such as tutorials, blogs related to how to build scripts in grasshopper for simulation studies. All the scripts were built by the author in the Grasshopper and the details are given in the Annexures.

- **DAYLIGHT SIMULATION**

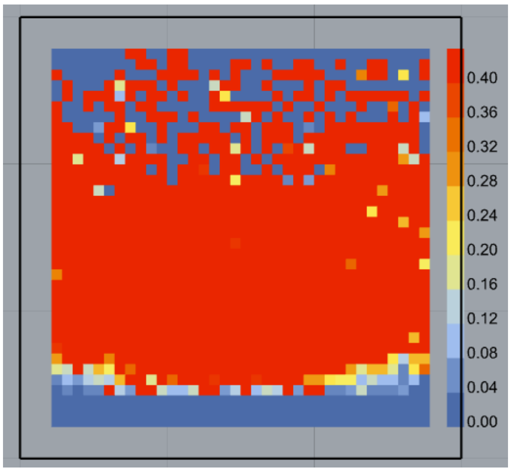

Figure 16: Daylight simulation results for Clear Glass Window system

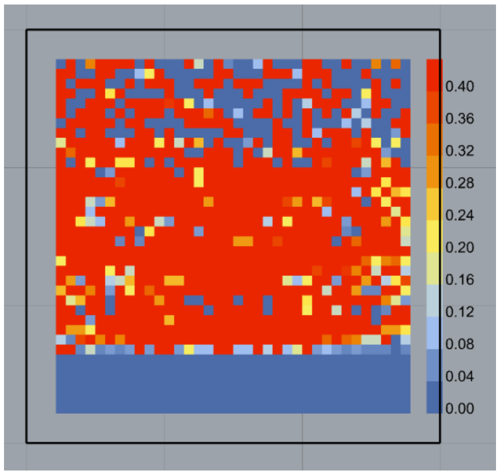

Figure 17: Daylight simulation results for the proposed PuzzleGlaze Window system

Table 1: Legends showing daylight simulation scale

DF Scale	Lighting condition
0 - 0.12	Poor daylight
0.12 - 0.16	Low daylight
0.16 - 0.24	Moderate daylight
0.24–0.28	High daylight
0.28–0.4	Possible glare

Figure 16 shows the daylight analysis for a lower-side clear glass window with a light transmittance of 85%. A higher amount of natural light enters through the window and gradually spreads deeper into the room, resulting in increased daylight levels across the interior space. Refer to Table 1 to understand the daylight simulation scale and associated lighting conditions. The corresponding Grasshopper script used to perform the simulation is also presented (refer Figure 22 in Annexures). Whereas Figure 17 shows the daylight analysis for a lower-side sunfilm-coated glass window with a light transmittance of 45%. Due to the reduced transmittance, the amount of daylight entering the room is lower, resulting in more controlled and evenly distributed illumination levels within the space. This indicates the effectiveness of the sunfilm in reducing excessive daylight penetration while still maintaining adequate indoor lighting. The accompanying Grasshopper script illustrates the simulation workflow (refer Figure 23 in Annexures), and all daylight results are expressed in lux.

