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Optimizing the Perforation Ratio of Mosques' Solar Screen by Using Genetic Algorithms: A Case Study on El-Farouq Mosque, Cairo, Egypt

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Abstract

Mosques are skin-load-dominated buildings; the temperature of their surrounding environment has a direct influence on their indoor thermal comfort and energy demands. So, it is thought that mosques' envelope design is a key element in optimizing their thermal and energy efficiency. Typically, perforated solar screens (PSS) are used as an outer skin to control solar radiation, reduce energy consumption, and improve visual appeal. The study aimed to use genetic algorithms (GAs) to identify the ideal perforated ratio of PSS that can reduce the annual solar irradiance in a hot, dry climate zone to its lowest values and consequently lessen thermal radiation and energy consumption. The analysis was performed on the men's prayer hall of El-Farouq Mosque in Cairo, Egypt, by applying an Islamic perforated screen to its southeast and southwest facades and roof. Galapagos optimization engine, via Grasshopper interface in Rhinoceros 3D software, was utilized to detect the optimal perforation ratio with the least annual solar irradiance. After that, an analysis was performed to measure the effect of the generated PSS on the thermal comfort and cooling loads of the hall during the hottest week of the year. The results showed that, compared to the current screen, a 0.25% PSS on the southeast and southwest facades and a 0.2% PSS on the roof could reduce the peak annual solar irradiance by 19%, improve thermal comfort measurements, and slightly lessen the cooling loads. Finally, a comparison was conducted between the thermal and energy performance of the current and the proposed PSS.

Keywords

Genetic Algorithms (GAs); Optimization; Mosque Building; Perforated Solar Screen (PSS); Thermal Comfort; Energy Efficiency.

1. Introduction

Mosques are classified as skin-load-dominated buildings, which implies that their thermal and energy performance is greatly affected by their local climate. Research showed that mosques has higher energy demands than other buildings in the same region, particularly when it comes to cooling loads. Others found that proper wall and roof thermal treatment in mosque buildings can save up to 25% of their energy consumption, as enhancing thermal performance directly leads to a decrease in energy demands. Furthermore, it is essential to make sure that the mosque exterior envelope provides worshippers with sufficient thermal comfort so they can feel relaxed, comfortable, and serene (Azmi & Ibrahim, 2020) (Azmi & Kandar, 2019) (Abdullah et al., 2016).

Perforated solar screens (PSS) are passive vernacular shading systems that are applied on building facades to control solar heat gain, energy use, daylighting, and glare effects. In recent decades, there has been a growing interest in incorporating these vernacular technologies into modern structures. Researchers began to explore the relations between PSS various shapes, materiality, and perforation ratios, as well as how they can affect indoor environmental performance (Elzeyadi & Batool, 2018).

The research aims to use genetic algorithms to investigate the optimal perforation ratio of a proposed solar screen applied on a mosque in a hot, dry climate zone that can reduce the solar irradiance value to its lowest level and investigate its influence on indoor environmental thermal quality and energy demands. To attain this aim, the research methodology was divided into four parts. **First,** a literature review clarifies; mosque building functional and operational requirements. Thermal comfort definition and PMV thermal comfort model categories. PSS definition, history, and interrelated research on its performance. Along with genetic algorithms concept, usage, and capabilities. **Second,** introduce the selected mosque location, climate readings, functional zones, and modeling process. Clarify the simulations performed: annual solar irradiance, PMV thermal comfort, and energy simulation. Present the proposed PSS design, perforation ratio and parameters, and optimization process. Compare the measurements of the current and proposed PSS. Third, discuss and analyze results and outputs of the research. Lastly, present the conclusion and future recommendations.

2. Literature review

2.1. Mosque Building

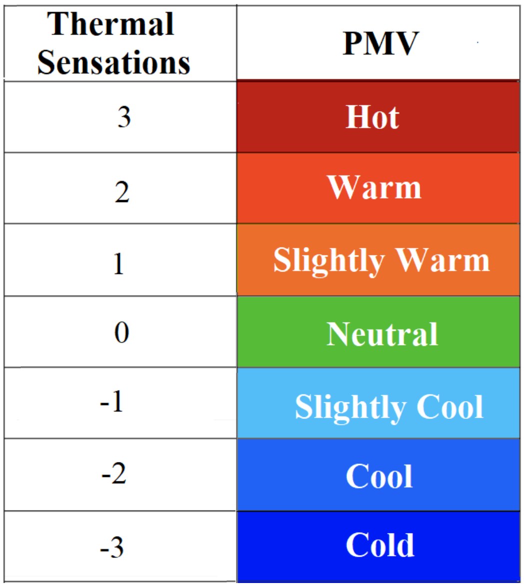
Mosques are religious buildings with a unique set of functional and operational requirements coupled with particular aesthetic characteristics. The most basic design of a mosque is a simple single-story rectangular structure (a prayer hall), with a dome and minaret as its traditional symbols, (Abd Rahman et al., 2021). The longer side of the rectangular prayer hall is usually oriented towards the Qiblah (direction of the Ka'bah in KSA), along which the worshipers pray in rows facing the Qiblah wall, with an entrance at the opposite wall to ensure undisturbed prayer. The prayer hall is often designed as a multiple-volume space to maintain a proper scale of the interior with relation to the floor area and for visual comfort. Mosques usually also have a female prayer space, either on one side of the main prayer hall or in a separate space. The men's prayer hall is usually surrounded by a number of functional requirements that are somewhat similar in all mosques, regardless of climatic and regional differences or cultural influences, such as ablution facilities, toilets, a maintenance office, services, lecture halls, etc. (Azmi & Kandar, 2019) (Azmi & Ibrahim, 2020).

Unlike other buildings, mosques have intermittent occupancy patterns and varying user levels throughout the day. The occupancy level is usually high during the five daily prayer times, which are determined based on the position of the sun: Fajr prayer (at the first light of dawn), Dhuhr prayer (after midday), Asr prayer (late in the afternoon), Maghrib prayer (after sunset), and Isha prayer (beginning part of the night). However, the occupancy level reaches its highest or full level at the weekly Jumuah prayer (held instead of the Dhuhr prayer on Friday). Each prayer typically lasts from 30 to 45 minutes. Beside these prayers, mosques usually arrange other activities, such as Quran memorization lessons or community gatherings, with different occupancy levels. Consequently, mosque functional prerequisites and occupancy patterns are followed by periodic operational characteristics that play a vital role in the thermal comfort of the worshipers as well as the thermal and energy performance of the mosque buildings (Azmi et al., 2023) (Azmi & Ibrahim, 2020) (Azmi & Kandar, 2019).

2.2. Thermal Comfort

Thermal comfort is a worldwide accepted scale for measuring indoor environmental quality (Azmi & Kandar, 2019). It is defined as a state of mind that expresses thermal satisfaction or acceptability within the environment. Providing appropriate thermal comfort leads to enhanced health, well-being, and productivity and helps the occupants to satisfy themselves physiologically and psychologically. However, thermal sensations are different from one person to another, as several factors influence the sensation. These factors can be divided into two categories: environmental parameters, including air temperature, air velocity, relative humidity, and mean radiant temperature; and personal parameters, including metabolic rate and clothing insulation (Arsad et al., 2023) (Abdullah et al., 2016) (Abd Rahman et al., 2021). The environmental parameters change according to the building location and climate zone, while the personal parameters depend on the activity level, gender, age, health, etc. In mosques, activities such as prayers and lectures are considered light activity levels that require sitting in a quiet position or standing with minimal movement. Therefore, the metabolic rate is the same for everyone throughout the year (Azmi & Kandar, 2019).

During the past few decades, several thermal comfort evaluation models have been developed to evaluate thermal comfort, such as the predicted mean vote (PMV) model, the two-node model, and the multi-node model; however, the PMV model is the most commonly used one, as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55 has used PMV to assess interior thermal comfort and ensure acceptable thermal comfort for building occupants. The PMV model is calculated by Professor Fanger's comfort equation for human heat transfer. It is a comprehensive evaluation index that treats the human body as a whole being to predict its thermal response in a steady-state air-conditioned environment. It considers the fundamental equation of human thermal balance, which indicates the level of psychophysical thermal sensation and thermal comfort. The PMV model measures the thermal comfort sensation on a scale from -3 to +3, which corresponds to the categories: cold, cool, slightly cool, neutral, slight warm, warm, and hot, respectively, Figure 1. According to ASHRAE standard 55-2020, in hot climates or in summer, the optimal thermal comfort conditions occur at an air velocity of 0.2 m/s and a PMV between -0.5 and 0.5, with a temperature range of 23.5 to 27 °C (hot temperature) and 20 to 24.5 °C (cold temperature). (Ni et al., 2023) (Sabbour et al., 2023).



Thermal Sensations	PMV
3	Hot
2	Warm
1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Figure 1. PMV thermal comfort model (Sabbour et al., 2023) (Edited by the Author).

In mosques, providing acceptable thermal comfort is essential to allow users to feel comfortable and relaxed enough to concentrate on their prayers. In addition, it is a place for social-cultural gatherings, education, and welfare activities (Abdullah et al., 2016) (Azmi & Kandar, 2019). Most mosques install a heating or cooling system to provide the worshipers with adequate thermal comfort during prayer times, systems that use up to 80% of the overall mosque energy consumption. Despite that, these systems mostly fail to achieve the required comfort temperature levels due to the low efficiency of their external envelope Research had found that the mosque envelope (walls, roofs, windows, and openings) contributed to 90% of the overall thermal load, as the thermal load from humans or equipment is negligible compared to the volume of the mosque. Thus, it has a significant impact on users' thermal comfort and degree of satisfaction. (Azmi & Ibrahim, 2020).

