Development of a parametric optimization concept for the sun control of the outdoor spaces: the case study of 5A business park, Cairo, Egypt

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Abstract

Purpose – Comfortable outdoor workspaces are important for employees in business parks and urban areas. Prioritizing a pleasant thermal environment is essential for employee productivity, as well as the improvement of outdoor spaces between office buildings to enhance social activities and quality of outdoor workplaces in a hot arid climate has been subjected to very little studies Thus, this study focuses on business parks (BPs) landscape elements. The objective of this study is to enhance the user's thermal comfort in the work environment, especially in the outdoors attached to the administrative and office buildings such as the BPs.

Design/methodology/approach – This research follows Four-phases methodology. Phase 1 is the investigation of the literature review including the Concept and consideration of BP urban planning, Achieving outdoor thermal comfort (OTC) and shading elements analysis. Phase 2 is the case study initial analysis targeting for prioritizing zones for shading involves three main methods: social assessment, geometrical assessment and environmental assessment. Phase 3 entails selecting shading elements that are suitable for the zones requiring shading parametrize the selected shading elements. Phase 4 focuses on the optimization of OTC through shading arrangements for the prioritized zones.

Findings – Shading design is a multidimensional process that requires consideration of various factors, including social aspects, environmental impact and structural integrity. Shading elements in urban areas play a crucial role in mitigating heat stress by effectively shielding surfaces from solar radiation. The integration of parametric design and computational optimization techniques enhances the shading design process by generating a wide range of alternative solutions.

Research limitations/implications – While conducting this research, it is important to acknowledge certain limitations that may affect the generalizability and scope of the findings. One significant limitation lies in the use of the shade audit method as a tool to prioritize zones for shading. Although the shade audit approach offers practical benefits for designers compared to using questionnaires, it may have its own inherent biases or may not capture the full complexity of human preferences and needs.

Originality/value – Few studies have focused on optimizing the type and location of devices that shade outdoor spaces. As a result, there is no consensus on the workflow that should regulate the design of outdoor shading installations in terms of microclimate and human thermal comfort, therefore testing parametric shading scenarios for open spaces between office buildings to increase the benefit of the outer environment is very important. The study synthesizes OTC strategies by filling the research gap through the implementation of a proper workflow that utilizes parametric thermal comfort.

Keywords Outdoor thermal comfort (OTC), Behavioral mapping, Space syntax analysis, Shading optimization, Universal thermal climate index (UTCI)

Paper type Research paper

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Nomenclature

BPs	Business parks	PET	Physiologically equivalent temperature
UVR	Ultraviolet Radiation		
aAT	Adjusted Apparent Temperature	OUT-SET*	Outdoor Standard Effective Temperature
OTC	Outdoor thermal comfort	PPD	Predictable Percentage of dissatisfied
CLO	Clothing Insulation		
TOP	Operative temperature	PMV	Predict mean vote
UTCI	Universal Thermal Climate Index	SET	Standard effective temperature
Met	Metabolism	GAs	Genetic Algorithms
PT	Perceived temperature		