- **HEAT RADIATION SIMULATION**

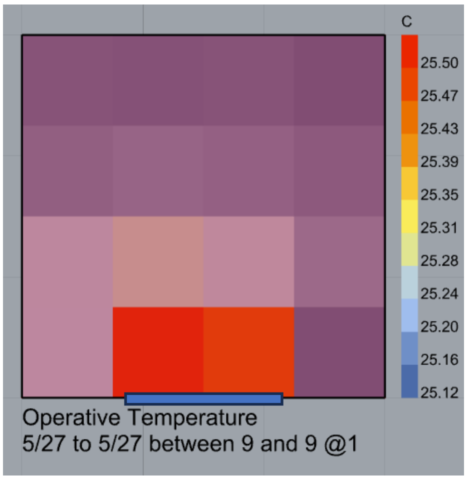

Figure 18 Operative temperature analysis with clear glass window at 9 am

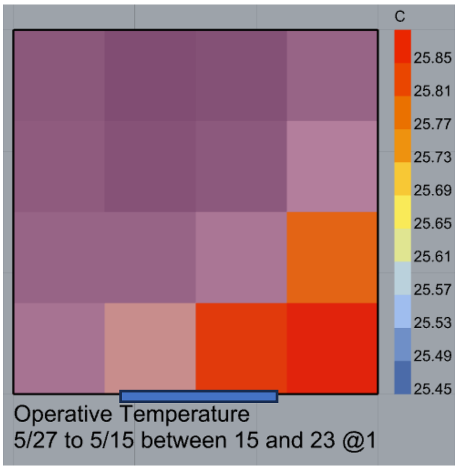

Figure 19: Operative temperature analysis with clear glass window at 3 pm

The figure shows the operative temperature simulation carried out on 27 May at 9 AM and 3 PM for a space with a clear glass window located at the bottom. Higher temperatures are observed near the window due to increased solar heat gain through the clear glass surface. The afternoon condition at 3 PM shows slightly higher temperatures compared to the morning at 9 AM, indicating greater heat accumulation during later hours of the day. The simulation results are represented in degrees Celsius (°C), (refer Figure 24 in Annexures).

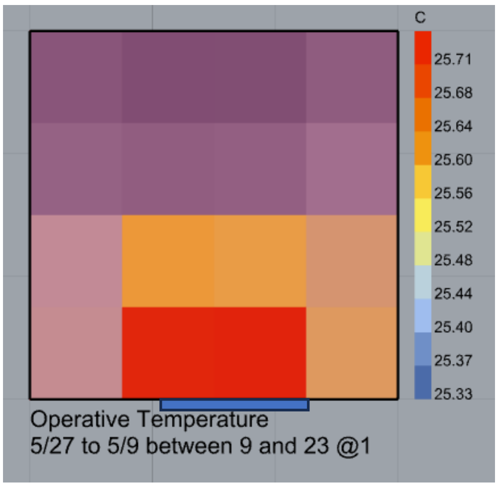

Figure 20: Operative temperature analysis with sun-film coated glass window at 9 am

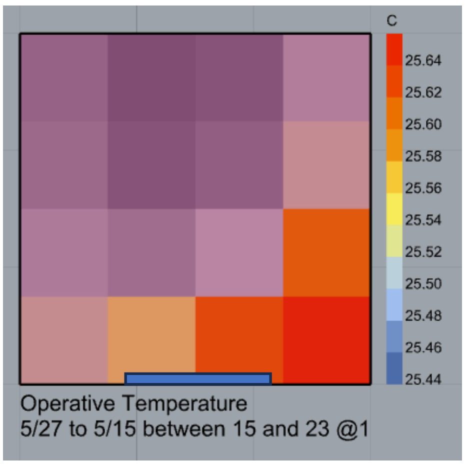

Figure 21: Operative temperature analysis with sun-film coated glass window at 3 pm

The figure shows the operative temperature simulation carried out on 27 May at 9 AM and 3 PM for a space with a sunfilm-coated glass window located at the bottom. The sunfilm helps reduce solar heat gain, resulting in more uniform and slightly lower temperatures near the window area. Although the afternoon condition at 3 PM still records slightly higher temperatures than the morning at 9 AM, the overall indoor thermal conditions remain comparatively more comfortable. The simulation results are represented in degrees Celsius (°C), (refer Figure 25 in Annexures).

4. CONCLUSIONS

PuzzleGlaze is a window designed using a puzzle system, made of nine panels that can be moved and arranged. Some panels are with clear glass to let in light, some have sun film coating to block glare, and one is left open for fresh air. This simple design gives people the freedom to adjust their windows based on the sun's position, keeping rooms bright, comfortable, and cool without depending too much on electricity. From the simulations, it shows that the clear glass has higher solar heat gain (Figure 18 & Figure 19) that increases indoor temperature, while sunfilm-coated glass reduces heat gain (Figure 20 & Figure 21) and maintains indoor temperature. Therefore, the PuzzleGlaze window prototype is a mixture of both clear glass and sunfilm which helps balance daylight and thermal comfort, allows light to enter with lesser heat gain in the peak sun hours. The novelty lies in three features: first, the tongue-and-groove modular panel mechanism that allows occupant-driven repositioning in response to solar angle; second, the hybrid panel configuration that distributes sun-film and clear glass within a single frame, rather than applying uniform glazing across the entire window; and third, its deliberate design for replicability at low cost, demonstrated through a functional prototype built for approximately INR 1,200. However, a formal performance validation of the PuzzleGlaze through full scale physical set-up and sensor-based data collection for radiation and daylight represents a key limitation of the present study and constitutes the most critical direction for future research. Unlike fixed glass or costly automated systems, PuzzleGlaze is easy to use, affordable, and saves material because sun film is only used where it is really needed. It works well in homes, but it is also especially valuable in Schools, where children can enjoy sliding the panels like a game. By playing with the system, they not only improve their classroom comfort but also learn in a hands-on way how daylight can replace electric lights and how sustainable design can save energy. In this way, PuzzleGlaze is not just a window, it is a simple, low-tech, and educational tool that makes buildings more comfortable while teaching the next generation about the importance of saving energy.