To create an appropriate mosque envelope, it is necessary to study the surrounding environmental climate and its influence on the envelope. The current research focuses on mosques in the hot, dry (HD) climate. The HD climate is characterized by its high temperatures, up to 45 °C in the daytime, with much lower temperatures at night that remain above 7 °C throughout the year. Regions with a hot-dry climate generally receive less than 50 cm of annual precipitation and humidity lower than 40%. The thermal load of mosques in an HD climate is in the form of cooling loads because of heat gain through the building envelope (Azmi & Ibrahim, 2020) (United States Department of Energy, n.d.). Especially on the western side, as it is exposed to the afternoon sun, which results in increasing the heat gain in the interior and raising the cooling load (Azmi & Kandar, 2019).

2.3. Perforated Solar Screens (PSS)

Perforated solar screens (PSS) are flat, opaque, perforated shading panels forming a double skin for partially or fully glazed building façades. The opaque parts of the screen act as solar control systems that reflect sunlight and reduce solar heat gain, manage daylight penetration, glare, energy consumption, and provide privacy protection. While the perforated parts filter direct sunlight, permit airflow, and allow users to view the surrounding environment. Consequently, PSS has a direct influence on the users' thermal comfort as well as lighting, heating, and cooling energy requirements (Chi et al., 2017) (Elzeyadi & Batool, 2018).

In the past, PSS was used for daylighting and thermal comfort control in Middle Eastern countries, known as "Mashrabiya" (Sabry et al., 2012). Mashrabiya was one of the most famous design elements in traditional mosque architecture. It was used to cover windows and openings of mosques that are considered the weakest components in its envelope thermal design, as it allows direct and indirect solar rays to enter the interior, especially in hot climates. Mashrabiya was also used to maintain the privacy of the interior and permit daylight and airflow into the interior while ensuring shading from the direct sun, Figure 2. Nowadays, the mashrabiya is adapted in mosque architecture as a lightweight latticework that shades the wall and prevents its direct exposure to solar radiation, limiting heat gain, decreasing cooling loads, and providing Islamic aesthetic characteristics (Azmi & Ibrahim, 2020), Figure 3.

Figure 2. Traditional mashrabiya
Al-Maridani Mosque (Egypt, 1340 CE)
(Flickr, 2016).

Figure 3. Modern Mashrabiya (Latticework)
DIFC Grand Mosque (United Arab Emirates, 2020)
(Abdullatif Al Fozan Award, n.d.)

With the increased interest in using PSS, many researchers have studied and analyzed the impact of using various screen geometries, materialities, and perforation ratios on indoor environmental quality in different climate zones. (Elzeyadi & Batool, 2018). Their findings showed how PSS has a large influence on enhancing indoor environmental performance. Among them was a study performed on an office building in Tokyo, Japan (a humid subtropical climate), which studied the screen perforated ratio influence on heat removal. It used EnergyPlus and DesignBuilder software to evaluate natural ventilation performance and energy consumption, and then applied a mathematical model to calculate the net heat removal by the perforated screens. The results showed that optimal heat removal throughout a year occurred when the perforated ratio on the south was 10% and on the west was 30% (Srisamranrungruang & Hiyama, 2021).

Another related study studied the influence of the shading screen perforation ratio on the energy performance and indoor thermal comfort of an office building on the south and west facades in two different hot climate zones: Doha, Qatar (a hot, dry desert climate) and Lahore, Pakistan (a hot, humid climate). It used a dynamic environmental modeling software and the IES-VE Apache thermal engine to simulate the impact of the solar-screen shading system on energy performance, solar heat gain coefficient, and indoor thermal comfort. According to the findings, 30% screen perforation improved thermal comfort and energy efficiency in Doha, while 50% perforation performed better in Lahore (Elzeyadi & Batool, 2018).

Another research performed on an open-plan office space in Seville, Spain (a Mediterranean hot summer climate), studied the solar radiation entering through the perforations and its influence on enhancing daylighting and reducing solar gains. It used Rhinoceros software to model the office, EnergyPlus for the energy performance simulation, DIVA/Grasshopper for an annual solar irradiation, and Archsim/Grasshopper linked with EnergyPlus for thermal analysis. The study found that perforation percentage should not exceed 37.5% in the south façade to give intermediate values with respect to lighting, heating, and cooling energy consumption and reduce total energy demand by 55% (Chi et al., 2017).

Additional research was performed on typical residential buildings in the Kharga Oasis in Egypt (a hot, dry climate). It studied the perforation ratio effect on energy consumption by using EnergyPlus software. The study's findings revealed that an 80–90% perforation ratio with a 1:1 depth/opening width ratio could effectively achieve energy savings of up to 30% of the total energy consumption in the west and south facades. (Sherif et al., 2012). These studies have generally evaluated the PSS in office buildings and residences. In this study, the PSS proposed was examined specifically for mosques.

2.4. Genetic Algorithms

Genetic algorithms (GAs) are evolutionary algorithms that resemble biological evolution processes such as the transfer of genes, reproduction, and natural selection, and mutation. In the GAs process, the best genes (parameters) are continuously selected and transferred to the next generation (step). The process repeats continuously and stops only if it reach the required criteria, so at the end of the process, a new generation with ideal characteristics would be generated (Altun & Örgülü, 2014). GAs are usually used to find optimal solutions, especially if there are numerous alternatives (Çağlar & Gedik, 2021).

GAs were used in a wide variety of tools and programs to operate toward the best-performing solutions. For instance, Galapagos/Grasshopper, a genetic algorithm plugin that takes sets of parameters and criteria to search for the fittest alternative that fulfills the objective requirements (Souza & Pauletti, 2016). EifForm, a generative structural design system, uses GAs and Shape Grammar to reformulate, analyze, and promote structural efficiency (Varela, 2013). GENE_ARCH, an evolution-based generative design system that combines GAs with DOE2.1E building simulation software, analyzes thermal heat, daylight, and energy efficiency until it achieves optimal sustainable solutions (Caldas, 2006).

The research used Galapagos optimization engine in its optimization process. Galapagos is an evolutionary solver and a GAs optimization tool used within the platform of the grasshopper interface within Rhinoceros 3D software (Çağlar & Gedik, 2021). It is considered one of the first optimization plugins in Grasshopper. Galapagos takes an objective and one or more sets of variable parameters to search for the optimally optimized solution that fulfills the required objective. It has the ability to select the optimal solution by performing continuous simulations until it reaches the optimal one. It can also perform both environmental and structural optimization processes (Cubukcuoglu et al., 2019) (Souza & Pauletti,2016) (Chi et al., 2017).

Galapagos optimization process could be divided into three main steps (Touloupaki. & Theodosiou, 2016) (Author), Figure 4.

1. *Parametrization:* in Grasshopper, the designer defines the variables and constraints that control the simulation parameters to create an initial population of randomly generated solutions.
2. *Simulation:* use a simulation tool like Ladybug or Honeybee to simulate the generated solutions.
3. *Optimization:* Galapagos uses the variable parameter to perform numerous simulations based on an objective function or a requirement, analyze the solutions, and eliminate unfit ones. After several iterations, it selects the optimal solution.

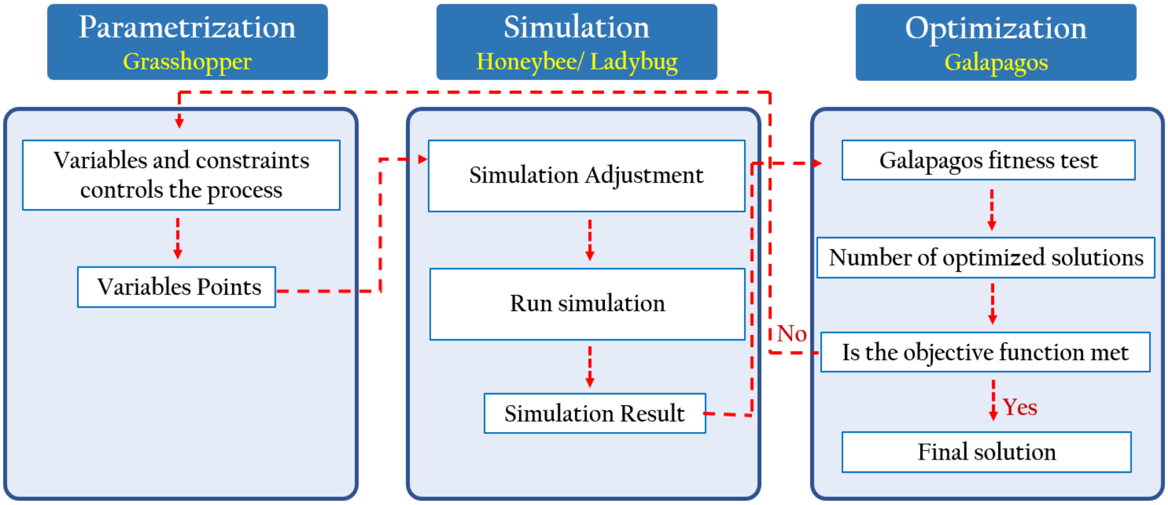


Figure 4. Galapagos optimization process (Author)

3. Materials and Method

This part addresses the processes involved in modeling, generating, and determining the ideal perforation ratio for the proposed solar screen, with the aim of optimizing the thermal and energy efficiency of the chosen mosque. It was divided into four phases. ***First,*** introduce the selected mosque, its location, climate readings, description, and modeling. The mosque was modeled with Rhinoceros 3D software, and then its functional zones, openings, construction materials, current shading screen, and occupancy schedule were coded by Honeybee plugin in Grasshopper/Rhinoceros 3D software. In addition, Ladybug plugin was used in importing, analyzing, and visualizing the location climate data. ***Second,*** discuss the three simulation processes and steps performed. In Grasshopper interface, Honeybee plugin was used as an engine for Radiance, OpenStudio, and EnergyPlus for annual solar irradiance, thermal, and energy simulations. Ladybug plugin was used to visualize the simulation results. ***Third,*** discuss the proposed PSS design, parameters, perforation ratio, and optimizing process steps. The PSS was coded in grasshopper interface, and then Galapagos optimization engine was used to detect its optimal perforation ratio. ***Fourth,*** compare the readings of the existing and optimized shading screens, including their annual solar irradiance, thermal, and energy performance. Figure 5 shows the simulation and optimization methodology.

