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Optimizing Parametric Green Facades for Daylighting and Thermal Comfort in Egypt's Hot Climates

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ABSTRACT

As a result of population growth, the utilization of heat-absorbing materials in urban construction has increased, leading to significant thermal discomfort for city dwellers. Integrating vegetation within urban environments is crucial for enhancing both indoor and outdoor comfort. Green facades offer a promising solution for introducing greenery into densely populated areas. This research investigates the performance of parametric green facade (PGF) systems in the hot climate of Egypt. The primary objective of this study is to analyze the impact of parametric facade design on daylighting and thermal performance within residential buildings. This involves exploring four distinct parametric design scenarios, each with unique characteristics and configurations. The study utilizes Grasshopper and Lunchbox plugins, to create detailed simulations of the four designs. These simulations allow for a comprehensive assessment of how each design influences daylighting and thermal comfort within residential buildings. Through this investigation, the study aims to provide valuable insights into optimizing green facade designs for improved daylighting and thermal performance in hot urban climates. By evaluating the effectiveness of different parametric designs, the research seeks to establish recommendations for the implementation of green facades in densely populated areas, contributing to the creation of more sustainable and comfortable urban environments. Finally, the study's main conclusions are that the PGF effective design reduced DGP by 60% when compared to the basic design while maintaining an acceptable average lux and ASE. It also reduced energy consumption by 28% and operational energy expenses by 29%.

Keywords: Green façades -Parametric façade design - Residential buildings - Hot dry climate - Daylight performance – Thermal Comfort

1 INTRODUCTION

Despite growth in environmental protection, urbanization has greatly reduced green spaces, harming biodiversity and ecological health and lowering human quality of life. This causes environmental, health, and economic problems. The World Bank predicts that 70% of the population will live in urban areas, by 2050[1]. Besides, buildings and surfaces made of materials with a high capacity for heat absorption and preservation are becoming more and more prevalent as a result of this trend toward fast urbanization [2]. Moreover, a phenomenon known as the "Urban Heat Island" (UHI) happens in the absence of green spaces when the heat produced from these artificial surfaces is not offset by vegetation [3]. Owing to increased use of air conditioner and long heat stress in urban areas, the Urban Heat Island (UHI) phenomenon raises peak power consumption. [4]

In the design and construction of buildings, bio-architecture and environmentally friendly architecture are becoming more and more substantial. It is crucial to address energy usage and climate change in the modern world [5]. Planting vegetation throughout cities is known as urban green infrastructure (UGI), and it has several advantages. These include lower energy use, less pollution entering waterways, and the removal of air pollutants. Adding vegetation layers to building envelopes, vertical greenery systems (VGSs) are especially advantageous because they don't need more urban space. Generally speaking, VGSs are divided into living walls (LWs) and green façades (GFs) [4].

However, the residential sector uses over 25% of the world's energy, and residential buildings are thought to be the world's fourth-largest source of carbon dioxide emissions, both of which have a substantial negative impact on the environment [6]. Façades of residential buildings significantly influence energy performance and indoor comfort. Properties and configurations of façade elements, such as wall or glazing material, solar transmission, and window-to-wall ratio, affect the application of natural resources like daylight, solar heat, and wind. This, as a result, impacts the energy required for heating, cooling, ventilation, and artificial lighting in households [7]. The following subsections present a review of the literature on the three primary concepts: glazed façade, parametric façade design, and green envelope, and draw attention to the primary research gap in this area, which is the interaction between parametric façade design and green façade design, particularly as it relates to residential buildings in hot, dry climates.

1.1 Glazed facade

Many research works have highlighted the role of glazed façade elements to the energy and interior thermal performance of buildings. In a temperate environment, Raji et al. (2016) evaluated the energy-saving envelope design alternatives for a high-rise glazed office building. They discovered that the most influential criteria they looked into were the glazing type and the window-to-wall ratio [8]. The impact of façade design characteristics in office buildings situated in hot and humid climates in Asia was studied by Hwang and Chen (2022)[9]. According to Hu et al. (2023), one of the most effective passive cooling techniques is to adjust the window-to-wall ratio. This was discovered in a recent analysis of interior thermal comfort and energy savings in residential structures.[10]

Bhattacharjee et al used a parametric research to assess the energy and indoor thermal performance of a residential high-rise structure with glazed balconies and façades in a Nordic climate. According to the findings, reducing the ratio of windows to walls and switching from single- to double-pane glazing also assisted in lowering energy consumption and overheating. [11]

1.2 Parametric façade design

Many researches studies parametric façade design and its role in enhancing daylighting and thermal façade performance, they suggest parametric design inspired from natural elements like flowers or geometric shapes as [12–14]. For instance, Khidmat et al. demonstrated the use of multi-objective optimization and parametric design as a design approach that examined the application of extended metal shading related to daylight performance given Japan's sky conditions. [15]

Meloni et al. suggested lowering potentially hazardous reflected solar radiation in outdoor urban contexts by implementing an origami-based adaptive façade for the Walkie-Talkie building in London. The principal results of the research indicate that the peak reflected solar radiation in outdoor metropolitan situations can be considerably decreased by the use of origami folding. [16].

1.3 Green envelope

Many articles confirmed the relevance of using vegetation in buildings to mitigate the effects of heat and improve the thermal comfort of inhabitants like [17] [18] [19] [20] [21].Others focused on how vegetation's size and orientation may improve the role of a green façade. Shu et al. evaluated the sizes and visual characteristics of 12 plant taxa in connection to substrate pH, floor height, façade orientation, and mycorrhizal inoculation, using data from a field experiment carried out in Southern Finland. The findings support the implementation of coniferous species in Nordic regions by highlighting the crucial impact that façade orientation plays in plant selection for vegetated façades.[22]

Besides, Sharbafian et al evaluated the impact of green façades on daylight regulation, visual comfort, and heating and cooling loads, by simulating 30 different green façade designs, increasing the density of greenery from 20% to 100% reduced daylight autonomy (DA), useful daylight illuminance (UDImax), and cooling load, but enlarged the heating load [23]. Conversely, Nicolini and colleagues sought to confirm the efficacy of a vegetated façade during exceptionally windy circumstances in conjunction with periods of rain and/or high levels of radiation on the east, west and south façades. The results of the analyses indicate that the green wall's effective wind-barrier capacity is noticeable in both walls, but it is more so in the south. When irradiation is taken into account, the differences between the orientations are more pronounced, indicating that the wall can cool down more in the summer than it can in the west by roughly 4 ◦C. [24]

1.4 Research gap, Objective and Scope

It is clear that there is a research gap when it comes to the few studies that look at how parametric façade design and green façade design interact, especially when it comes to residential buildings in hot dry regions. The ways in which these two components can be combined to improve thermal comfort, energy efficiency, and overall building performance in such demanding environmental circumstances have not been sufficiently investigated in the majority of current research. Comprehensive studies that look into these connections and offer recommendations for maximizing the use of green façades in hot, dry climates for residential buildings are needed.

