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A Study of the Impact of Parametric Façade Openings' Design on Thermal Comfort and Energy Consumption of Office Spaces in Egypt Using Simulation Based Techniques

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Abstract

This research presents the findings of an experimental study probing the impact of façade opening design on energy consumption in offices in Egypt. This study aims to provide considerations and insights for architects and relevant professionals for designing office façades. This will be achieved through conducting a trial on a software design program with the aim of overcoming high energy costs and optimizing interior thermal comfort of occupants. The exploration builds upon former studies that stressed the significance of façade design in achieving optimal thermal comfort and energy effectiveness. Accordingly, the research adopts a comprehensive experimental approach that incorporates building simulation using a design program (Rhino and Design Builder) based on recommendations from former studies. The program encompasses factors such as window-to-wall ratios, shading systems, glazing options, office façade exposure, and interior partition types. The trial involves the development of computer-generated mock office model of parametric façade design and other façade design configurations. The temperature, moisture, and energy consumption are then measured and analysed for each design alternative. This exploration contributes to the advancement of sustainable design practices in Egypt by providing valuable information and insights for designing office façades. Architects, engineers, and relevant professionals can utilize these findings in the design process to optimize the energy efficiency of office spaces in Egypt, offering a more comfortable and productive space for users.

Keywords: lighting, parametric design, office building, façade design

1. Introduction

A well-designed office space is vital for providing all employees with the needed comfort. A comfortable working environment is crucial for productivity and well-being [1]. Providing adequate lighting and temperature that suits both employees and clients is of extreme importance [2]. Employee productivity can be boosted in workstations by providing sufficient daylighting through façade openings [3]. Furthermore, it was found that temperature, ventilation, humidity, and lighting are major determinants of a comfortable workplace. The effects of thermal and visual discomfort on a worker's general well-being and productivity could prove significant. It has been proven that the internal environment and ergonomics affect employee productivity [4]. Long-term exposure to thermal and visual discomfort can cause weariness, reduced productivity, and concentration [5]. An office building typology is frequently characterized by glazed façades which often cause major solar gain values, heavily influencing the building's cooling energy demand, thermal and visual comfort, and artificial lighting energy demand [6]. According to Bande et al. (2022), buildings' façades are responsible for the loss of heat in winter seasons and heat gain in summer seasons [7]. These aspects have a severe impact on energy consumption. Accordingly, this necessitates a study to evaluate the effect of various façade design alternatives on the thermal and energy performance of office buildings.

1.1. Factors Affecting the Design of Façade Openings in Office Spaces

The primary source of light is daylight, which benefits a person's biological demands as well as their visual and psychological comfort [8]. To reduce the need for electric lighting and save energy, daylighting is a way of admitting natural light, i.e.: direct sunlight and diffused light, into a building under controlled circumstances. Daylighting aids in fostering a visually engaging and productive atmosphere for occupants while saving up the overall energy expenses of the building by offering a direct connection to the dynamic and continually changing outdoor lighting patterns. Thus, it can be inferred that daylighting minimizes the reliance on using artificial lighting and thus saves electricity and helps in reducing the building's energy consumption [9, 10]. Additionally, reading, productivity, and project engagement are all significantly impacted by the amount of daylight in a space. Daylight is also recognised as one of the factors that improves the quality of an environment and influences how long an individual passes time there [11]. Moreover, there are several "passive" design techniques that should be considered to admit daylighting successfully into a building as well as minimize its undesirable effects such as the building orientation, form, interior finishes, shading devices, opening size, spacing, and location, as well as glazing material [9].

Building form and façade orientation are important to regulate the interaction between the building and the external elements such as the amount of sunlight penetration, wind, and views [2]. The orientation and design of a façade can significantly impact the building's energy efficiency, daylight performance, natural ventilation, thermal comfort, and overall architectural design [12, 13]. In a hot arid zone climate like Egypt, building orientation has a large impact on the level of energy consumed in a building and achieving thermal comfort for its occupants [14].For example, in the northern hemisphere (which includes Egypt), the northern façade has diffused daylight with minimal solar heat gains and offers a pleasant and aesthetically pleasing light all day, only requiring shading in the early morning or late afternoon. East and west facing windows are the least preferred sources of daylighting since these two sides get low angle sunlight due to the lower altitude of sun during the year in the late afternoon and evening. In the summer, windows that face east or west can contribute significantly to heat gain in the morning and afternoon, respectively, and thus more energy consumption. Southern facades have high levels of light intensity during the day and the year, which provide an excellent source for daylighting, however, the downside is that it is considered a huge source of solar heat gain [15, 16].