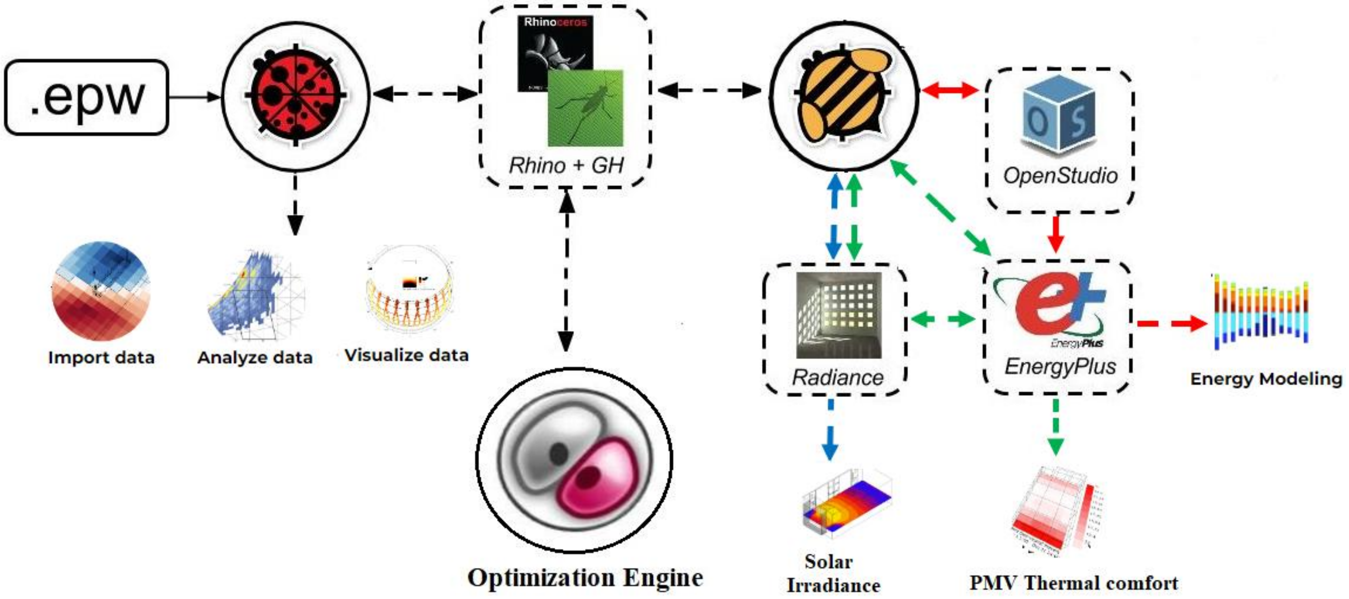


Figure 5. The simulation and optimization methodology: the links between Rhinoceros software, Grasshopper interface, and Galapagos, Honeybee, and Ladybug plugins (Ladybug Tools. Tools, n.d.) (Author).

3.1. The Selected Mosque

3.1.1. The Mosque Location and Climate Readings.

The selected mosque is El-Farouq Mosque in the Sheraton Residences neighborhood, Cairo, Egypt (30.1055° N, 31.3854° E). Egypt is a highly arid country that receives very little annual precipitation; most of the rain falls along its coast and decreases toward the south. Cairo (the capital of Egypt) is an inland city with a hot and dry summer season (May to September), with varying temperatures from 7°C at night to 43°C during the day. Cairo receives about 10 mm of precipitation each year; it also experiences high humidity during the summer months (Climate

Change Knowledge Portal, n.d.).

The Ladybug tool was used to perform the climate analysis of the study region. It is a comprehensive tool that can import EnergyPlus weather files (.epw) into Grasshopper interface in Rhinoceros 3D software, allowing Grasshopper's visual programming interface to work in tandem with simulation engines and validated environmental data sets. Figure 6 shows the meteorological data of Cairo, generated by the Ladybug tool in grasshopper interface/ Rhinoceros 3D software.

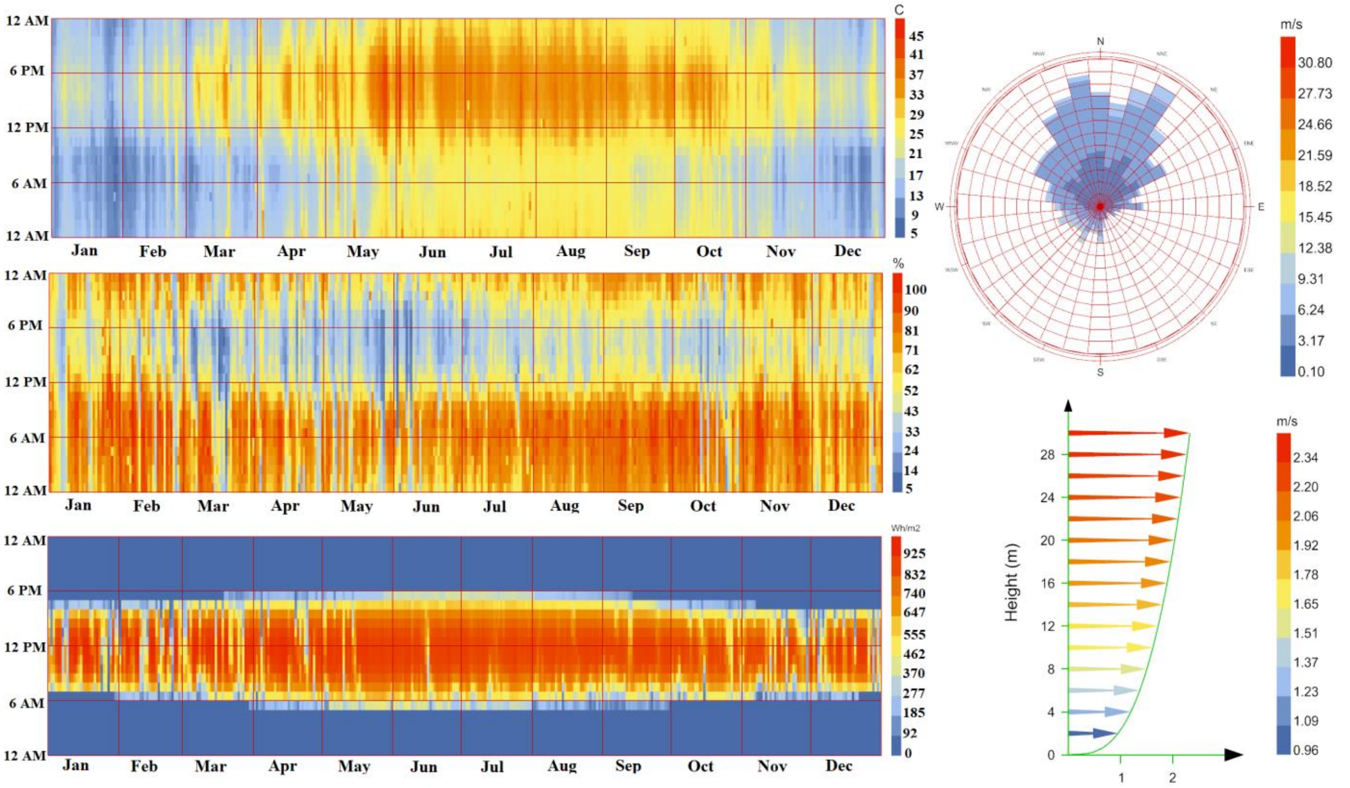


Figure 6. The meteorological data of Cairo: the monthly dry bulb temperature, relative humidity, direct radiation, wind rose, and wind speed, respectively (Author)

3.1.2. The Mosque Description

El-Farouq Mosque is 2090 m^2 and 16.5 m high, built with concrete and brick, Figure 7. It has three floors: a lower ground floor has the women entry, kindergarten, stairs, occasion halls, administration rooms, and toilets; a high ground floor has the men entrance, a double-height men prayer hall, stairs, and toilets; and a first floor has the women prayer hall, stairs, and toilets, Figure 8. The study was applied to the male prayer hall on the high ground floor, which is 2.5 m above the ground. The hall is 1230 m^2, with a 1250 worshipper capacity (the floor area divided by the area required per worshipper to perform various prayer motions: 0.80 x 1.2 = 0.96 m^2) (Hossam Eldien & Al Qahtani, 2012). The hall has a rectangular plan (44× 28× (8-10.5) m), and its longer side faces the Qibla 138° SE. It has a flat roof with two brick skylights (14× 8× 2.5 m), six doors, and 27 rectangular windows topped with 27 arched windows, in addition to 30 arched windows topped the doors and skylight. The windows on the northeast, northwest, and southwest façades (exterior walls) have single glass panels covered with steel shading screens with an 89.4% perforation ratio, while the windows on the southeast side (interior wall) and on the skylight have single glass panels with no shading screens. In summer, the mosque depends on freestanding air conditioners and fans, while in winter it depends on natural ventilation. Since the hall's longer side was directed toward the Qibla, two of its sides faced the southeast and southwest, causing increases in solar gains, thermal discomfort, and energy consumption.

El-Farouq Mosque was chosen for two reasons. ***First,*** its location in Cairo, an inland Egyptian city with a hot and dry summer and daytime highs of 43 °C. ***Second,*** the low efficiency of its external envelope, which raises solar heat gain, thermal loads, discomfort, and energy consumption.