The goal of this study is to determine how the parametric green facade design affects daylight control, one of the primary features influencing the thermal load of residential buildings. Green facades were thus positioned in four different parametric designs by defining various scenarios.

1. METHODOLOGY

1.5 Simulation process

This study evaluated how a PGF impacts energy consumption by simulating an architectural model with a variable, which is the PGF design in order to control sunlight radiation, and avoid sunlight glare. The steps of the methodology are demonstrated in Figure 1.

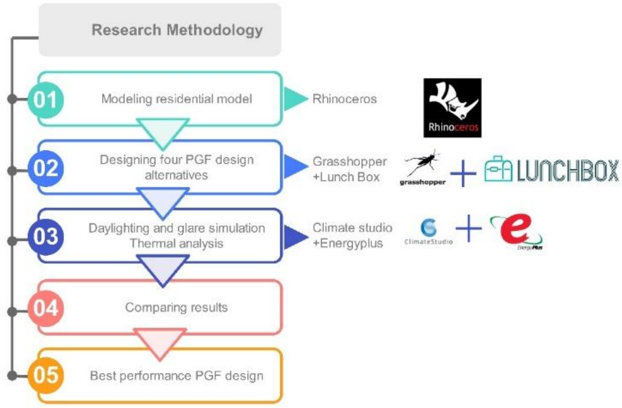


Figure 1: Research methodology

Using Rhino software and the Grasshopper plugin, the first model for the simulation was made. Then using lunch box plugin, the four PGF design was modeled. In order to execute dynamic and static daylighting simulations based on two factors of daylight quantity, and glare probability, the Climate Studio plugin can accept common EnergyPlus weather data (EPW). Daylight quality was assessed in terms of daylight distribution and glare using daylight glare possibility (DGP), while daylight quantity was assessed using daylight factor (DF), Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Average Lux.

Climate studio has been validated in many studies in simulating the conditions of indoor thermal comfort in buildings, proving the software's precision in forecasting indoor climatic parameters, as proved in [25][26]. The sensor spacing was set at 0.5 m, the simulation regions were excluded from the 0.5 m border distance to the walls, and the simulation planes were likewise 0.8 m above floor level. Every simulation for both tools was based on regional meteorological data (.epw file).

1.6 Model configuration

A. Changing variable

The design of the parametric green facade is the main parameter that is studied, four different designs were tested. For this simulation, the Grasshopper algorithm was employed for parametric façade modeling.

B. Case study description

This study focuses on a residential building's four stories to suit building regulations in Egypt. Each floor comprises one main zone, a living room 4 x 4 with one window in the south measuring 1.5 by 3 meters, the dimensions of the case study residential building is shown in Figure 2.

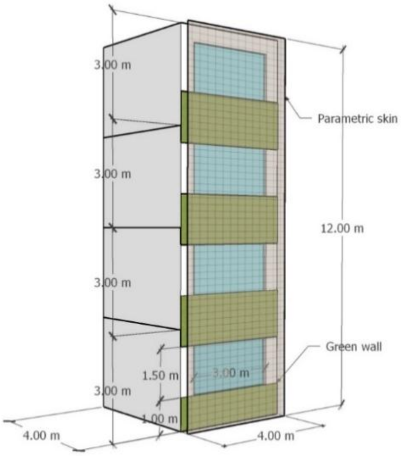
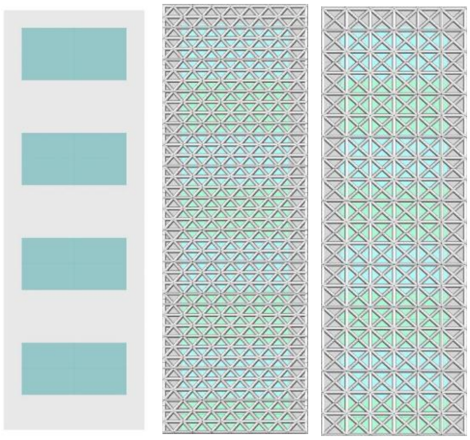
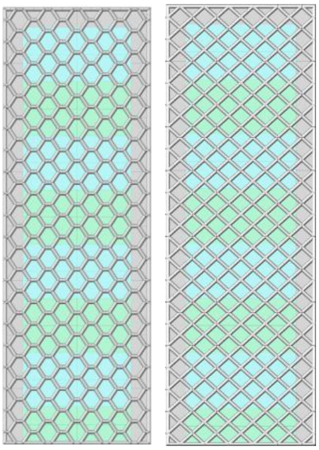


Figure 2: Dimensions of proposed model

Four different PGF designs are examined, the parametric single unit dimensions are similar in the four designs, but various configuration is used, in order to compare daylighting and thermal performance. The basic design of the residential building, which lacks a green façade or parametric skin is also simulated, the basic design and four suggested designs are demonstrated in Figure 3.



a) Basic design **b) PGF design 1** **c) PGF design 2**



d) PGF design 3 **e) PGF design 4**

Figure 3: Proposed PGF designs

LEED report is exported for every case, certain parameters are measured to assess daylighting performance, including Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Average Lux.

On the other hand, the occupation schedule is from 8am to 6pm. Besides, work plane offset is 0.8 from the ground level and sensor spacing is 0.5 m. Besides, the materials used for each object are shown in Table 1; in the case of the basic design, there are no parametric or green layers. Every simulation is based on regional meteorological data (.epw file) for Portsaid city.

Table 1 Used material for climate studio in simulation stage

Object	Material	Rvis	Tvis
Walls	**Matte white wall**	**80.7%**	**0.0%**
Ceiling	**White ceiling**	**85.7%**	**0.0%**
Floor	**Ceramic tile floor**	**70.3%**	**0.0%**
Window	**Clear (Argon)**	**14.9%**	**77.4%**
Green layer	**Greenish grass**	**10.4%**	**0.0%**
Parametric layer	**Grey aluminum facade cladding**	**20.0%**	**0.0%**

1.7 Site details

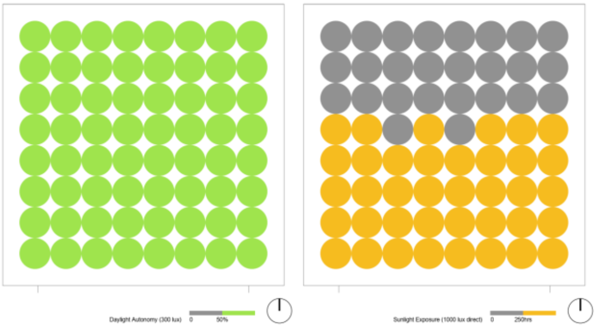
In Portsiad, a coastal city on Mediterranean Sea. The climate is classified as arid desert hot according to the Köppen climatic classification (BSk), although cooling winds from the Mediterranean Sea significantly reduce the excessive heat.