1. Introduction

In the contemporary context of workplace design, there exists a profound distinction between office environments that merely avoid harm and those that actively promote employee well-being and productivity. This distinction becomes particularly pertinent as the demand for expansive office spaces drives the construction of towering high-rise buildings, which, while catering to spatial needs, simultaneously exert adverse effects on ecological equilibrium and demographic dynamics (Atwa *et al.*, 2017). Large facilities should have outside areas for employees to relax and play. Utilizing building compounds, which provide their own windbreaks and shade, will help to construct a protective enclosure with a human scale (Ellis and Llc, 2014). In order to experience comfort in hot arid climates, shade plays a crucial role in passive cooling by preventing heat accumulation. The ideal temperature range for most individuals varies from 20 °C during winter to 25.6 °C in the summer (Yıldırım, 2020). BP's urban environment, characterized by building distribution, open space shape and greenery, impacts indoor thermal comfort and outdoor activities. The quality of life in cities is assessed based on the thermal balance and suitability of open spaces for outdoor activities (Tsitoura *et al.*, 2017). Business parks can be referred to as micro urban settlements. Hence, it is critical to investigate the relationship between units and the spatial performance of outdoor spaces. Since they do not only provide a work environment but also chilling and shopping as well. When the thermal conditions hover near the comfortable range, a large number of people prefer to spend time outdoors (Yıldırım, 2020). The environmental aspects of the workplace should be thoroughly reconsidered to ensure the convenience, comfort and productivity of the workers, BPs have appeared recently as a method of accommodating business offices and light industrial corporations by grouping them together, the BP concept has emerged as a new form of development in Egyptian cities since 2000 (Atwa *et al.*, 2017). Against this backdrop, the research aims to explore the use of parametric design to optimize thermal comfort in outdoor work environments. To achieve this, it focuses on several key sub-objectives: bridging research gaps in parametric design's role in improving outdoor thermal comfort, defining essential thermal comfort indices, highlighting the importance of parametric simulation software in outdoor space redesign, establishing a methodological framework for business park redevelopment using parametric tools and creating a comprehensive parametric design framework, especially for shading elements, to enhance human thermal comfort.

2. Methodology

The research methodology consists of a theoretical approach, an experimental approach and a deductive approach, to accomplish the objectives of this study, a research methodology is proposed as shown in Figure 1. The first part will present a detailed literature review that