Figure 7. El-Farouq Mosque (Author)

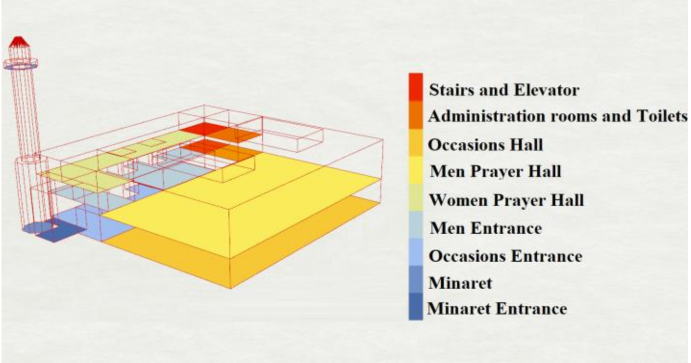


Figure 8. Zone Analysis for El-Farouq Mosque,
The analysis was performed on the men prayer hall (Yellow) (Author)

3.1.3. The Mosque Modeling

The analysis was performed on the male prayer hall only; yet, to ensure the accuracy of the simulations and its measurements, the whole mosque was modeled with its real dimension in Rhinoceros 3D software, Figure 9. Then, the mosque functional zones, openings, construction materials, current shading, and occupancy schedules were defined by using Honeybee plugin in grasshopper interface. First, each zone function was identified using the "HB Room from Solid" component. The construction materials were then identified using the "HB ConstructionSet" component: brick exterior and interior walls, insulated concrete roofing, carpeted interior floors, wooden doors, and single glass windows. The material settings were plugged into the "HB Room from Solid" component, which was then connected to the "HB Solve Adjacency" component to solve the interior and exterior wall adjacencies. After that, the hall windows and doors were then located using the “HB Add Subface” component, and the existing PSS on the hall windows, as well as the external shading on the entrance and patio, were identified using the “HB Shade” component. Then, The "HB Apply Room Schedules” component was used to set the prayer hall occupancy schedules and Quran lessons that were adjusted according to the daily prayers' times and occupancy level (the occupancy levels were adjusted according to an analysis performed on three mosque occupancy patterns) (Azmi & Kandar, 2019). Later, the cooling setpoints were set to adjust the temperature from 23 to 27 °C (the recommended comfort temperature range by ASHRAE (Azmi et al., 2023) to be changed within this range according to the occupancy level. The "HB IdealAir” component was used to condition the hall and control the air conditioning working hours according to the occupancy schedule of the hall. Lastly, all the previous setups were plugged into the “HB Model” component to create an HB model. However, to start performing the required environmental simulation, the “HB Model” component needed to be connected into the “HB Sensor Grid Rooms” component to create a sensor grid on the model floor, which was set to be 1.1 m high (the height of the gravity center of the human body) (Matzarakis et al., 2014), then connected to the “HB Assign Grid and Views” component to add a radiance sensor gird to the model. The final model was visualized by using the “HB Visualize by Type” component to ensure its accuracy, Figure 10.

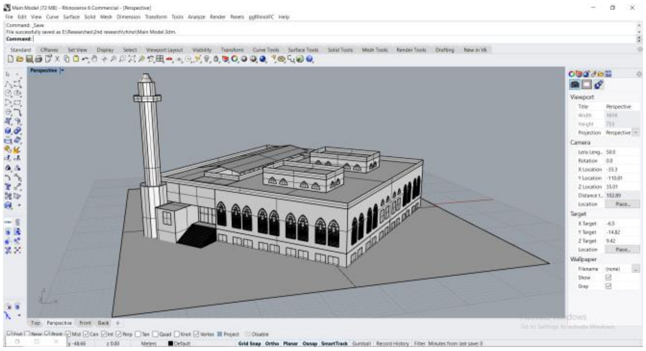


Figure 9. El-Farouq Mosque model in Rhinoceros 3D software (Author)

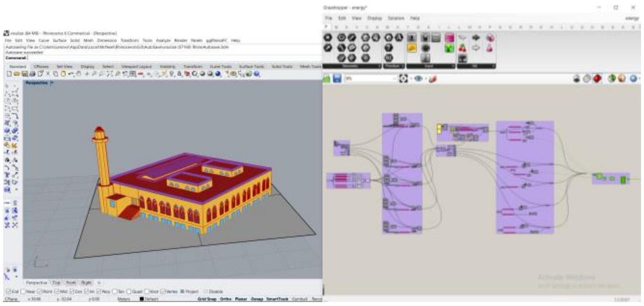


Figure 10. Identifying the mosque components in Honeybee/Grasshopper and visualizing them by the “HB Visualize by Type” component (Author)

3.2. Environmental Simulations

Three simulations were performed on the hall. ***First,*** an annual solar irradiance simulation, which reduces its value to the lowest degrees, was the main target of the optimization process. ***Second,*** a PMV thermal comfort simulation was used to detect the reduced solar irradiance effect on indoor thermal comfort: PMV thermal comfort value, thermal comfort percent, operative temperature, mean radiant temperature, and air temperature. ***Third,*** an energy simulation was used to detect the reduced solar irradiance effect on the energy performance: cooling loads, heat index hours, and Humidex hours.

3.2.1. Annual Solar Irradiance Simulation

Solar irradiance is the total power from the sun falling on a unit area of a surface (perpendicular to the sun’s rays), and it is measured in watts per square meter (W/m2) (Solank et al., 2013). The levels of solar irradiation entering through the perforations can directly affect the indoor thermal comfort and energy demand of mosques; thus, their reduction was the main target of the optimization process. To measure the annual irradiance peak value, the “HB Annual Irradiance” component was used to simulate the worst solar load case that happens over a clear sky for each sensor in the model’s sensor grids. It has two prerequisites: an HB model file and an EPW file. The "HB Assign Grid and Views” component was used for the HB model, while the "LB Download Weather" component was used for the EPW weather file by using the Cairo URL (Ladybug Tools. EPW Map, n.d.).

3.2.2. PMV Thermal Comfort Simulation

The “HB PMV Comfort Map” component was used to simulate the indoor thermal comfort for the extreme hot week in the year (at the daytime; from 9 a.m. to 6 p.m., as the hottest time of the day with the highest thermal and energy loads) as an examination period. It was used to measure the PMV thermal comfort, thermal comfort percent (TCP), and air temperature, as well as the operative temperature, and the mean radiant temperature (MRT). The operative temperature is an indoor environmental standard for the thermal environment and the room temperature requirements; it is defined as the uniform temperature of an enclosure in which a person would radiatively exchange the same amount of heat as they would in a non-uniform environment (Simone et al., 2007). While the MRT is a main parameter for human energy balance, especially during hot and sunny days; it is defined as the uniform temperature of an imaginary environment in which the radiant heat transfer from the human body is equivalent to that in the actual environment (Li, H., 2016).

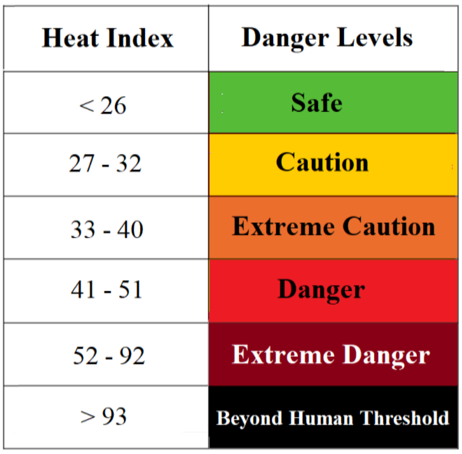
The “HB PMV Comfort Map” component uses both

EnergyPlus and Radiance Software to perform the simulation for each sensor in the hall surface. The component has three prerequisites: an HB model file, an EPW file, and a DDY file. The “HB Assign Grid and Views” component was again used for the HB model, and the "LB Download Weather" component for the EPW, DDY, and STAT weather files of Cairo (Ladybug Tools. EPW Map, n.d.). The STAT weather file was used to determine the extremely hot week in the year period by plugging it in the “LB Import STAT” component, which stated that the required duration was from 20/7 to 26/7 in Cairo. Afterwards, the “LB Analysis Period” component was used to set the required week and time, then was plugged into the “HB PMV Comfort Map” component as the run period. After running the “HB PMV Comfort Map” component, multiple components were used to visualize the required measurements. First, the “HB Read Thermal Matrix” and “HB Visualize Thermal Map” components were used to visualize the PMV thermal map and the operative temperature. Second, the “LB Spatial Heatmap” component was used to visualize the TCP. Lastly, the “HB Read Environment Matrix” and the “HB Visualize Thermal Map” components were used to visualize the MRT and the air temperature.

3.2.3. Energy Simulation

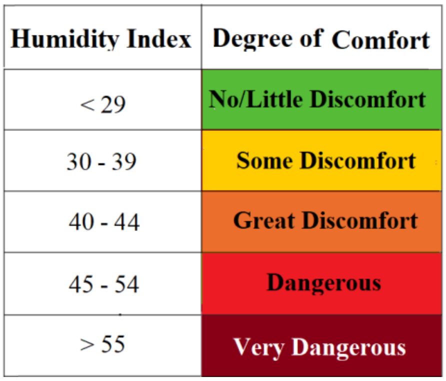
The "HB Model to OSM” component was used to simulate the energy efficiency and detect the cooling loads, heat index hours, and humidity index hours during the hottest week in the year (from 20/7 to 26/7).

The heat index, also known as the apparent temperature, is what the temperature feels like to the human body when the air temperature and relative humidity are combined (National Weather Service, n.d.). Figure 11 illustrates the danger levels associated with the different heat index ranges as reported by the US National Weather Service (ISGlobal Barcelona Institute for Global Health, n.d.). While the humidity index, or humidex, is an index number that describes how comfortable a place is for the typical human when combining the effects of humidity and heat. The Canadian meteorologists devised the Humidex range as shown in Figure 12 (Canadian Centre for Occupational Health and Safety, n.d.) (Lukić et al., 2019).