Moreover, a building's geometry significantly impacts the daylight availability within a space. Long and narrow footprints are considered more effective than bulky square shaped ones for the purpose of maximizing daylight into a building. In addition, the positioning and size of the openings enable effective daylighting inside building spaces by regulating the quantity of light as well as heat gain. Openings' location impacts the amount of natural light that penetrates the interior space. For instance, wide vertical windows positioned at the top of the wall optimizes the daylighting in a room. On the other hand, horizontal roof lighting is considered more effective when compared to vertical windows [17]. According to Köppen classification, Egypt (where the study is conducted) has a hot, arid climate "BWh", and the country experiences very high radiation intensity from the sun for most of the year. Maintaining enough daylighting in such a place is somewhat difficult, especially that most office buildings in Egypt tend to consume artificial lighting at night due to inadequate daylighting distribution [18], and this in turn also affects the thermal comfort of employees.

1.2. Thermal Comfort

Thermal comfort refers to the subjective satisfaction of individuals with the thermal conditions in a specific space. It is stimulated by using several elements, including temperature, humidity, and ventilation. Understanding and implementing appropriate thermal comfort standards act as crucial role in achieving optimal indoor environments [5]. Poor environmental conditions in an office can have negative consequences on workers' performance and well-being. Extremes in indoor room temperature and humidity can cause thermal discomfort and in some cases health problems [19]. Accordingly, temperature control within buildings is a critical factor in ensuring occupant's comfort and well-being. Glare control measures, such as adjustable blinds, diffusing screens, and proper window orientation, were found to mitigate thermal discomfort and improve visual comfort in office spaces [9]. To guide designers and engineers in developing comfortable indoor environments, diverse international standards were developed. Those requirements provide pointers for temperature stages and other elements associated with thermal comfort in different types of spaces. The ASHRAE Standard 55 offers standards including those related to indoor thermal environmental factors (temperature ranges, humidity ranges, and air velocities) for various occupancy types and activities, in addition to other personal factors (such as metabolic rate), which will be used in the experimental study [20].

1.3. Parametric Façade Design

Parametric shapes imitate inorganic and organic natural forms, that originates from natural features. Forms that resemble nature and buildings that imitate the biological developments of natural features are produced by parametric design, as opposed to the forms produced by preceding design movements. Parametric façade design refers to the application of computational algorithms and digital tools to generate complex and intricate building facades. This design approach allows architects and designers to create dynamic and responsive building envelopes that can adapt to various environmental, contextual, and functional requirements. Parametric modelling software, such as Grasshopper for Rhino or Dynamo for Revit, enables designers to change and control design parameters, such as shape, geometry, and material properties, in a systematic and algorithmic manner. By using parametric façade design, architects can achieve highly customized and optimized solutions that blend aesthetics, performance, and sustainability in addition to the exploration of infinite design iterations and enables the integration of complicated geometries and patterns. Parametric façade goes beyond aesthetics; it allows for overall performance optimization. By integrating computational algorithms, designers can analyse and simulate various environmental elements, which include sun radiation, wind patterns, and daytime penetration. This information-driven method permits architects to optimize the façade's performance through controlling sun heat gain, maximizing natural lighting, and minimizing energy intake. The dynamic nature of parametric façade’s design permits adaptive responses to changing environmental conditions, enhancing each occupant’s comfort, and improving energy performance [7].