2. RESULTS

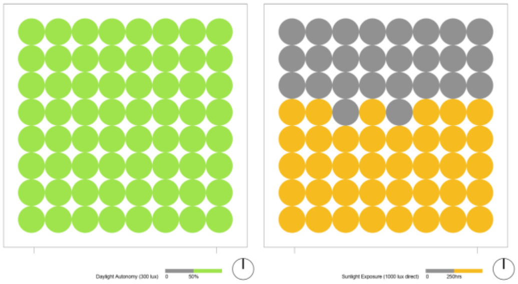
1.8 Daylighting and glare results

1.8.1 Basic case

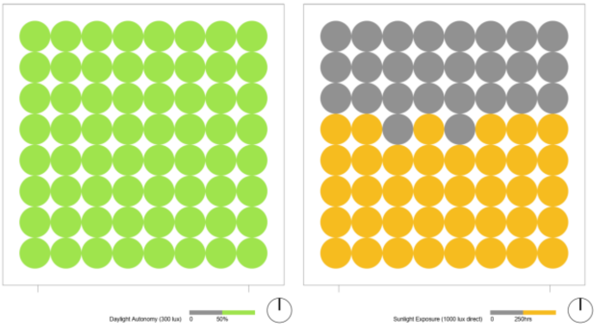
Basic design achieved Annual Sunlight Exposure (ASE) of 59.4 percent for all floors and 8512 average lux. Additionally, Spatial Daylight Autonomy (sDA) of 100% was attained for all floors. The distribution of sDA and ASE for PGF basic design is shown in Figure 4.



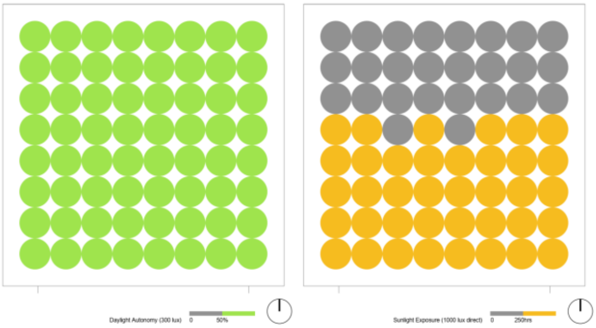
a) Ground floor



b) First floor



c) Second floor



d) Third floor

Figure 4: sDA and ASE in basic design

On the other hand, Figure 5 shows Annual DGP in basic design without any shading, the annual DGP reaches 100%, with 34% imperceptible glare, 9% perceptible glare, 13% distributing and 45% intolerable glare.

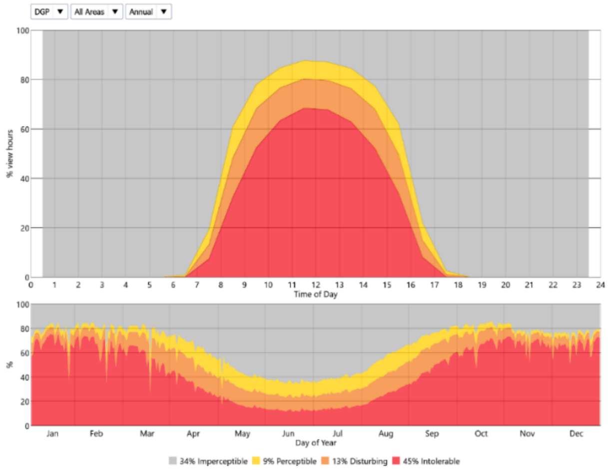
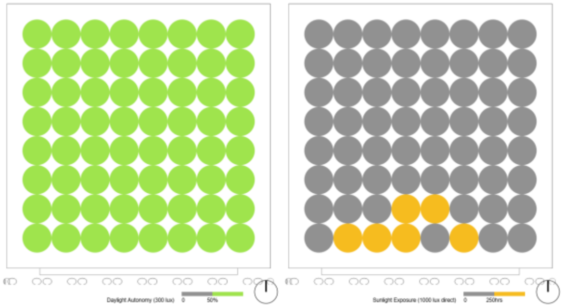


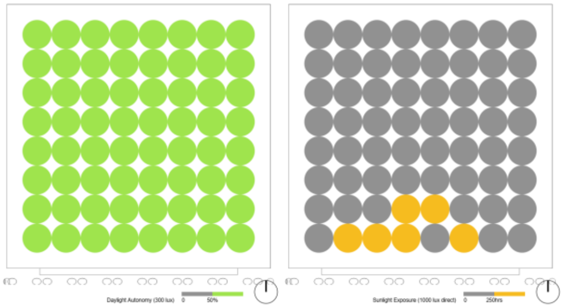
Figure 5: Annual DGP in basic design

1.8.2 PGF design 1

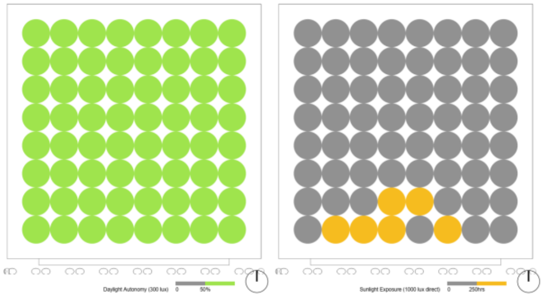
Design 1 achieved Annual Sunlight Exposure (ASE) of 9.83 percent for all floors and 850 average lux. Additionally, Spatial Daylight Autonomy (sDA) of 100% was attained for all floors. The distribution of sDA and ASE for PGF design 1 was shown in Figure 6.



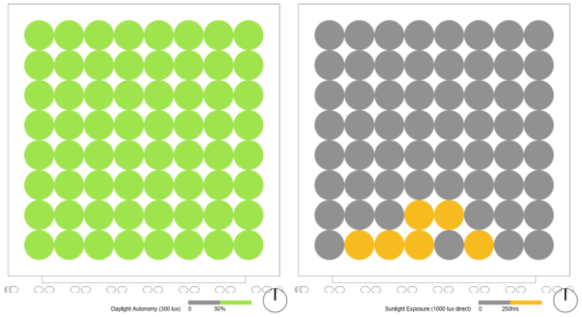
a) Ground floor



b) First floor



c) Second floor



d) Third floor

Figure 6: sDA and ASE in PGF design 1

Conversely, Figure 7 illustrates the Annual DGP in design 1; it reaches 26.7%, with 92% of the glare being undetectable, 4% being perceptible, 3% being distributed, and 2% being intolerable.