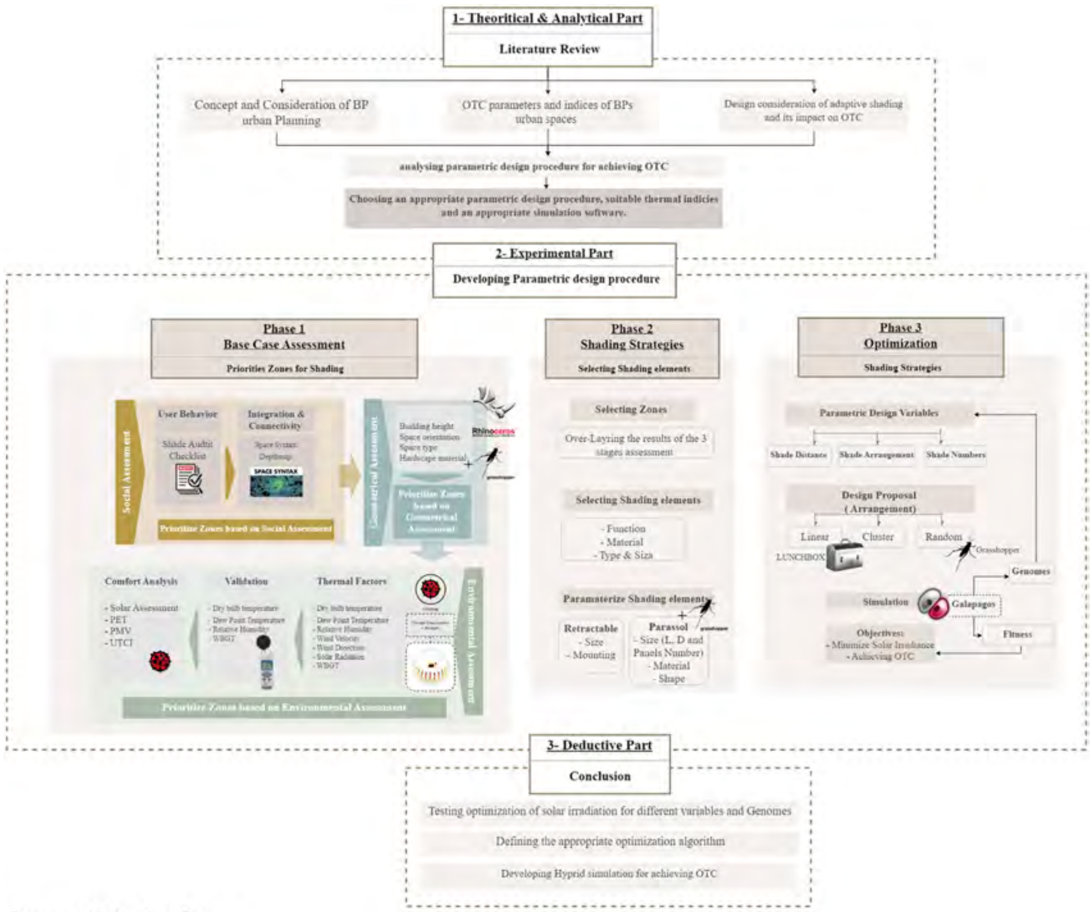

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Figure 1.
Methodology

addresses the new concept of the administrative buildings and then discusses the business parks definitions, Moreover, some fundamental knowledge about thermal comfort indices; The last part of the literature presents the role of using adaptive shadings in achieving OTC. Then analyzing the importance of using parametric tools in the redesign process for outdoor environments in achieving OTC. The outcomes of the literature help in choosing the appropriate procedure, thermal comfort indices and the simulation software. The second part of the methodology presents the case study as the experimental approach which test optimization of OTC of 5A BP that settled at 5th settlement, Cairo. In this study, three phases were followed to examine the OTC in work environment and the interaction between the user and the space, each phase consists of several methods to gather relevant data and insights.

The 1st Phase used for prioritizing zones for shading involves three main methods: social assessment, geometrical assessment and environmental assessment. Phase 2 of the experimental approach focuses on the enhancement of the study. It consists of overlaying the results obtained from the three main stages of assessment in Phase 1. By combining these results, a comprehensive understanding of the park's environmental conditions is achieved. Selecting shading elements that are suitable for the zones requiring shading. This ensures that the chosen elements align with the specific functions and requirements of each zone. In the final stage of Phase 2, the selected shading elements are parametrized, Phase 3 of the experimental approach is dedicated to simulation, defining the design variables that will be utilized in the simulation process. Lunchbox and Grasshopper, powerful design software tools, are employed to compare different design arrangement proposals. In the last stage of

Phase 3, the focus shifts to optimizing the simulation results. This is accomplished by setting the fitness and genomes values of Galapagos, by fine-tuning these parameters, the simulation results can be refined to identify the most optimal design arrangement proposal. The deductive approach presents the results and conclusion of the experiment.

3. Literature review

3.1 Concept and consideration of business park urban planning

Outdoor spaces attached to office buildings have a significant impact on human perception and relaxation. Factors such as visual sensations, auditory sensations and thermal comfort play a crucial role in shaping the experience in these open spaces. The outdoor areas, known as Exterior Hybrid Zones Figure 2, are designed to provide a climate-protected zone that simulates an outdoor environment (Chan *et al.*, 2017). The use of shade features can significantly improve outdoor thermal comfort by lowering extreme weather conditions (Dizdaroglu, 2021). The aspect ratio H/W and street orientation have a significant impact on the spatial distribution of PET across the canyon. For all orientations, wide roadways ($H/W \leq 1$) are extremely uncomfortable. Shade covering must extend to at least 50% of the area night (Jamei *et al.*, 2015). Shading contributes significantly to the decrease in PET and the level of discomfort in cities (Dizdaroglu, 2021). BPs are naturally ventilated and have some control over mean radiant temperature (MRT). However, humidity cannot be regulated. The use of shade features is effective in improving outdoor thermal comfort by reducing extreme weather conditions (Cao and Kang, 2021).

3.2 Achieving outdoor thermal comfort (OTC)

The simulation of thermal comfort for open spaces is critical, especially when it comes to realizing the thermal comfort and recreation potential of business parks (Ndetto and