2. Methodology

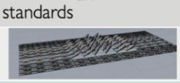
This research adopted a quantitative approach that provided insights into the effectiveness of active and passive techniques in improving the energy efficiency of a building. By utilizing the Design Builder software application, a comprehensive analysis can be conducted to assess the impact of active and passive techniques on the building's energy consumption and thermal comfort. A virtual model of an office building was designed and modelled on Rhino software and then the computer-generated model was imported into Design Builder software application to measure the occupants’ thermal comfort and energy consumption inside the modelled office space. The building's geometry, construction details, and environmental conditions were defined within the software. Active techniques, such as kinetic parametric facades, were incorporated into the model and their effects were analysed through simulations. Similarly, different window materials were simulated to assess their effect on the thermal performance. The first aspect under investigation is the application of active techniques in parametric façade design. Active techniques typically include mechanical systems that involve the integration of dynamic building elements. While the second aspect of the study focuses on passive techniques that are design features that do not rely on mechanical systems such as windows’ materials and insulation that include low-emissivity glass or double-glazing. By incorporating these elements, the study aims to quantify their impact on the energy performance of the building in terms of the cooling and heating demands, thermal comfort, as well as the overall energy consumption. The results obtained from the simulations will enable architects and designers to make informed decisions regarding the selection of appropriate strategies for achieving sustainable and energy-efficient buildings.

2.1. Building Simulation

Design Builder software application is an effective building simulation software program that allows architects and engineers to analyse and optimize the energy performance of buildings. It affords a complete set of gear and capabilities to model, simulate, and examine numerous design techniques, allowing for knowledgeable selections and creating energy simulated buildings. To use Design Builder in simulation, a systematic approach that incorporates several key steps should be considered. The software program provides users with the ability to define the building's geometry, creation substances, HVAC systems, and different applicable parameters in addition to a library of pre-defined additives and substances for smooth choice and customization. A top-level view of the software program and description of the general workflow for the use of Design Builder is discussed in this paper.

The workflow typically begins with the introduction of constructing the model. This involves importing architectural drawings or creating the version from scratch inside the software. Users can define the construction’s layout, along with partitions, flooring, roofs, and fenestration factors, with measurements and orientations. For instance, the layout is drawn with the exact dimensions of the office building. The northern façade should be indicated to avoid incorrect orientation of the building for more accurate results. In this study the examined zone is located on the 3rd floor with a south-east façade with an external wall of South façade of 33.309 m^2 and East façade of 45.169 m^2. Four alternatives were chosen to examine the applied studies and observe the discrepancy of the attained results as shown in Table 1.

Table 1. Comparative Analysis of the Four Alternatives with Different Inputs

	Basic Method Alt. 1	Passive Technique Alt. 2	Active Technique Alt. 3	Advanced Technique Alt. 4
External Window Type	Single Glass 6mm	Double Blue Glazed Window	Single Glass 6mm	Double Blue Glazed Window
Thickness	6mm Single Glass	6mm/ 13mm Argon filled	6mm Single Glass	6mm/ 13mm Argon filled
Height (m)	1.5	1.5	1.5	1.5
Sill Height (m)	0.8	0.8	0.8	0.8
Glazing (%)	10	30	10	30
Window to wall (%)	30	30	30	30
Total Solar Transmission	0.62	0.48	0.62	0.48
Cost per area (EGP)	4089.32	6691.61	4089.32	6691.61
Luminaire Type	Suspended	Suspended	Suspended	Suspended
Max. Allowable Glare Index	22	22	22	22
Roof	Generic Egypt's roof standards	Bitumen sheets insulated	Generic Egypt's roof standards	Bitumen sheets insulated.
External Façade Design	Original Building's Façade	Original Building's Façade		

A comparative analysis was conducted between four different alternatives. The first alternative is the basic method which replicates the already existing conditions as shown in Figure 1 with inputs of density 0.111 person/m2 and a metabolic rate 123.00 (Watt/person). The heating setpoint temperature is 22 degrees Celsius and the Cooling setpoint temperature is 22 degrees Celsius. The specifications of Alternative (1) are single glass window of 6mm thickness, height of 1.5 m and the height of the windowsill is 0.8 m. Also, the glazing is 10%, window to wall ratio is 30% and the total solar transmission is 0.62. Alternative (2) has the same specifications; however, the external window type is double blue glazed window and of 6mm thickness and filled with 13mm Argon, the glazing is 30%, and the total solar transmission is 0.48. While in Alternative (3), the parametric design of the façade was applied with the same specifications for Alternative (1) in terms of window thickness and glazing. In Alternative (4), the parametric design of façade was applied but of double blue glazed window type filled with 13mm Argon as in Alternative (2).