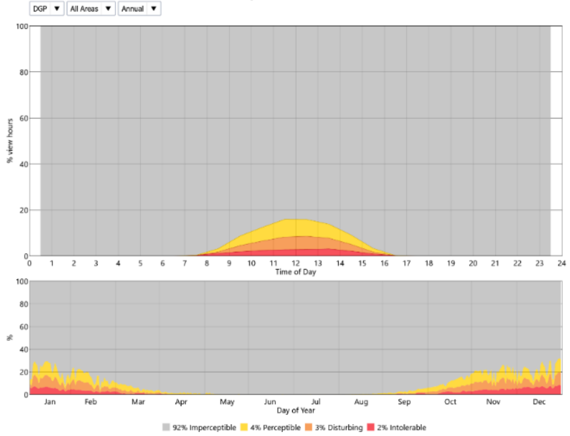
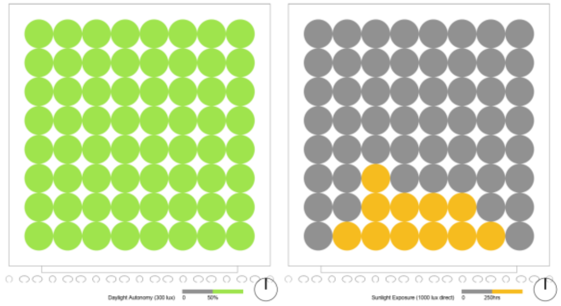


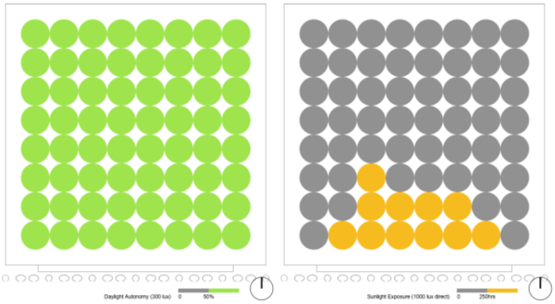
Figure 7: Annual DGP in PGF design 1

1.8.3 PGF design 2

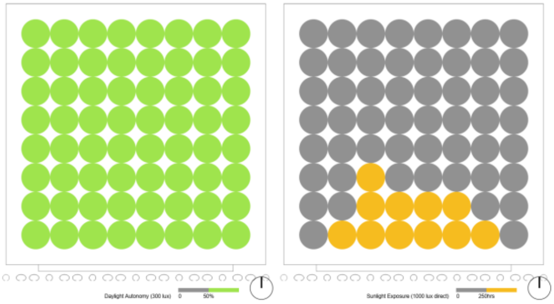
Design 2 achieved Spatial Daylight Autonomy (sDA) equals 100% for all floors and Annual Sunlight Exposure (ASE) reaches 18% for all floors and 2082 average lux. Figure 8 demonstrated the distribution of sDA and ASE in case of PGF design 2.



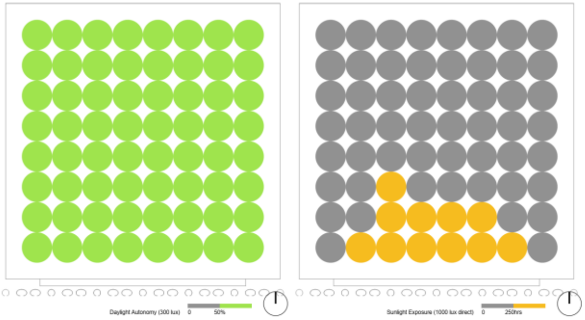
a) Ground floor



b) First floor



c) Second floor



d) Third floor

Figure 8: sDA and ASE in PGF design 2

Alternatively, Figure 9 shows the Annual DGP in design 2, which is 29.1%; 89% is undetectable, 5% is perceptible, 4% is dispersed, and 2% is unbearable.

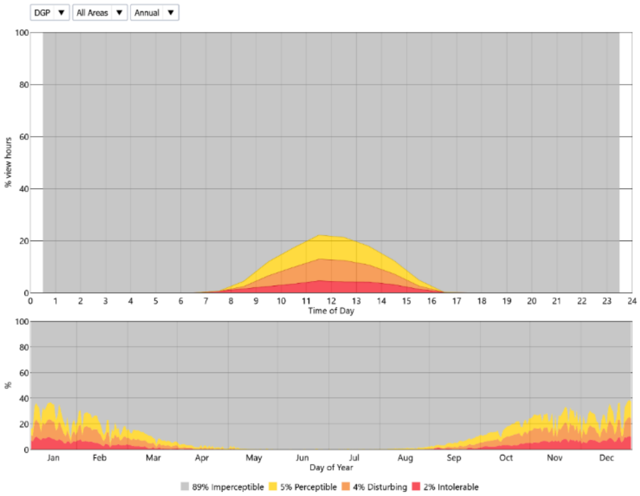
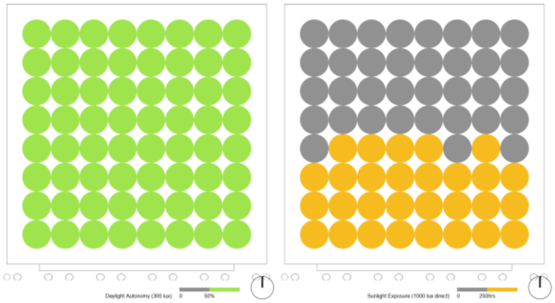


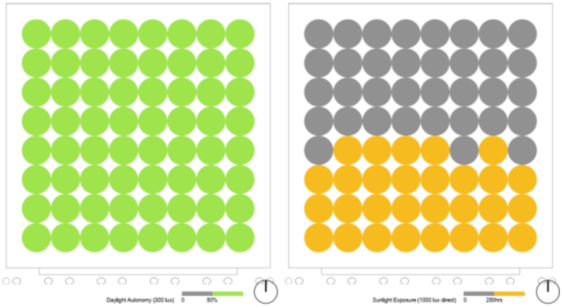
Figure 9: Annual DGP in PGF design 2

1.8.4 PGF design 3

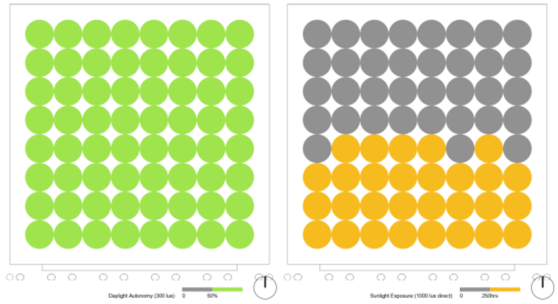
Design 3 attained average Annual Sunlight Exposure (ASE) equals 46.1%, and 4632average lux. In details, ASE equals 45.31%, in case of ground, first and second floor and 48.44% in case of third floor. Additionally, Spatial Daylight Autonomy (sDA) of 100% for all floors was attained. The distribution of sDA and ASE for PGF design 3 was shown in Figure 5.