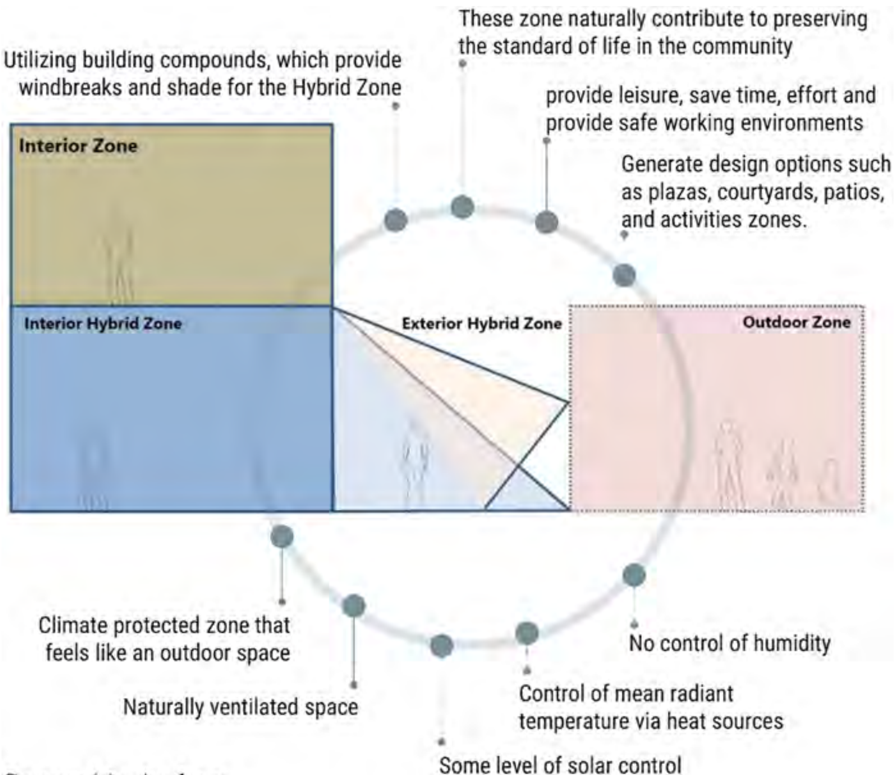

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Figure 2.
Exterior hybrid zone

Matzarakis, 2013). When determining conditions for thermal comfort, six key parameters must be considered: metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity, and humidity. Anthropogenic parameters account for the first two, while Meteorological parameters account for the remaining four (Grifoni *et al.*, 2013).Comfortable temperature varies per person. CLO measures clothing insulation, met measures activity-related metabolism; both are anthropogenic parameters. Heat transfer occurs through radiation (45%), convection (30%) and evaporation (25%), with percentages varying based on circumstances (Rijal *et al.*, 2019). Open space design can provide a variety of comfort options not only through shape or scale, but also through a comprehensive understanding of the environment and its adaptation (Li and Zhang, 2019). There are Several Thermal indices of outdoor thermal comfort that integrate thermal environmental factors and heat balance of the human body are applied for accessing thermal comfort (Fan *et al.*, 2021), the main three indices that designed for evaluating outdoor conditions and used in outdoor thermal comfort studies are (1) PET (physiologically equivalent temperature), (2) UTCI (Universal Thermal Climate Index) (3) OUT-SET* (Outdoor Standard Effective Temperature) besides those main indices there are other common indices which include (4) AT (apparent temperature), aAT (Adjusted Apparent Temperature) (5) TDI (thermal discomfort index) (6) SET (standard effective temperature), TOP (operative temperature) and PT (perceived temperature) (7) PMV (predict mean vote) and PPD (Predictable Percentage of dissatisfied) (Blazejczyk *et al.*, 2012; Shooshtarian *et al.*, 2020). The most recent research and case studies used PET or UTCI as an outdoor thermal comfort index (Tarek, 2021; Abdallah and Mahmoud, 2022). For a comprehensive review of thermal comfort indices Table 1.

Previous field studies on outdoor thermal comfort have revealed a number of software packages and its noted that most of studies that use the UTCI, MRT, WBGT, PMV and PET indices to evaluate OTC uses software Ladybug (Eltaweel *et al.*, 2021), and studies that uses SET*, PET and MRT uses software ENVI-met and RayMan is usually used to calculate PMV, (SET*), PET and WBGT (Naboni *et al.*, 2017).