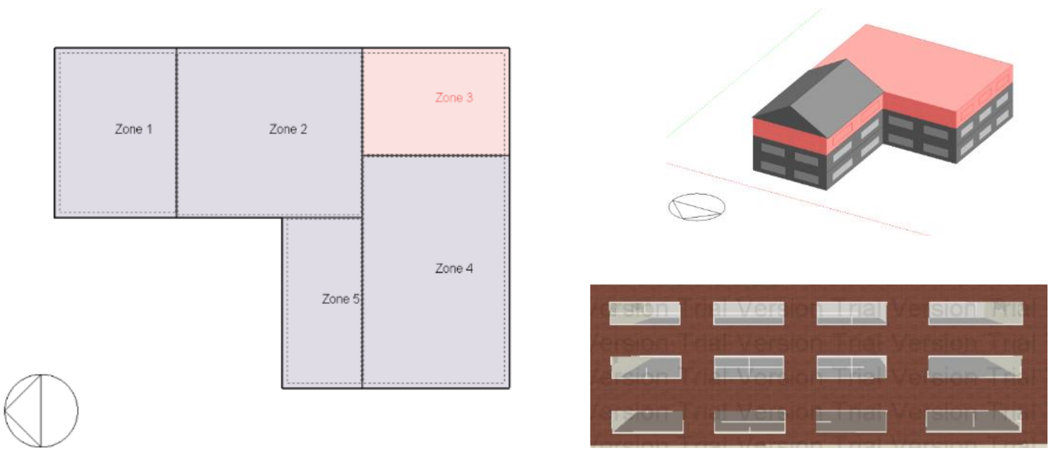


Fig. 1. Alternative 1 Existing Conditions (Developed by the Author, 2023).

3. Results and Findings

The present study explored the possibility of Design Builder as a comprehensive energy simulation software in optimizing thermal comfort and reducing the building's total energy consumption with reference to ASHRAE 55 standards for thermal comfort. The simulation identified some design variations and functional strategies that could effectively enhance occupant's thermal comfort while reducing energy consumption.

Total Site Energy results indicate the energy consumption of the building. By comparing the conventional (basic) case which is Alternative 1 with the applied techniques' results in Alternative 2, it was concluded that applying passive techniques to the office building reduced discomfort hours in zone 3 by 84.8% which enabled the employees to avoid thermal discomfort inside the building, thus being more productive. Likewise, total site energy (energy consumption) decreased by 26% when double glazed windows and roof insulation were used as shown in Table 2.

Table 1. Total Site Energy Results using Alternative 2

	Total Site Energy (KWH)	Cooling	Heating	Unmet
Conventional Case	1149466.26	694832.06	10569.57	1262.5
Passive Technique	843225.67	430759.53	792.28	191.5
Passive Percentage%	26.64198164	38.00523108	92.5041416	84.8316832

In Alternative 3 active techniques were applied, and a parametric façade design was employed based on extracting an equation from a natural element which is the monkey puzzle tree leaf as shown in Figure 2. Furthermore, its algorithms were calculated, and its parameters were reformed. The unit was chosen based on its form's characteristics. It is a green, stiff, and spiky leaf of a rhombus shape. A shape grammar of a zigzag formula can be described as 0 – 1 – 0 – 1 next to each other on the same axis as shown in Figure 2 was created since the monkey leaves on the same axis have a gap that is equal to the width of leaf of the other axis. Moreover, parametric criteria of design were applied and resulted in forming a diagonal line which is rotating around the tree stem with an angle of 45 degrees. The leaves rotate around the stem on the z axis & on the x-axis that resulted in a single diagonal axis that gives a spiral shape around the stem as shown in Figure 2. Several rules and commands were applied on Rhinoceros software to design the 3D unit, and then the whole façade. The modelling commands, rules and process are shown in Figure 3. This form when applied on the building's façade paves the way for air ventilation, filters the air, allows for reduction of air temperature thus producing cooler air leading to lower HVAC usage, enhances indirect sunlight thus better thermal comfort and sustainable façade design. The final developed façade design is shown in Figure 4.