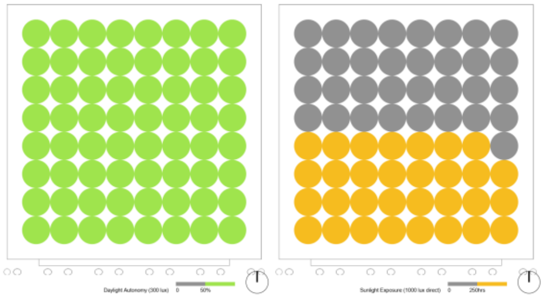
a) Ground floor



b) First floor



c) Second floor



d) Third floor

Figure 10: sDA and ASE in PGF design 3

In contrast, Figure 11 illustrates the Annual DGP in Design 3, which is quantified at 99.9%. The data reveals that 62% of this is undetectable, 8% is perceptible, 11% is dispersed, and 20% is classified as unbearable.

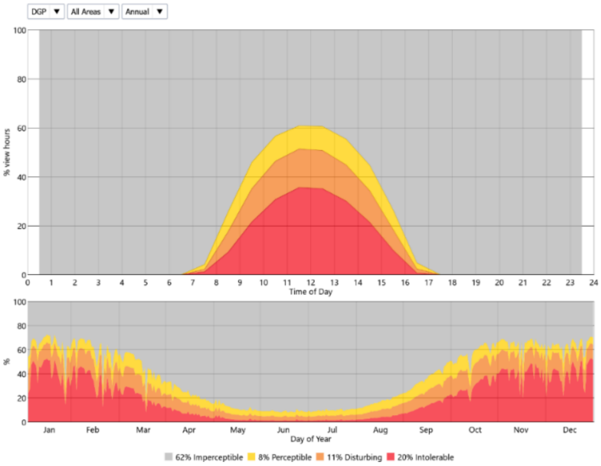
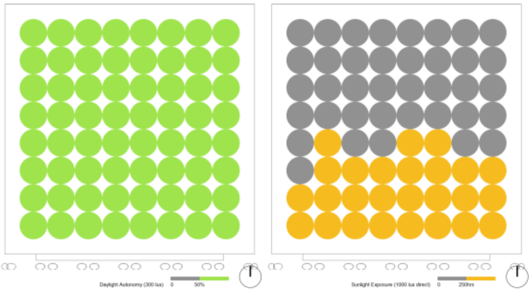


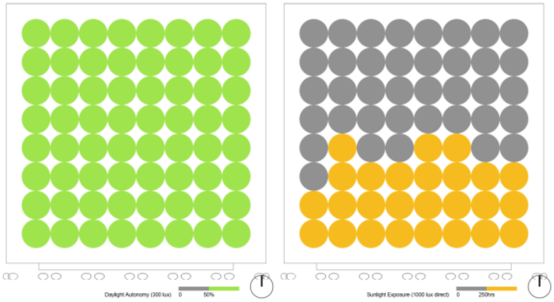
Figure 11: Annual DGP in PGF design 3

1.8.5 PGF design 4

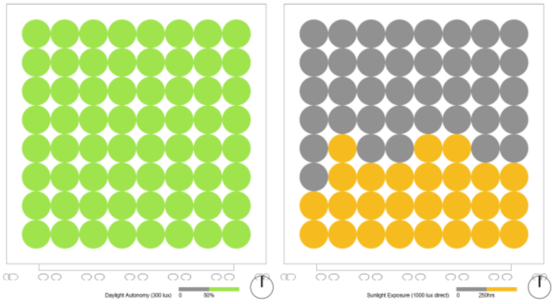
Design 4 attained average Annual Sunlight Exposure (ASE) equals 41.8%, 40.63% for ground, first and second floor and 45.31% for third floor. On the other hand, it achieved 4126 average lux. Additionally, Spatial Daylight Autonomy (sDA) of 100% for all floors is attained. The distribution of sDA and ASE for PGF design 3 is shown in Figure 12.



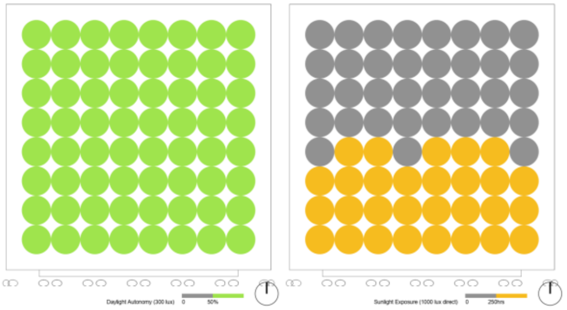
a) Ground floor



b) First floor



c) Second floor



d) Third floor

Figure 12: sDA and ASE in PGF design 4

Figure 13 illustrates the Annual DGP in design 4, where it equals 91.4%. The breakdown is as follows: 76% of the time, the DGP remains undetectable, 7% of the time, it is perceptible, 8% of the time, it is dispersed, and for 9% of the time, it is considered unbearable.

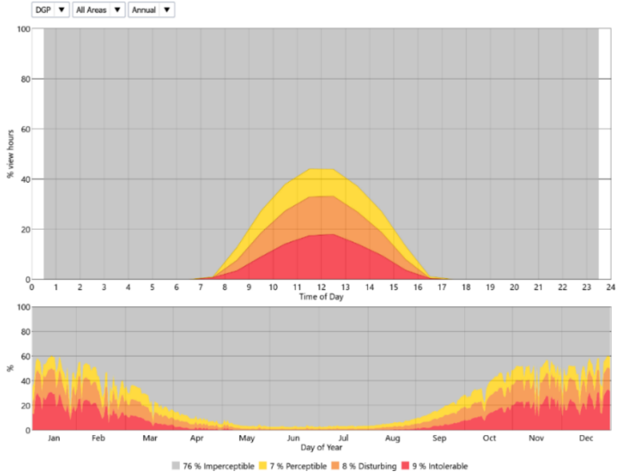


Figure 13: Annual DGP in PGF design 4

1.9 Energy consumption

1.9.1 Basic case

When the basic design is implemented without any PGF, the annual carbon emissions equals 158 $kgCO^2/m^2$, the site's energy use intensity (EUI) reaches 272 kWh/m^2, and the costs associated with operational energy consumption are 27 $\$/m^2$. The building's overall monthly EUI values for equipment, lighting, HVAC, and lighting are displayed by Energy Use Intensity as demonstrated in Figure 14. It Ranges from 13 kWh/m2 in February to 37 kWh/m^2 in October. Also, ClimateStudio provides hourly dry bulb, mean radiant, operative, and relative humidity RH readings at the zone level, all at the center of a zone as shown in Figure 15. Finally, RH reaches approximately 50% and the air temperature ranges from 20 to 26 º C.