3.3 Design considerations for adaptive shadings

Shading elements in urban areas provide effective heat stress relief for humans by shielding surfaces from solar radiation, including the urban floor, seating areas, building façades and roofs, thereby maintaining lower temperatures. Urban shading enhances outdoor thermal comfort. It reduces direct sun radiation, cools the area and shapes the outdoor thermal environment (Elgheznawy and Eltarabily, 2021). Shading plays a crucial role in enhancing the resilience of urban areas to climate change by reducing the risk of heat-related fatalities. Heat waves have been responsible for a significant number of weather-related deaths in cities

PET (°C)	UTCI (°C)	Grade of psychological stress
>41 °C	46 °C≤	Extreme Heat Stress
35–41 °C	38–46 °C	Strong Heat Stress
29–35 °C	32–38 °C	Moderate Heat Stress
23–29 °C	26–32 °C	Slight Heat Stress
18–23 °C	9–26 °C	No Heat Stress
13–18 °C	0–9 °C	Slight Cold Stress
8–13 °C	−13–0 °C	Moderate Cold Stress
4–8 °C	−27 to −13 °C	Strong Cold Stress
<4 °C	−40 to −27 °C	Very Strong Cold Stress
–	<−40 °C	Extreme Cold Stress

Source(s): Kakovkina *et al.* (2020)

Table 1. Gradations of PET and UTCI indices

during the past decade (Andreou, 2014). Cities struggle with building shading to stay cool. Urban centers face the Urban Heat Island effect due to their size, shape and materials as well as canyons may trap and release radiation (Li and Zhang, 2019). The design of public space furniture often lacks consideration for environmental conditions and social interaction mechanisms. It is commonly standardized, neglecting factors such as location, orientation and formal qualities that could impact the environmental conditions and social interactions within the specific sites where they are placed (van Ameijde *et al.*, 2022; Abdollahzadeh and Biloria, 2021). Excessive UV radiation poses health risks. Effective outdoor shading depends on location, including solar angle, distance and ozone concentration. By considering these factors, enclosures protect against UV radiation, ensuring well-being in outdoor spaces (Adriaenssens *et al.*, 2014).

Combining architectural form-finding and structural optimization with a data-driven approach to analyzing urban visibility and environmental conditions could result in suitable public space canopies (van Ameijde *et al.*, 2022). Parametric design uses adjustable variables to influence equations or models. It treats design elements as parameters, enabling complex geometries. Designers can generate new shapes and forms by manipulating these variables (Rodonò *et al.*, 2020). The individual's adaptability to the external environment greatly impacts thermal comfort through the theory of adaptive thermal comfort, widening their actual comfort range beyond traditional comfort indices (Li and Zhang, 2019). Figure 3 Shading design should consider multiple factors: aesthetics, social aspects, environmental impact and structural integrity. It enhances user experience, promotes sustainability and ensures safety. By integrating these considerations, designers create visually appealing and functional shading solutions.

3.3.1 Climatic condition. Effective shade design considers the location's environment for year-round comfort. Factors like temperature, humidity, air movement and solar heat impact the environmental comfort of shade structures (Guo *et al.*, 2023). Solar radiation is a crucial factor in determining the outdoor thermal conditions, and it not only affects thermal comfort but also has a notable impact on health concerns. Solar radiation can be classified into various types, including ultraviolet radiation, based on its spectrum (Ji *et al.*, 2022). The main seven factors that influence the UV level are sun Height, Latitude, cloud cover, Altitude, ozone, ground reflection and season (Lee *et al.*, 2020). Various skin types respond to exposure to the