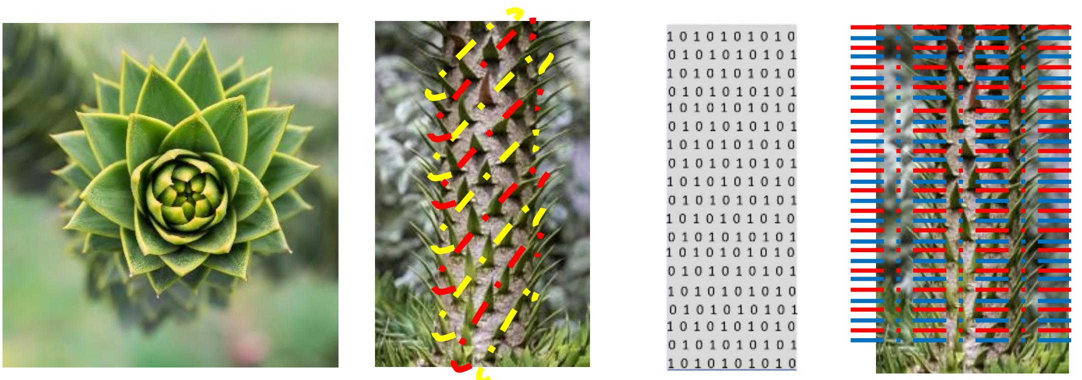


Fig 2. Parameters and Algorithms Based on Monkey Puzzle Tree Leaf (Developed by the Author, 2023)

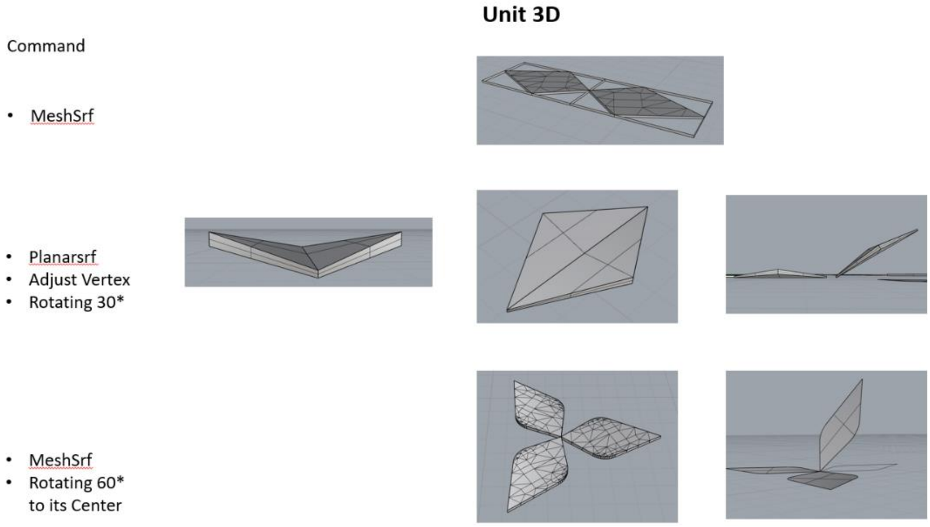


Fig 3. Applied Commands on Rhinoceros (Developed by the Author, 2023).

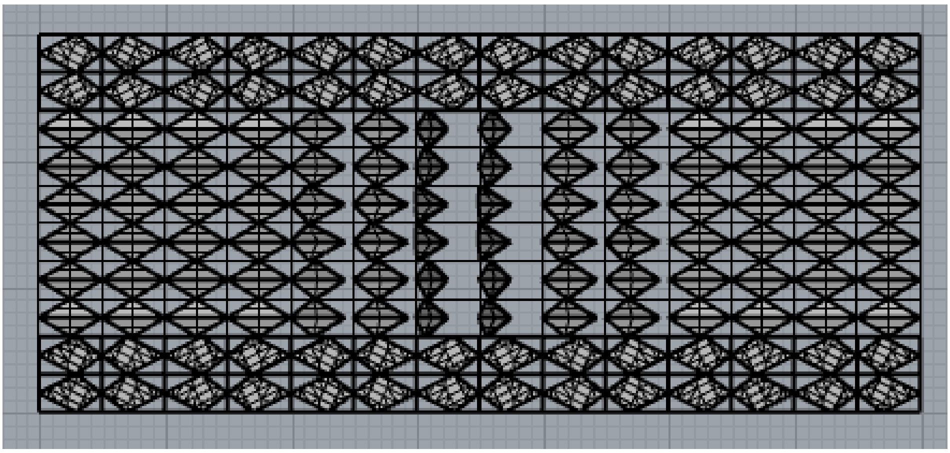


Fig 4. Developed Parametric Façade Design (Developed by the Author, 2023).