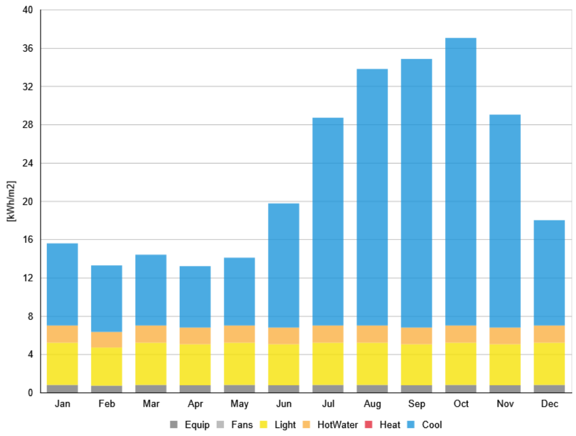


Figure 14: Energy Use Intensity in basic case

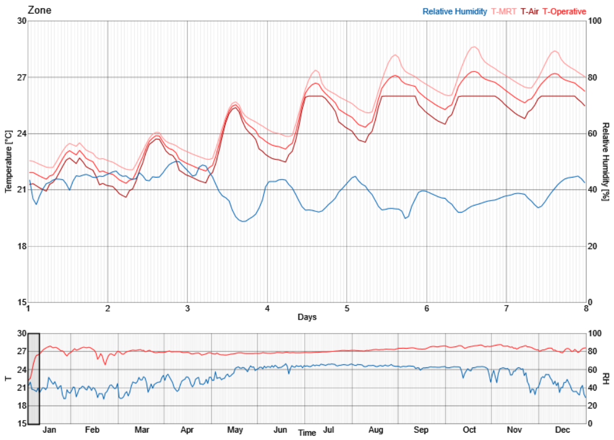


Figure 15: Daily Weekly Zone Temperature in basic case

1.9.2 PGF design 1

When it comes to PGF design 1, the site's energy use intensity (EUI) is reached 196 kWh/m^2, the annual carbon emissions are equal 112 kgCO^2/m^2, and the operational energy consumption expenses are 19 \$/m^2. Energy Use Intensity of PGF design 1 is demonstrated in Figure 16, it ranges from 7 kWh/m^2 in February to 30 kWh/m^2 in August. On the other hand, RH rangers from 35% to 55% and the air temperature ranges from 25 to 26 º C as shown in Figure 17.

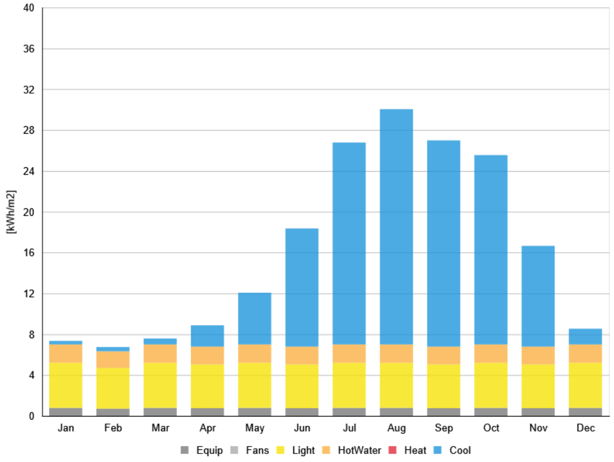


Figure 16: Energy Use Intensity in PGF design1

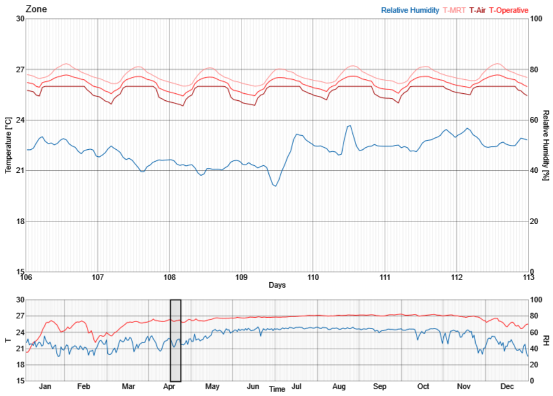


Figure 17: Daily Weekly Zone Temperature in PGF design 1

1.9.3 PGF design 2

Regarding PGF design 2, the site's energy use intensity (EUI) is reached 196 kWh/m2, the annual carbon emissions are equal 112 kgCO2/m2, and the operational energy consumption expenses are 19 \$/m2. Energy Use Intensity of PGF design 2 is demonstrated in Figure 16, it ranges from 7 kWh/m2 in February to 30 kWh/m2 in August. On the other hand, RH reaches ranges from 35% - 55% and the air temperature ranges from 25 to 26 º C as shown in Figure 19.

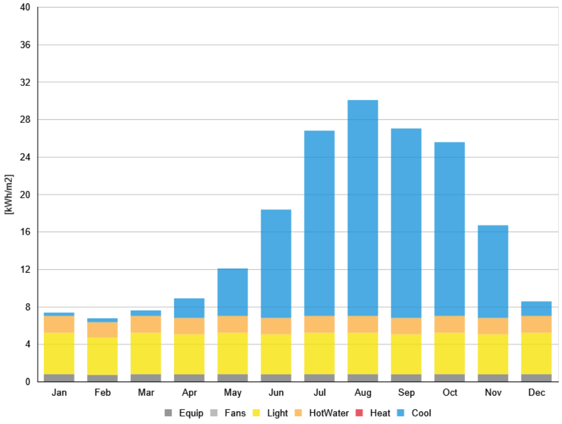


Figure 18: Energy Use Intensity in PGF design 2

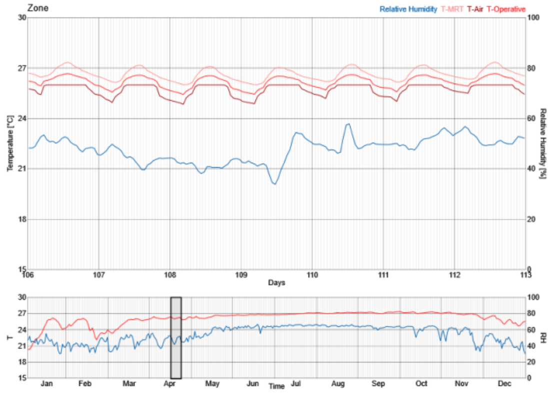


Figure 19: Daily Weekly Zone Temperature in PGF design 2

1.9.4 PGF design 3

Regarding PGF design 3, the site's energy use intensity (EUI) reaches 195 kWh/m^2, the annual carbon emissions equal 111 kgCO^2/m^2, and the operational energy consumption expenses are 19 \$/m^2. Energy Use Intensity of PGF design 3 is demonstrated in Figure 20, it ranges from 7 kWh/m^2 in February to 30 kWh/m^2 in August. On the other hand, RH reaches ranges from 35% to 55% and the temperature ranges from 25 to 26 ° C as shown in Figure 21.