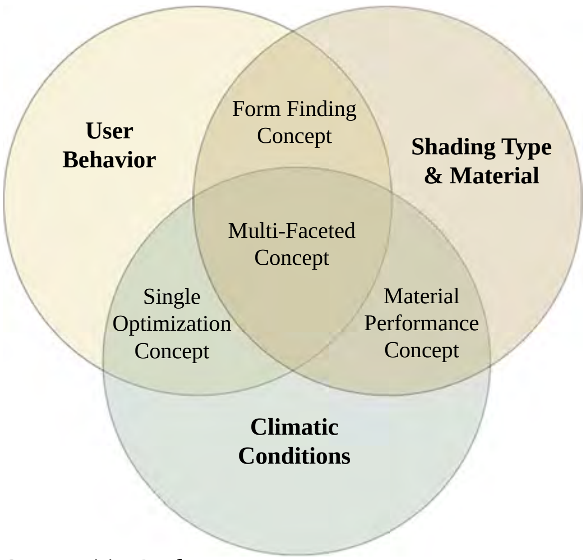

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Figure 3.
Shading concept reinterpretation

sun differently. The World Health Organization (WHO) 2 has divided phototypes, or skin types, into six groups based on how well they handle sun light (Sánchez-Pérez *et al.*, n.d). Understanding the sun's path is crucial for determining where a shade structure will cast its shadow (Sánchez-Pérez *et al.*, n.d). Solar exposure, shade conditions and the configuration of streets, including street patterns and building heights, all influence the microclimates at street level (Yıldırım, 2020). In conclusion, solar factors and criteria play a pivotal role in both thermal comfort and human health as shown in Figure 4. UTCI emerges as the finest measuring tool for accurately evaluating solar exposure and ensuring optimal outdoor thermal comfort, as it is a temperature scale index used to measure the level of thermal comfort. It considers not only environmental factors like air temperature, mean radiant temperature, relative humidity and wind speed, but also human parameters like metabolic rate and clothing ratio (Peng *et al.*, 2019). It also seems to be valid in all climates and seasons, especially for the outdoor thermal environment. The new generation of multi-node human thermal balance models considers all heat transfer and exchange both within the human body and between the skin and the surrounding air layer, resulting in a new air temperature that preserves thermal balance (Kakovkina *et al.*, 2020; Kamel, 2021) supported the ladybug and honeybee by employing algorithmic techniques and tools. One of the chosen tools, known as the "Outdoor Solar Temperature Adjustor," was utilized to measure both the emitted and reflected beams from the sun. The "Outdoor Comfort Calculator" component combines various parameters, including the dry bulb air temperature, the Mean Radiant Temperature (MRT) from surrounding reflected surfaces, wind speed and direction and the percentage of Relative Humidity (RH%). These inputs are integrated and computed to determine the Universal Thermal Climate Index (UTCI) (Kamel, 2021).The UTCI instrument measures how comfortable it is for people to be outside, and the Grasshopper plugins Ladybug is used to calculate this index. The Galapagos plugin software uses an evolutionary process to optimize