Heat Index	Danger Levels
< 26	Safe
27 - 32	Caution
33 - 40	Extreme Caution
41 - 51	Danger
52 - 92	Extreme Danger
> 93	Beyond Human Threshold

Figure 11. The heat index ranges and its danger levels (ISGlobal Barcelona Institute for Global Health, n.d.) (Edited by the Author).



Humidity Index	Degree of Comfort
< 29	No/Little Discomfort
30 - 39	Some Discomfort
40 - 44	Great Discomfort
45 - 54	Dangerous
> 55	Very Dangerous

Figure 12. The Humidex scale and the degree of comfort (Canadian Centre for Occupational Health and Safety, n.d.) (Lukić et al., 2019) (Edited by the Author)

The “HB Model to OSM” component has two prerequisites: an HB model file and an EPW file. The "HB Assign Grid and Views” component was used for the HB model, and the "LB Download Weather" component was used for the Cairo EPW weather file (Ladybug Tools. EPW Map, n.d.). In addition, the “HB Simulation Parameter” component was used to set the required output and analysis period. It was set to run from July 20 to July 26 and measure the cooling loads, relative humidity, and mean air temperature. Afterwards, the “HB Model to OSM” component converted the HB model to an OpenStudio Model (OSM) file, which was then translated to an IDF file to run through

EnergyPlus to perform the energy simulation. The simulation results were produced in different formats, one of which is an HTML file that displays every energy simulation result in an EnergyPlus tabular report format.

It should be noted that the three simulations were run twice. ***First,*** on the hall with its current shading screen, to identify any areas with high thermal values and measure the thermal comfort and energy loads. This phase revealed that the central zone, which is under the hall skylights, has high sun irradiance values, as do the southwest and southeast zones. ***Second,*** after applying the proposed PSS to the southwest and southeast façades and the roof, to investigate any discrepancies in measurements between the current and the optimized PSS.

3.3. PSS Optimization

This part aims to generate a PSS with an optimal perforation ratio that can reduce the annual solar irradiance to its lowest value. The PSS was first designed in Grasshopper within definite parameters, then Galapagos optimization engine was used to detect its optimal perforation ratio.

3.3.1. The Design Process

The proposed PSS design was based on one of the fundamental forms of Islamic geometrical patterns (IGPs), which is a constructive polygon that creates a star-polygon by joining its vertices. The star-polygons are named according to the number of points in their basic polygons; for instance, a star that came from a hexagon is called a 6-point star (Abdullahi & Embi, 2013), Figure 13. An 8-point star polygon (octagon) and a 4-point star polygon (square) were used as the fundamental shapes of the proposed PSS, with a perforation ratio range of 20 to 90%, with a maximum 20% to allow natural ventilation and daylight and a minimum 90% to maintain the stars' aesthetic appeal. This ratio can be varied across the screen height, Figure 14. The stars cover the southeast and southwest façades and the roof; each 8-point star measures 1*1 m, while each 4-point star is 60*60 cm. Guided by the Islamic mashrabiya, they were set to be made of wood to further help in reducing thermal loads. Lastly, the screens were connected to the main HB model as shading screens by using the "HB Shade" component.

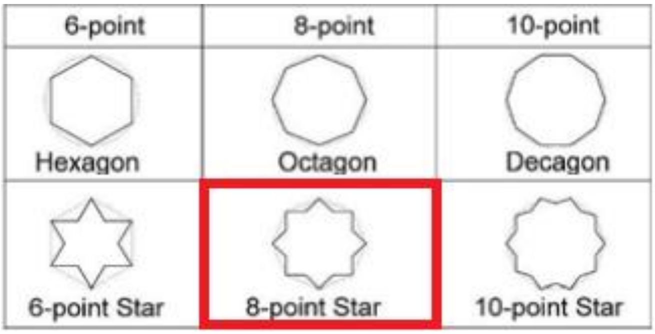


Figure 13. The selected 8-point star shape (Abdullahi & Embi, 2013)

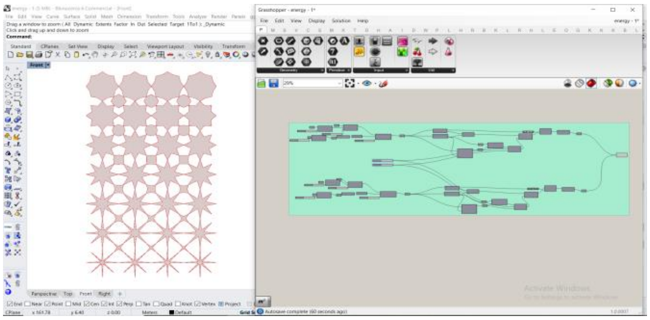


Figure 14. The screen perforation ratio, ranging from 20% (top) to 90% (bottom), and its algorithm in grasshopper (Author)

3.3.2. The Optimization Process

Galapagos optimization engine was used to determine the optimal perforation ratio on each façade and roof that could decrease the peak annual solar radiation to its lowest values. Galapagos required two inputs: the genome, which was connected to the sliders that control the façade perforation ratio, and fitness, which was connected to the average annual peak irradiance (an output from "HB Annual Irradiance" components). Galapagos started numerous continued solar irradiance simulations by changing the pattern perforation ratio, Figure 15. It had generated 1304 solutions until it reached the lowest annual solar irradiance value that occurred when the perforation ratio was 25% in the façades and 20% in the roof, Figure 16.

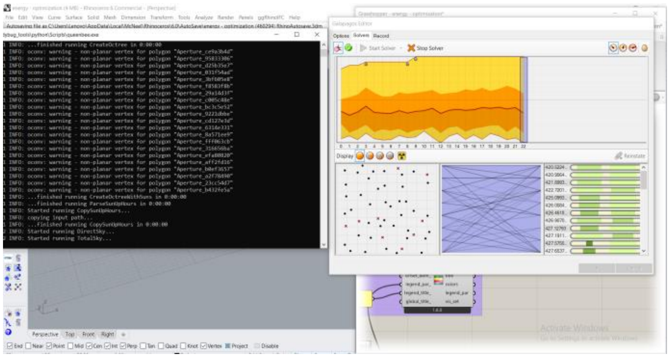


Figure 15. Galapagos calculations during the optimization process (Author)

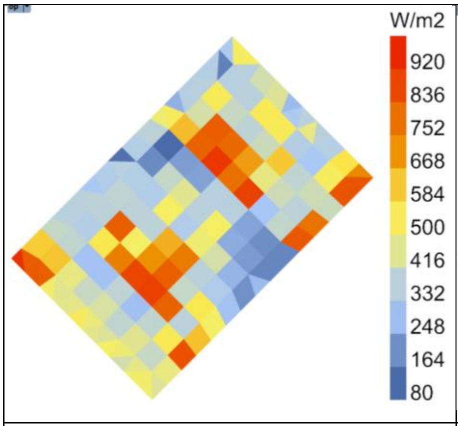
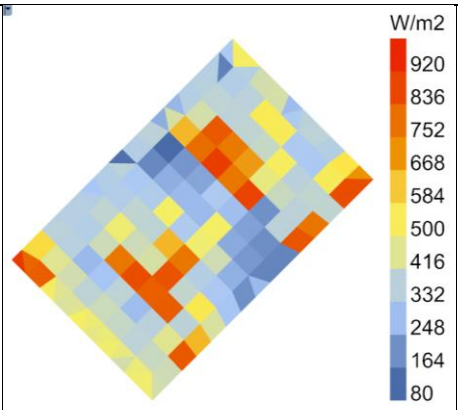
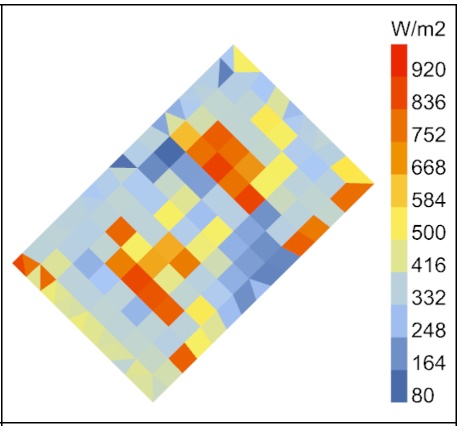
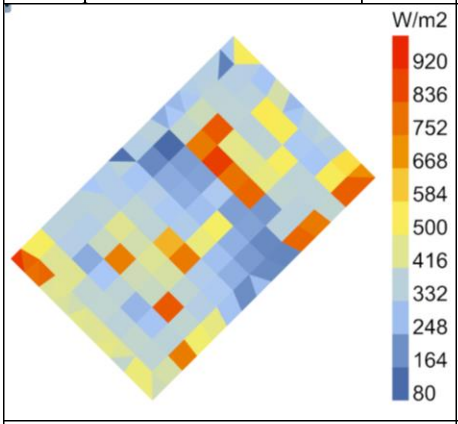
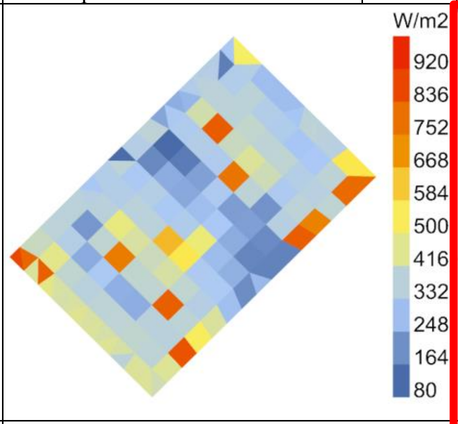
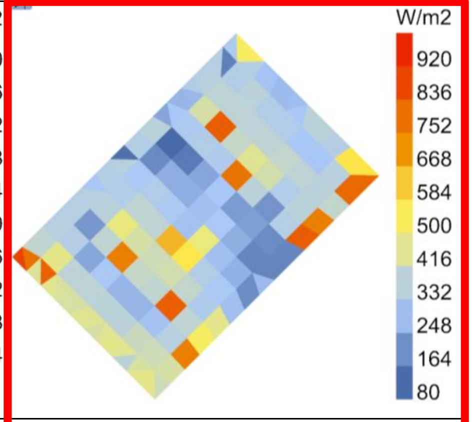
					