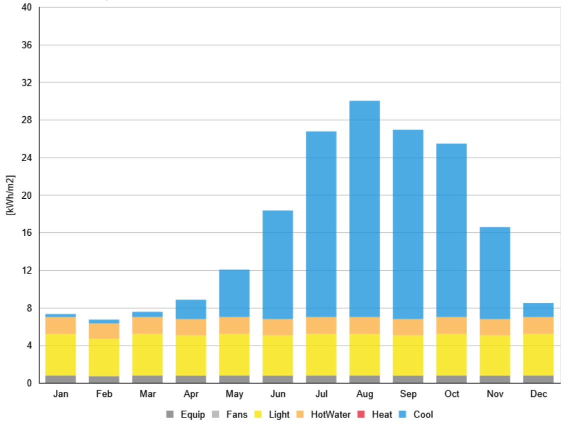


Figure 20: Energy Use Intensity in PGF design 3

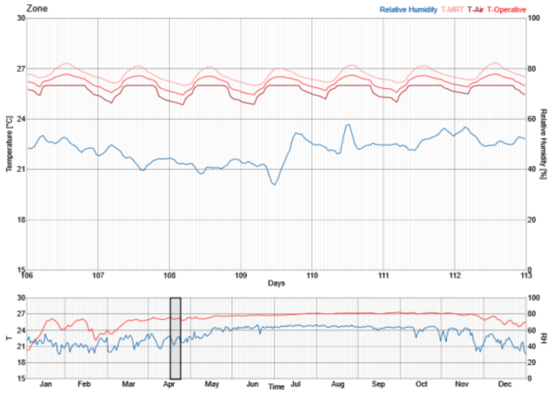


Figure 21: Daily Weekly Zone Temperature in PGF design 3

1.9.5 PGF design 4

In case of PGF 4, the annual carbon emissions equal 112 kgCO^2/m^2, the site's energy use intensity (EUI) equals 196 kWh/m^2, and the costs associated with operational energy consumption are 19\$/m^2. Energy Use Intensity of PGF 4 is demonstrated in Figure 22, it ranges from 7 kWh/m^2 in February to 30 kWh/m^2 in August. On the other hand, RH reaches a range between 32% to 55% and air temperature ranges from 25 to 26 ° C as shown in Figure 23.

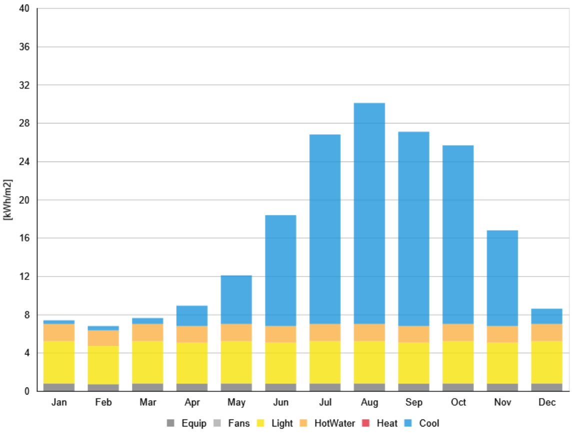


Figure 22: Energy Use Intensity in PGF design 4

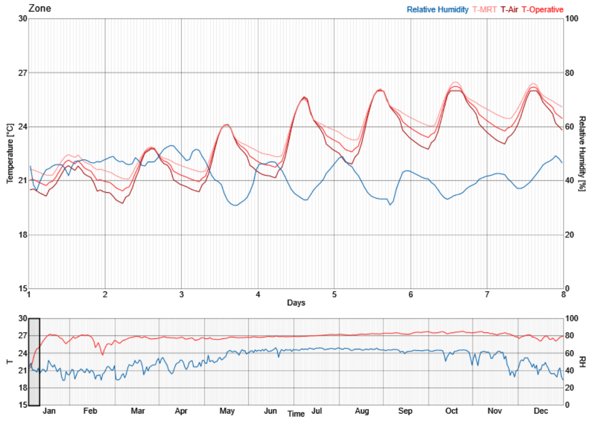
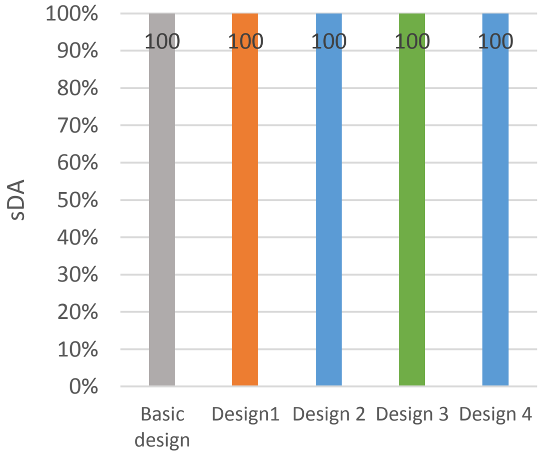


Figure 23 Daily Weekly Zone Temperature in PGF design 4

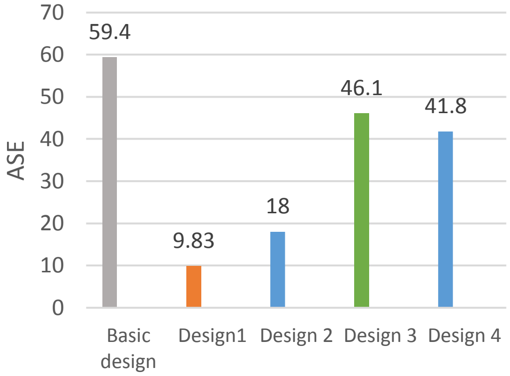
1 DISCUSSION

As seen in as shown in Figure 24-a, all designs achieve 100% Spatial Daylight Autonomy, ensuring consistent daylight availability across all floors. The basic design and PGF 3 and PGF 4 have higher ASE percentages as demonstrated in as shown in Figure 24-b, indicating more direct sunlight exposure, but with higher average lux levels, potentially leading to brighter and more uniformly lit spaces. Besides, PGF 3 significantly increased average LUX, resulting more direct sunlight and average lux as shown in Figure 24-c, which might not be suitable for environments where glare and overheating are concerns.