By comparing the conventional (basic) case with Alternative 3, the results showed 18% reduction in discomfort hours in the building, but this percentage is less than that the achieved percentage of the passive technique in Alternative 2. However, the total site energy results of the active method have a slightly better energy consumption reduction than the passive technique as shown in Table 3. This led the research to find a fourth alternative (advanced technique) that combines the passive and active techniques together.

Table 2 Total Site Energy for the Active Method (Alternative 3)

	Total Site Energy (KWH)	Cooling	Heating	Unmet
Conventional Case	1149466.26	694832.06	10569.57	1262.5
Active Technique_	839494.46	551931.97	14657.5	1030
Active Percentage%	26.96658534	20.56613364	-38.676408	18.4158416

The integrated techniques resulted in the optimal total site energy by reducing the energy consumption of the building by 40%. The percentage of the "Time Not Comfortable" in the building is reduced by 80%. Therefore, the advanced technique is considered as the optimal solution as it achieved the highest result in total site energy by 40% and exceptional percentage for the thermal comfort by 80% as shown in Table 4.

Table 3 Total Site Energy for the Active Method (Alternative 4)

	Total Site Energy (KWH)	Cooling	Heating	Unmet
Conventional Case	1149466.26	694832.06	10569.57	1262.5
Advanced Case	688583.22	406272.43	10245.66	245.5
Advanced Percentage %	40.09539523	41.5294064	3.06455229	80.5544554

4. Conclusions

According to the achieved results and illustrated graphs and tables, this research concludes that it is vital to study the environmental needs and the users' needs to obtain the most practical and sustainable techniques regarding energy consumption and efficient daylighting. Therefore, by applying the passive and the active methods and developing the optimal methods and materials, better results were achieved by implementing the optimal setting. Total Site Energy was reduced by 40% in the advanced case which proves that the factors studied and developed have positive impact on the performance of the building. The results of the simulation demonstrate the effectiveness of the energy design program in achieving advanced thermal comfort and reduced energy consumption. This, in turn, will help in enhancing employees' productivity. As illustrated in the annual energy consumption graph, the optimal case that integrates the active and passive techniques is more efficient than the conventional case as there was reduction in total site energy by 40%, heating by 3.06%, cooling by 41.5% and the not comfortable time inside the building by 80.6%.

This paper developed some design considerations while designing parametric facades of office spaces based on the thorough analysis of the literature and the simulation-based technique. To ensure natural lighting is evenly distributed to all workstations, it is recommended to use low-height partitions, also to encourage collaboration and result in an open office that allows daylighting. To design a parametric facade a thorough analysis of point position, solar exposure, prevailing wind direction, and girding environment should be conducted. The utilization of computational tool to design and optimize façade design to enhance energy efficiency, daylighting, and visual appeal is crucial. To design parametric facades, it is recommended to use modelling software to allow for a range of designs that integrates complex shapes. Furthermore, material selection is of high importance, thus appurtenances that offer good thermal sequestration parcels, continuity, and low conservation conditions should be considered. Also, the types of windows used should have applicable glazing systems to control solar heat gain and maximize natural daylight to balance between daylighting and the thermal performance. Ventilation and views should be considered to improve indoor air quality while offering occupants the desirable views. Select sequestration accoutrements that are resistant to humidity and ensure proper installation and humidity operation ways to maintain the integrity of the sequestration subcaste. Apply design strategies like shading, natural ventilation techniques, and sequestration to alleviate thermal discomfort.

5. Recommendations

Longitudinal Studies: Conduct long- term studies that gauge multiple seasons to capture variations in thermal comfort and energy consumption throughout the year. This would allow for a further comprehensive understanding of the impact of façade design under different climatic conditions.

Comparative Studies: Compare the performance of different façade opening designs and interior layout configurations to identify the most effective strategies for achieving optimal thermal comfort and energy effectiveness. This can involve comparing colourful window- to- wall rates, shading systems, partition types, and cabinet work arrangements.

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