(a) The Worst Solution		**(b) An Average Solution**		**(c) An Average Solution**	
Average annual irradiance	429 W/m^2	Average annual irradiance	406.8 W/m^2	Average annual irradiance	398.8 W/m^2
Southwest façade perforation	0.9 %	Southwest façade perforation	0.7 %	Southwest façade perforation	0.3 %
Southeast façade perforation	0.9 %	Southeast façade perforation	0.6 %	Southeast façade perforation	0.45 %
Roof perforation	0.9 %	Roof perforation	0.6 %	Roof perforation	0.65 %
					
(d) An Average Solution		**(e) An Average Solution**		**(f) The Optimal Solution**	
Average annual irradiance	379 W/m^2	Average annual irradiance	349.3 W/m^2	Average annual irradiance	349.2 W/m^2
Southwest façade perforation	0.4 %	Southwest façade perforation	0.2 %	Southwest façade perforation	0.25 %
Southeast façade perforation	0.3 %	Southeast façade perforation	0.2 %	Southeast façade perforation	0.25 %
Roof perforation	0.35 %	Roof perforation	0.2 %	Roof perforation	0.2 %

Figure 16. Six samples from the generated solutions, from the highest (worst case) to the lowest (optimal case) peak annual irradiance value (Author)

3.4. Comparison between the measurements of the current and proposed PSS

To verify the research objective and determine the effect of the proposed PSS on reducing the annual solar irradiance, indoor thermal loads and comfort, and energy loads in the hottest week of the year, a comparison was performed between measurements of the current screen and the proposed optimized screen in terms of annual solar irradiance, PMV thermal comfort, and energy simulations in Tables 1, 2, and 3, respectively

Table 1. Annual solar irradiance simulation (Author)

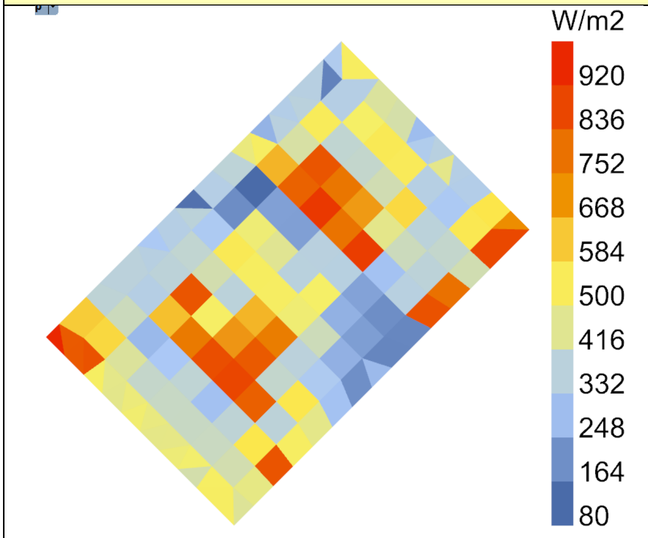
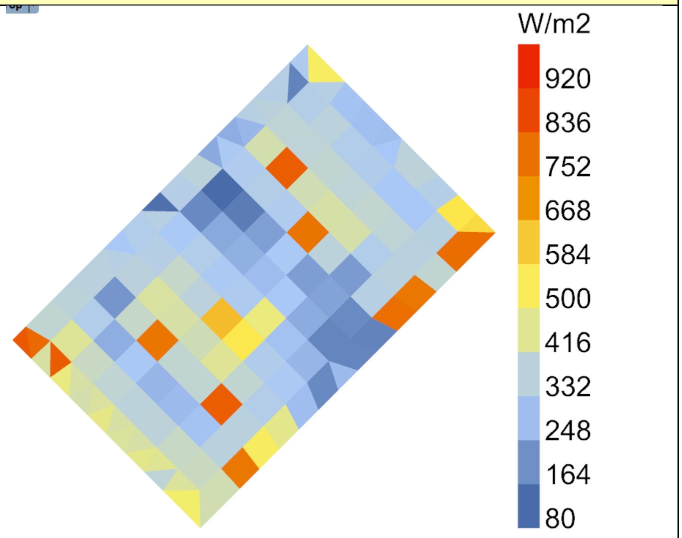
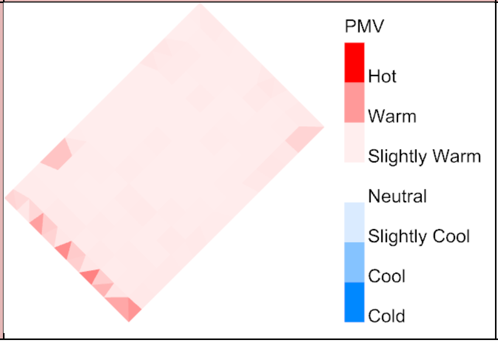
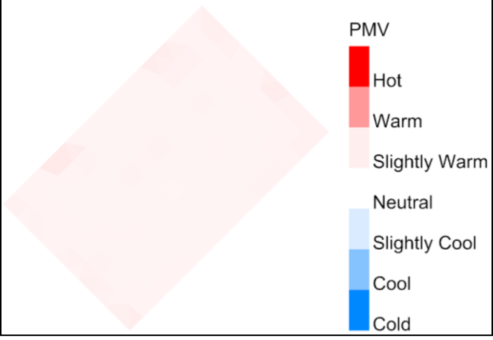
The Peak Annual Solar Irradiance	
The current shading screen	**The optimzed shading screen**
	
Average peak irradiance= 431 W/m² The results showed high values along the southwest and southeast zones and in the middle zone (under the hall skylights)	**Average peak irradiance= 349.2 W/m²** The results showed a decrease by 81.8 W/m² The thermal loads along the southwest, southeast, and middle zones have obviously decreased.

Table 2. The PMV thermal comfort simulation of the hottest week in the year (from 9 to 6 pm) (Author)

PMV Thermal Comfort Simulation			
	The current shading screen	**The optimzed shading screen**	**Result**
PMV thermal comfort map			**In the current case:** - 90.5% was in the slightly warm category. - 9.5% was in the warm category, along the southwest zones and some parts of the southeast and northwest zones. **In the optimized case:** - 100% was in the slightly warm category.