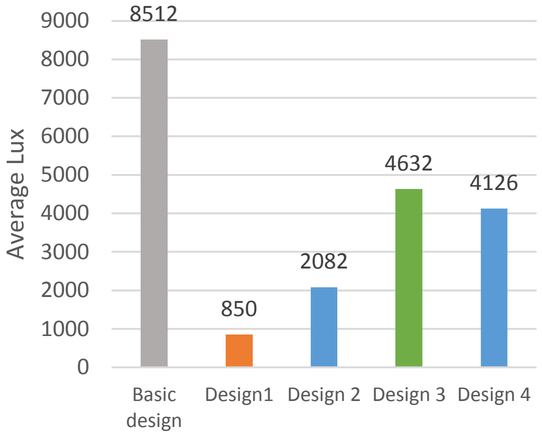
As a result, DGP has achieved the highest values in case of basic design and PGF 3 and PGF 4, while PGF 1 and PGF 2 have the lowest values as shown in Figure 24-d. So, in general PGF 2 has the most adequate daylighting performance with acceptable DGP level.



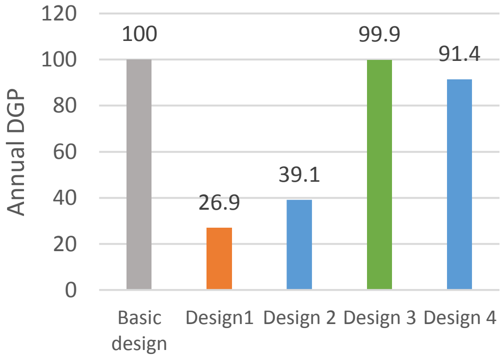
a) sDA in basic design and proposed designs



b) ASE in basic design and proposed designs



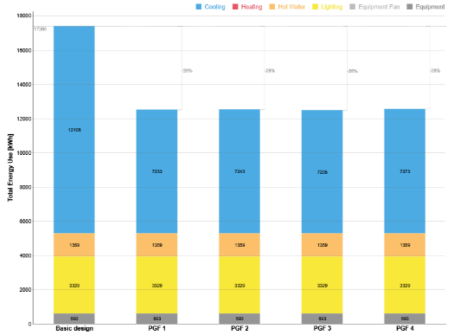
c) Average LUX in basic design and proposed designs



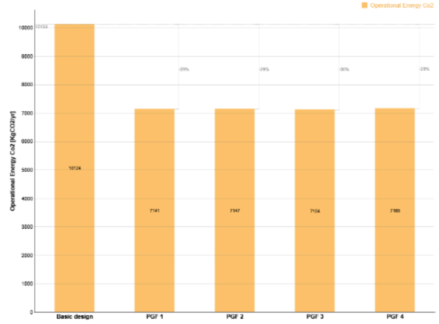
d) Annual DGP in basic design and proposed designs

Figure 24: Comparison of basic design and the four proposed PGF designs in daylighting performance

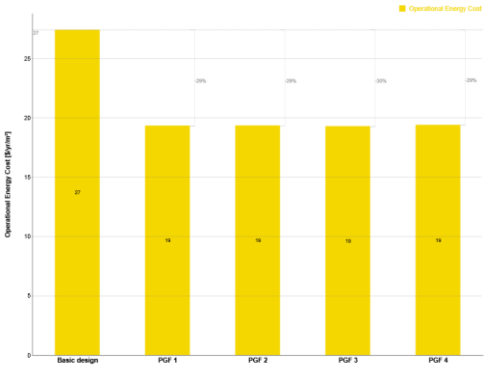
As demonstrated in Figure 25, When compared to the original design, all suggested changes improve the model's thermal performance, with relatively comparable values. Total Energy use has decreased by 28% in the proposed designs compared to the basic one as shown in Figure 25-a. Additionally, Figure 25-b showed that operational energy CO2 had decreased by 29% in the four suggested designs, and Figure 25-c showed that operational energy cost had decreased by 29% to 30%. Finally, as shown in Figure 25-d, it is clear that the four suggested designs have reduced the overall energy gain (Kw/h).



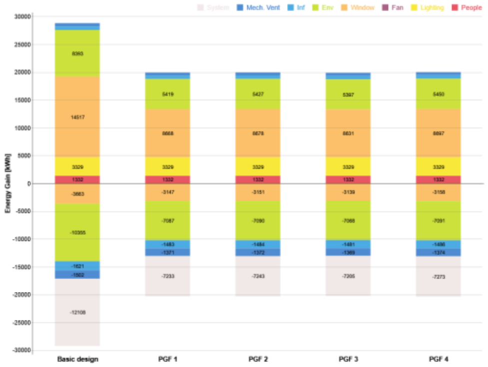
a) Total energy use (kW/h) in basic design and proposed designs



b) Operational energy CO^2 ($kgCO^2$/yr) in basic design and proposed designs



c) Operational Energy cost ($/yr/m^2) in basic design and proposed designs



d) Energy Gain (Kw/h) in basic design and proposed designs

Figure 25: Comparison of basic design and the four proposed PGF designs in thermal model simulation

In general, design 2 has approved the most acceptable performance in daylighting, glare and energy consumption, because it has a descent opening ratio and achieve adequate shading.

2 CONCLUSION

Parametric skin effectively increases interior daylighting and reduces glare. This study demonstrates that integrating a parametric facade with a green layer (PGF) can significantly enhance sustainable design in residential buildings. The most effective design reduced DGP by 60% compared to the basic design, achieving acceptable average lux and ASE levels, thus ensuring a balanced and comfortable indoor lighting environment.

From the thermal perspective, the implementation of parametric skin resulted in a notable reduction in energy consumption by 28% and a decrease in operational energy costs by 29%. However, the analysis revealed that the specific design of the parametric skin had a minimal impact on thermal performance, as all four proposed designs exhibited similar results. This suggests that while the concept of parametric facades holds promise for thermal efficiency, further refinement and optimization of the design are necessary to maximize its benefits.

The comprehensive analysis underscores the potential of integrating parametric facades with green layers to achieve sustainable design goals in residential buildings. The findings highlight that PGFs not only enhance daylighting and reduce glare but also contribute to energy savings and cost reduction. This dual benefit makes PGFs a valuable tool for architects and designers aiming to create energy-efficient and comfortable living spaces.

Future research should explore additional design variations and configurations to further optimize both daylighting and thermal performance. Investigating the impact of different materials, green layer compositions, and facade geometries could provide deeper insights into the capabilities of PGFs. Moreover, long-term studies assessing the durability and maintenance of these systems in various climatic conditions would be beneficial. By continuing to refine and innovate, the potential of parametric green facades to transform urban residential design can be fully realized.

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None

Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Funding

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