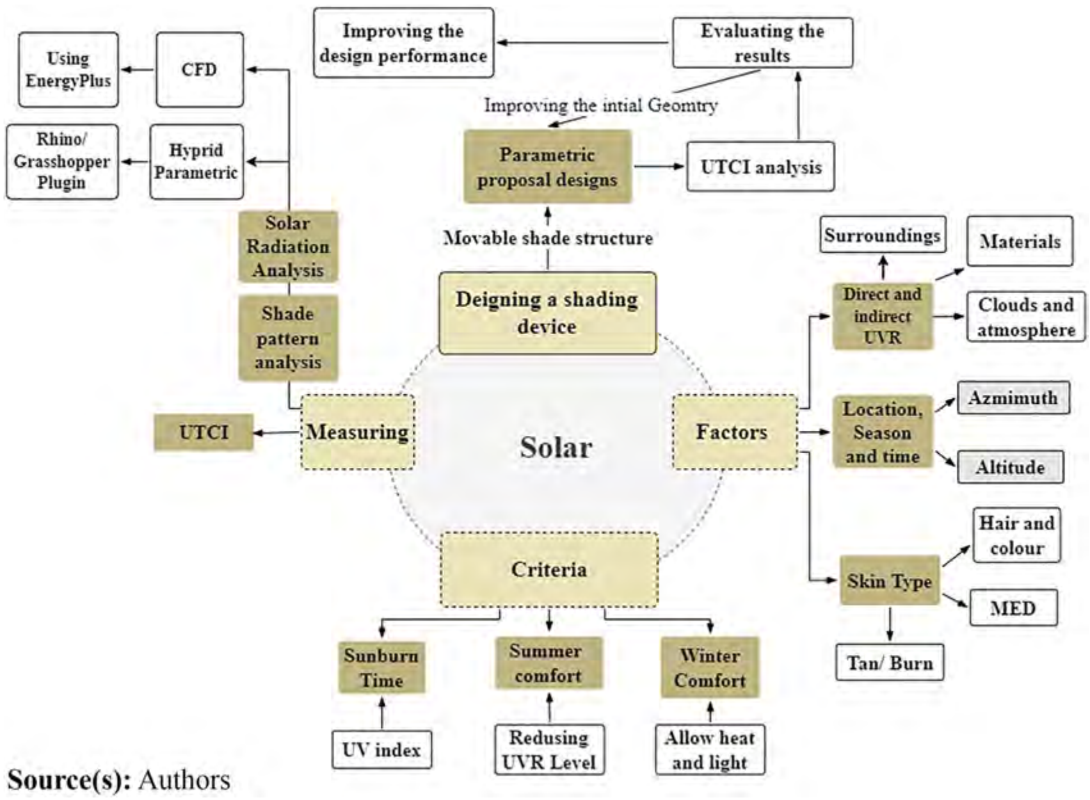

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Figure 4.
Parametric design cycle based on solar factor

the geometry for outdoor comfort. The optimization procedures need to be carried out for the many periods that the geometry has (Rodonò *et al.*, 2020).

3.3.2 User behavior. BPs are constructed to support a variety of events and activities, both planned and unplanned. They are frequently distinguished by a sizable open gathering space. Shade trees and other permanent buildings are usually restricted to the site's perimeter or other distinct areas (Othman *et al.*, 2020). Shading locations depend on four factors: time, duration, level of use and site nature. High UV radiation hours (10 a.m.–2 p.m.) prioritize shade in frequently visited areas. Prolonged use increases risk, favoring longer activity sites. High-usage areas take precedence. Sites like pools, lakes and beaches reflect UV radiation, posing greater risks and requiring top priority (Guo *et al.*, 2023). During the summer, people tend to seek shade to escape the heat, while in winter, they seek warm places. Students, when given the option, seem to prefer spacious and well-lit areas with comfortable and warm shading, where they can gather together (Turnbull and Parisi, 2005). Outdoor spaces connect buildings with nature, creating a cohesive experience. While not function-specific, they provide leisure opportunities. The main goal is community and social interaction, fostering conversations and connections. These spaces bridge indoor and outdoor environments, enhancing overall connectivity (Göçer *et al.*, 2018). The hot and arid climate requires a flexible approach to urban space design for shading, as the dynamic and interactive nature of shading patterns and daily pedestrian activities precludes the recommendation of a single, optimal solution (Khudhayer *et al.*, 2019). Shaded spaces that lack comfort will likely remain unused, whereas comfortable shaded areas will attract people looking for relief from heat rather than protection from UV radiation (Elrefai and Nikolopoulou, 2023). Environmental interventions can influence walkability and pedestrian behavior through their microclimatic effects. For instance, artificial shade can reduce solar radiation and decrease the radiant heat load on the human body (Lee *et al.*, 2020). Space syntax theory takes "space itself" as the starting point. It proposes that there is a certain relationship between society and space in the spatial structure. As a single independent element, space analyzes the connection between architecture, society and cognitive fields (Zou *et al.*, 2021). According to the theory of space syntax, quantitative calculation indexes such as integration degree, connection degree and sight integration degree can be calculated to explore how spaces are organized together. Calculate and analyze its accessibility and visibility. Space syntax analysis is a tool that examines the relationship between spatial configurations and human movement patterns, particularly in terms of walkability. It focuses on assessing the ability of individuals to traverse through an area or landscape, considering factors like proximity, distance and permeability (Thorne *et al.*, 2020).