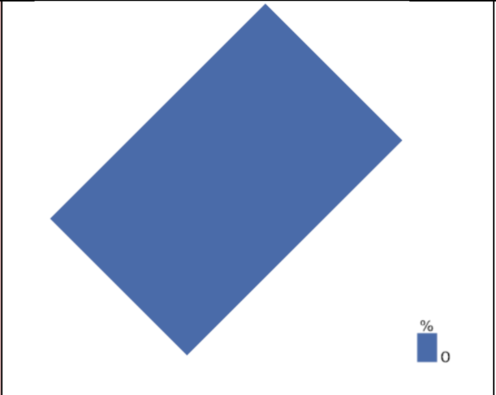
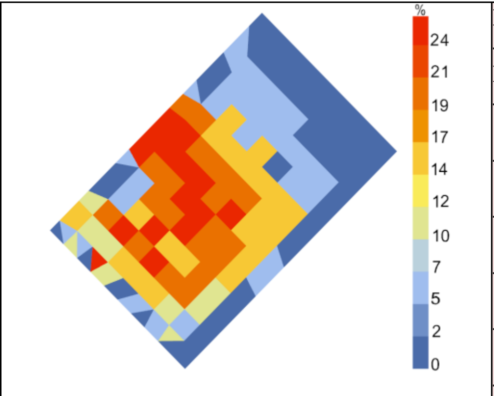
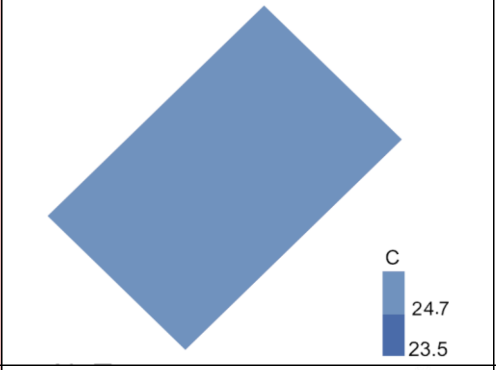
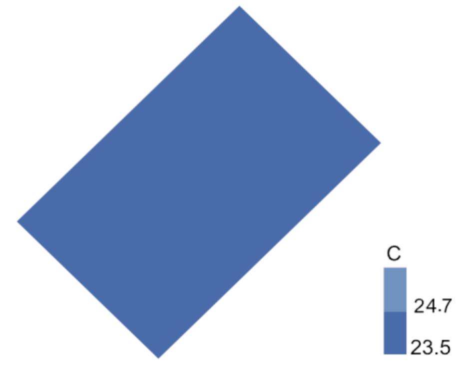
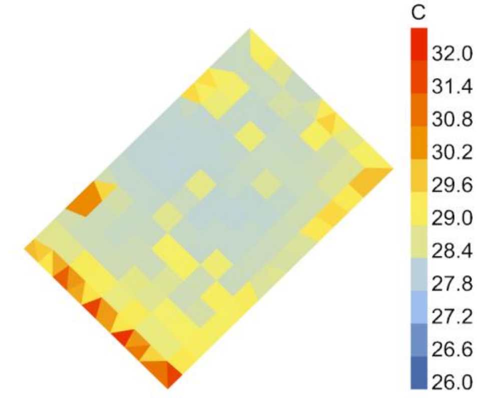
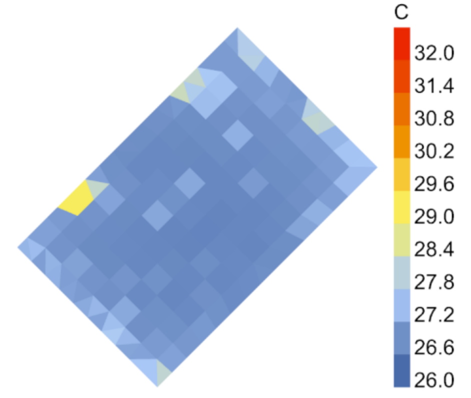
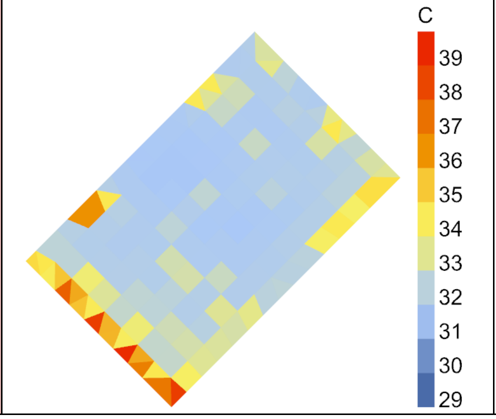
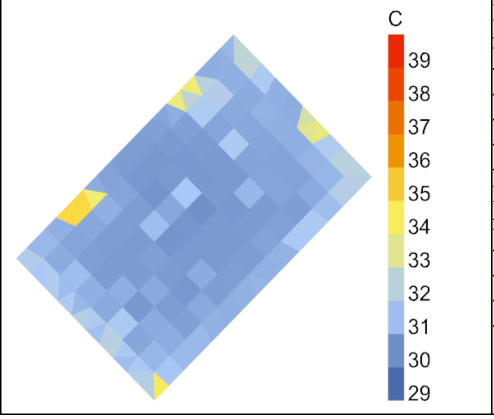
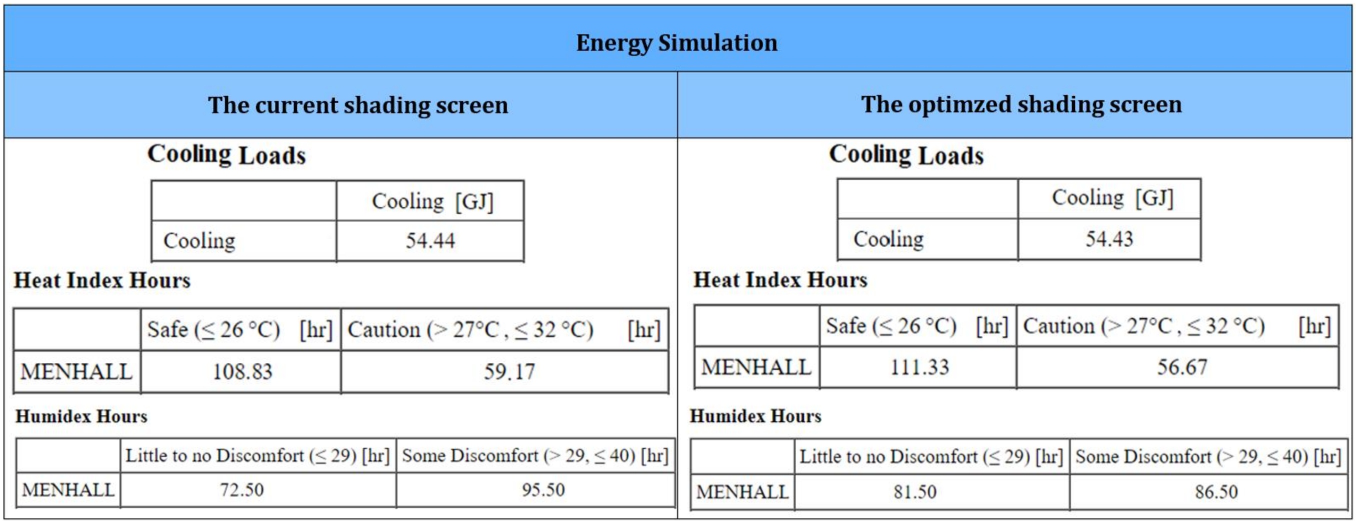
Thermal Comfort Percent (TCP)			**In the current case:** - 100% uncomfortable. **In the optimized case:** - 11.6% of the area was comfortable by 24%. - 15.9% of the area was comfortable by 19%. - 16.7% of the area was comfortable by 14%. - 6.4% of the area was comfortable by 10 %. - 19.4% of the area was comfortable by 5%. - 30% uncomfortable.
Air Temperature			**In the current case:** 24.67 °C. **In the optimized case:** 23.57 °C.
Operative Temperature			**In the current case (Range from 27.8 to 32°C):** - 1.2% is 32 °C - 2.8% is 30.8 °C - 2.4% is 30.2 °C - 3.2% is 29.6 °C - 22.8% is 29 °C - 22.8% is 28.4 °C - 44.8% is 27.8 °C. **In the optimized case (Range from 26 to 29°C):** - 1.6% is 29 °C - 2% is 28.4 °C - 2% is 27.8 °C - 16.6% is 27.2 °C - 38% is 26.6 °C. - 39.8% is 26 °C
Mean Radiant Temperature			**In the current case (Range from 31 to 39°C):** - 1.2% is 39 °C - 1.6% is 38 °C - 1.6% is 37 °C - 1.6% is 36 °C - 2.4% is 35 °C - 6.7% is 34 °C - 14.4% is 33 °C -15% is 32 °C - 55.5% is 31 °C. **In the optimized case (Range from 29 to 35°C):** - 2% is 35 °C - 1.2% is 34 °C - 1.2% is 33 °C - 7.5% is 32°C - 20.6% is 31 °C - 46% is 30 °C - 21.5% is 29 °C.

Table 3. The energy simulation of the hottest week in the year (Author)



Energy Simulation

The current shading screen

Cooling Loads

	Cooling [GJ]
Cooling	54.44

Heat Index Hours

	Safe (≤ 26 °C) [hr]	Caution (> 27°C , ≤ 32 °C) [hr]
MENHALL	108.83	59.17

Humidex Hours

	Little to no Discomfort (≤ 29) [hr]	Some Discomfort (> 29, ≤ 40) [hr]
MENHALL	72.50	95.50

The optimzed shading screen

Cooling Loads

	Cooling [GJ]
Cooling	54.43

Heat Index Hours

	Safe (≤ 26 °C) [hr]	Caution (> 27°C , ≤ 32 °C) [hr]
MENHALL	111.33	56.67

Humidex Hours

	Little to no Discomfort (≤ 29) [hr]	Some Discomfort (> 29, ≤ 40) [hr]
MENHALL	81.50	86.50

4. Results and Discussion

This section demonstrates the results of the research by comparing and analyzing the variations in measurements between the current and proposed PSS, and that via three stages, each of them represents the outcomes of one of the three main simulations. Then, highlight the role of genetic algorithms in detecting the optimal PSS perforation ratio, their influence on promoting thermal and energy performance, as well as the factors that can affect the optimization process.

4.1. The annual solar irradiance simulations

This phase reflects the main target of the research, which was how genetic algorithms can easily identify the ideal perforated ratio of PSS that can minimize the annual solar irradiance to its lowest values and, consequently, the thermal loads on the mosque's envelope. Genetic algorithms could generate 1304 different PSS solutions, filter and sort them based on their efficiency until they reached the conclusion that using a 25% perforation ratio on the façades and a 20% on the roof can reduce the peak annual solar irradiance by 81.8 W/m2 (19% less than in the existing screen), and that’s the lowest possible value. Figure 17 shows the reduction in the peak annual solar irradiance between the current and the proposed PSS generated by genetic algorithms.

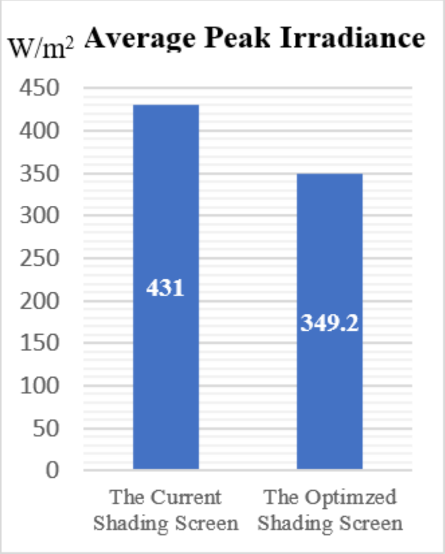


Figure 17. The reduction in peak irradiance value (Author).

4.2. The PMV thermal comfort simulations

This part shows how applying the generated PSS could directly affect the thermal performance of the hall, particularly during the daytime hours of the warmest week of the year. Multiple results have been revealed, showing the capabilities of the generated PSS compared to the current shade screen. ***First,*** it improved the PMV thermal comfort by 9.5% by turning all the warm zones in the current case to slightly warm zones, Figure 18. ***Second,*** it raised the thermal comfort percentage by 70% (with different percentages), as shown in Figure 19. ***Third,*** it decreased the air temperature by 1.1 °C, Figure 20. ***Fourth,*** it reduced the operating temperature by 3 °C at its highest and 1.8 °C at its lowest value, Figure 21. ***Lastly,*** it lowered the mean radiant temperature by 4 °C at its maximum and by 2 °C at its minimum value, Figure 22.