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6. ANNEXURES

Following are the Grasshopper scripts developed by the author to conduct Honeybee Radiance analysis.

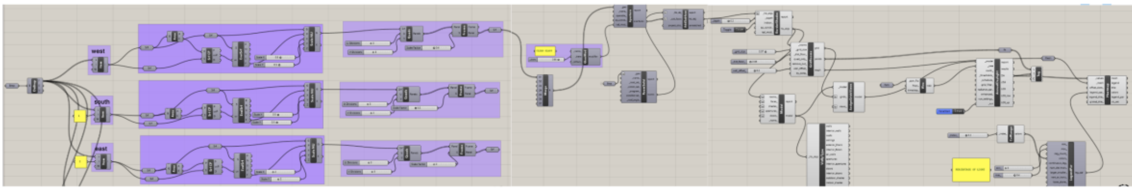

Figure 22: Daylight distribution analysis and grasshopper simulation script.

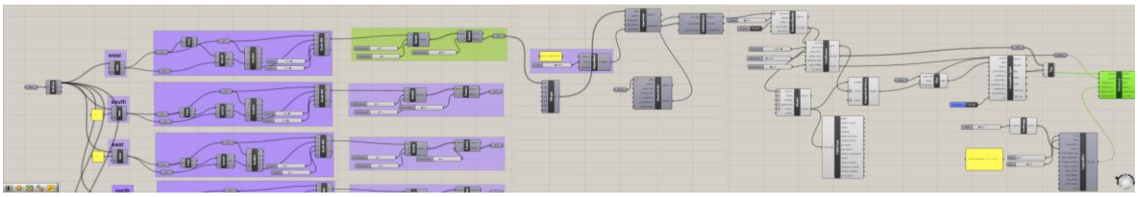

Figure 23: Daylight distribution analysis of sunfilm-coated glass and grasshopper simulation script.

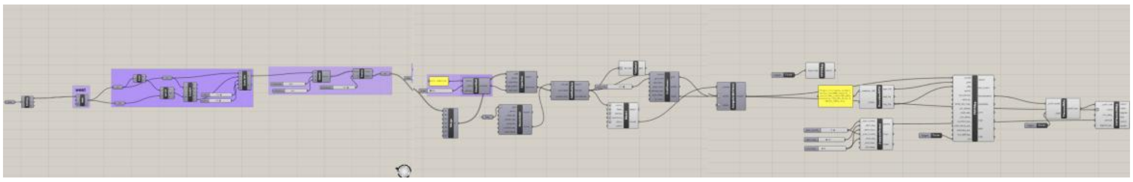

Figure 24: Operative temperature analysis with clear glass window at 9 am and 3 pm

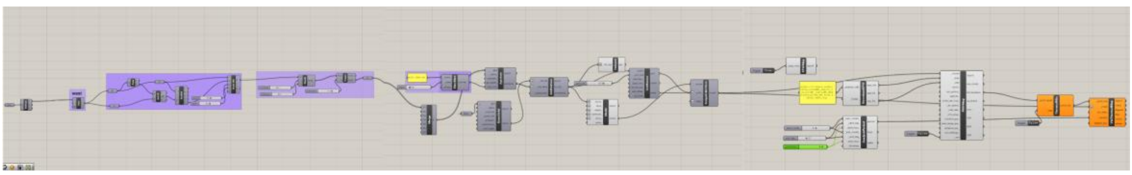

Figure 25: Operative temperature analysis with sunfilm-coated glass window at 9 am and 3 pm