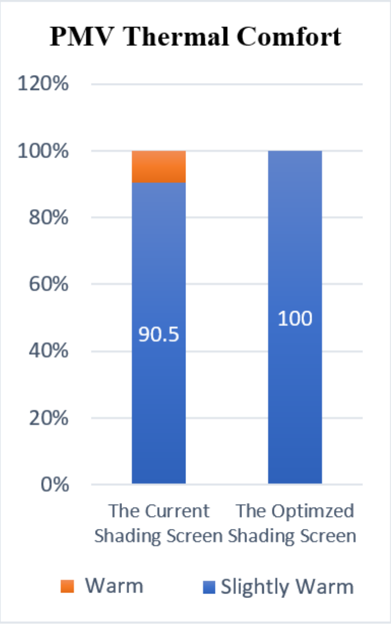


Figure 18. The percentage of PMV thermal comfort categories [Author].

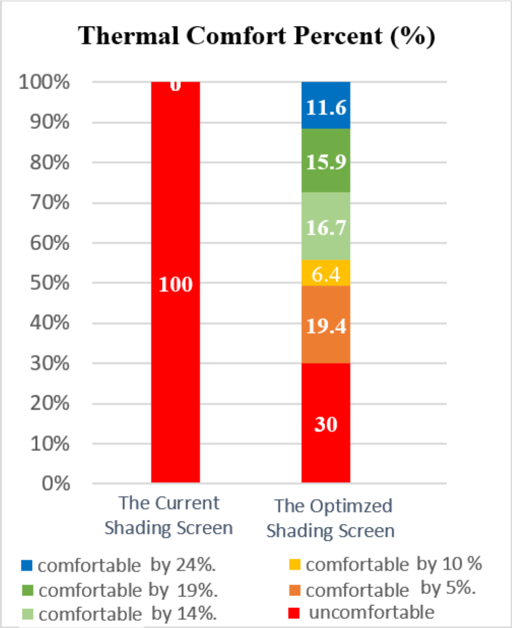


Figure 19. The thermal comfort percent [Author].

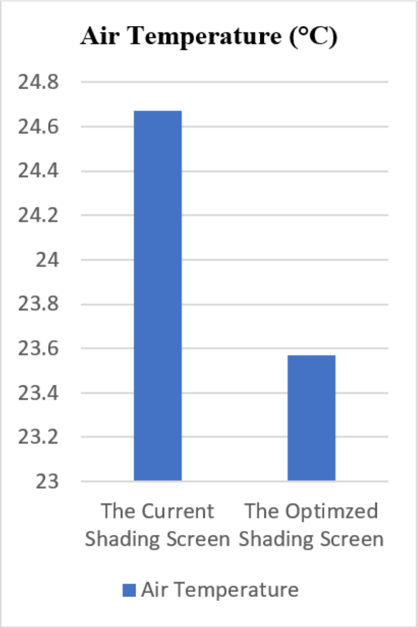


Figure 20. The air temperature [Author].

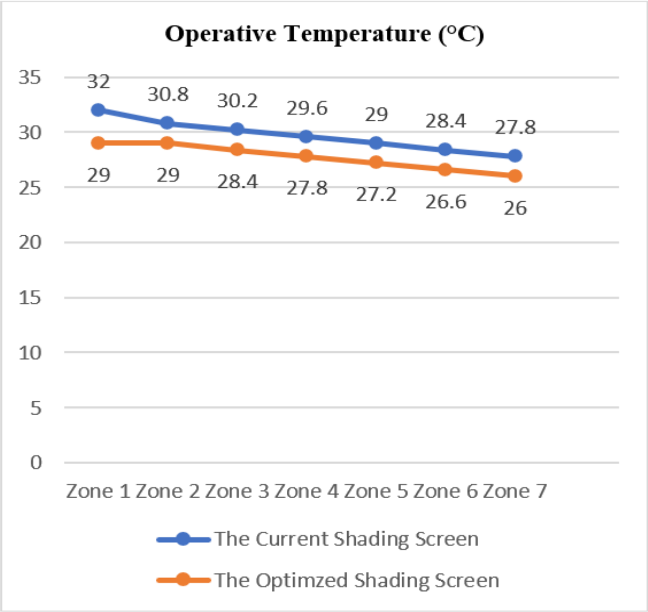


Figure 21. The maximum and minimum operative temperature [Author].

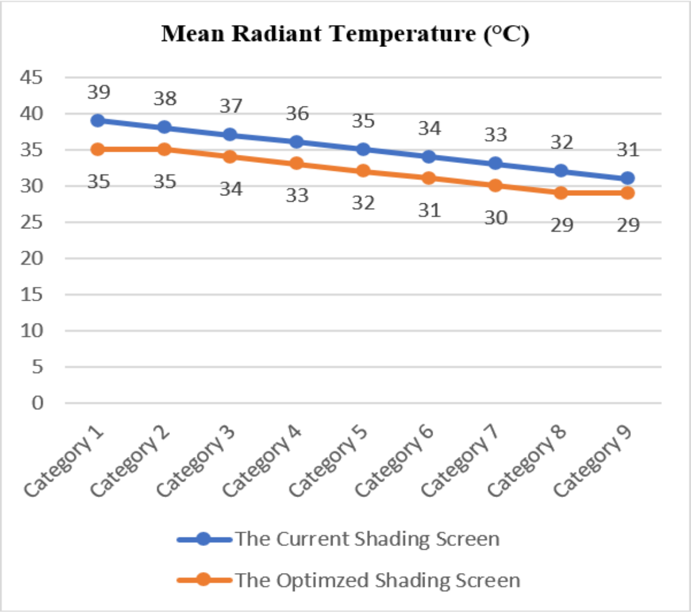


Figure 22. The maximum and minimum mean radiant temperature [Author].

4.3. The energy simulations

This phase shows how the cooling loads, heat index hours, and humidex hours have been affected by applying the proposed generated PSS during the hottest week of the year. ***First,*** it has slightly decreased the cooling loads from 54.44 GJ to 54.43 GJ. ***Second,*** the heat index safe hours have increased by 2.5 hours, which correspondingly decreased caution hours by 2.5 hours, Figure 23. ***Third,*** the humidex no discomfort hours have increased by 9 hours, which in turn decreased some discomfort hours by 9 hours, Figure 24. These results show that despite the proposed PSS having a small effect on the cooling loads, the heat and humidity index hours have noticeably improved with slightly lower cooling loads.

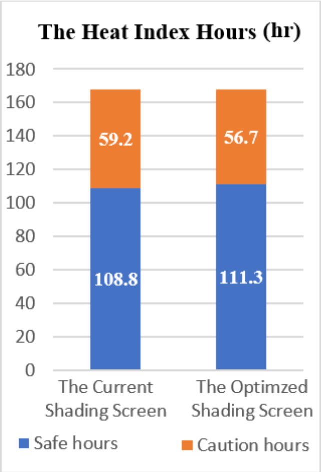


Figure 23. The heat index hours [Author].

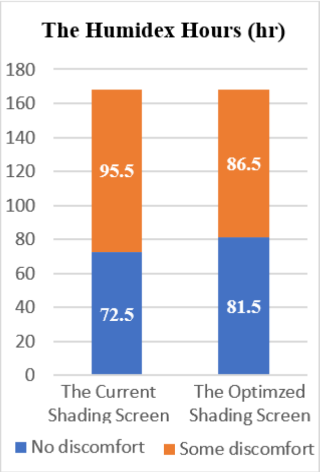


Figure 24. The humidex hours [Author].

As per the above-mentioned results, genetic algorithms could efficiently find the optimal perforation ratio of the required PSS for the prayer hall, which was 25% on each facade and 20% on the roof. These ratios could reduce the peak annual solar irradiance value by 81.8 W/m2, which consequently reduced the thermal loads on the hall envelope, promoted indoor thermal comfort in multiple disciplines (as the thermal comfort percent, air temperature, and heat and humidity index hours), and slightly decreased the cooling loads. These improvements could efficiently enhance the worshippers' comfort and relaxation during their daily prayers.

Lastly, it is essential to mention that the perforation ratios generated by GAs can vary according to several factors, including the location and orientation of the mosque, the size and design of the screen, or the target of the optimization process. However, a detailed, accurate design for the mosque and its required screen and the right coding algorithm can allow GAs to find the ideal ratio easily.

6. Conclusion

The study was performed with the aim of revealing the efficiency of using genetic algorithms in detecting the ideal solar screen perforation ratio and how choosing the correct percentage of perforation can maximize indoor thermal comfort and lower energy consumption in mosque buildings. The research has clarified the mosque building functional, operational, and thermal requirements, the history of PSS in mosque architecture, and genetic algorithm concept, usage, and capabilities. Then, genetic algorithms were used on a selected mosque in Egypt, in a hot, dry climate zone, to find the optimal perforation ratio of a proposed solar screen that can reduce its annual solar irradiance to the lowest value. The results demonstrated the effectiveness of Galapagos genetic optimization in comparing, sorting, and filtering 1304 solutions until it reached the ideal perforation ratio with the least amount of solar irradiation. The proposed PSS could reduce the peak annual solar irradiance of the selected mosque by 19%, improve its indoor thermal comfort, and slightly reduce its cooling loads in the hottest week of the year. The study has gone some way towards enhancing our knowledge and understanding of genetic algorithms capabilities to facilitate reaching a better performative solution. However, the current study has only examined the abilities of the genetic algorithms in detecting the optimal perforation ratio of mosques' solar screens; therefore, further studies with more focus on optimizing other PSS design factors, such as its material, thickness, and distance from the façade, by using genetic algorithms are suggested. It would be interesting to assess the effects of using genetic algorithms in finding the optimal solution in the whole design process.

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