3.3.3 Shading type and material. The provision of shade can be accomplished in a variety of ways, from "natural shade" solutions, which rely on plants like trees, large shrubs, vines and ground covers to block direct UVR and absorb indirect UVR, to "constructed shade," which is created specifically to address a given need and utilizes manufactured components. Additionally, "portable shade" devices are available to quickly and temporarily provide shade (Parisi *et al.*, 2019). Built shade can be stand-alone, or it can be built onto existing buildings or structures. Form-finding processes have long been conducted out using computational tools and physics-based algorithms, allowing the combination of previously separate processes of form generation and evaluation and transforming form-finding into an interactive dynamic process (Attar *et al.*, 2010).Tensile shading's lightweight nature and ease of installation make it a sustainable and cost-effective choice for shading solutions in parks, public squares, commercial spaces and even residential applications (van Ameijde *et al.*, 2022).The effectiveness of shading devices in cooling depends on their structure, components, and properties of the construction material (Lam *et al.*, 2023). Different shade materials have been explored, such as nylon sun sails, polyvinyl chloride (PVC) umbrellas, glass covers, aluminum structures, pergolas and photovoltaic canopies (Lee *et al.*, 2020).

3.4 Outdoor comfort parametric design

Genetic algorithms, also known as evolutionary algorithms (GA), are a powerful class of optimization algorithms inspired by the principles of natural evolution. They leverage concepts such as inheritance, mutation and selection to determine the most optimal solution to a mathematical problem. The methodology's circular workflow allows for the optimization of the geometry of human outdoor comfort. It's three steps (geometric design, outdoor comfort design and optimization) each need the usage of a certain tool and software, The digital parametric environment is used to improve the geometric design since it allows for interactive input control (Rodonò *et al.*, 2020). The GA approach involves a population of candidate solutions, referred to as individuals, which undergo a series of generations in order to converge towards the best possible solution for a given objective. These algorithms can tackle complex problems, including those that are non-linear in nature (Wu *et al.*, 2022). As a result, there has been a growing interest in utilizing parametric and generative design techniques, leading to a significant increase in research studies focused on GA-based optimization methods (Caetano *et al.*, 2020). Therefore, it was found that the most suitable approach to follow in this research is to use Rhino – Grasshopper via hybrid simulation in order to take the advantage of the strength of all plugins (Ladybug – Honeybee – Lunchbox) and the genetic algorithm advantage to make the microclimate analysis and the OTC environmental assessment (PET, MRT, PMV and UTCI), moreover, the optimization process that could be achieved by Galapagos plugin that could give wide number of alternative cases. This study employs the new environmental simulation software, Ladybug tool, which runs within Grasshopper in Rhino 3D modeling software. The software's parametric nature allows for quick feedback on various designs and the execution of numerous simulations in a relatively short time, particularly when excluding CFD simulations (Elrefai and Nikolopoulou, 2023).

4. Case study

4.1 Case study selection

Our case study is in one of New Cairo's most desirable areas, the 5A business park. The development looks out over the Maadi Ring Road, and its residents and visitors may take advantage of the convenient direct access that was developed just for them. This unparalleled location means 5A is right at the crossroads of tradition and modernity, connected to New Cairo and the New Administrative Capital on one end, the BP covers approximately 30,000 m^2 for the total land and built-up area around 10,500 m^2 which includes 8 buildings. Choosing the 5A BP as the case study is based on its location in a new city with a hot arid climate, and this type of climate needs investigation of thermal comfort in urban space, the whole project oriented to the west so it's important to evaluate thermal comfort on it and to find a way to enhance it. Finally, 5A was chosen because of its administrative, social and commercial value.

4.2 Social assessment

4.2.1 Observation analysis – shade audit. The study involved analyzing user activities in BP's main outdoor areas and their interaction with the surrounding buildings. To provide a more detailed explanation of the findings, 10 zones were identified as shown in Figure 5. These zones include two main entrances and four minor entrances at 5A BP, allowing for a comprehensive assessment of the shading requirements and shortcomings in different areas of the study site.

By evaluating the 10 main zones based on four factors: time, duration, level of use and site nature. Consider peak UV radiation hours and prioritize shading for frequently visited areas. Give importance to summer sites with higher UV intensity. Consider duration of outdoor

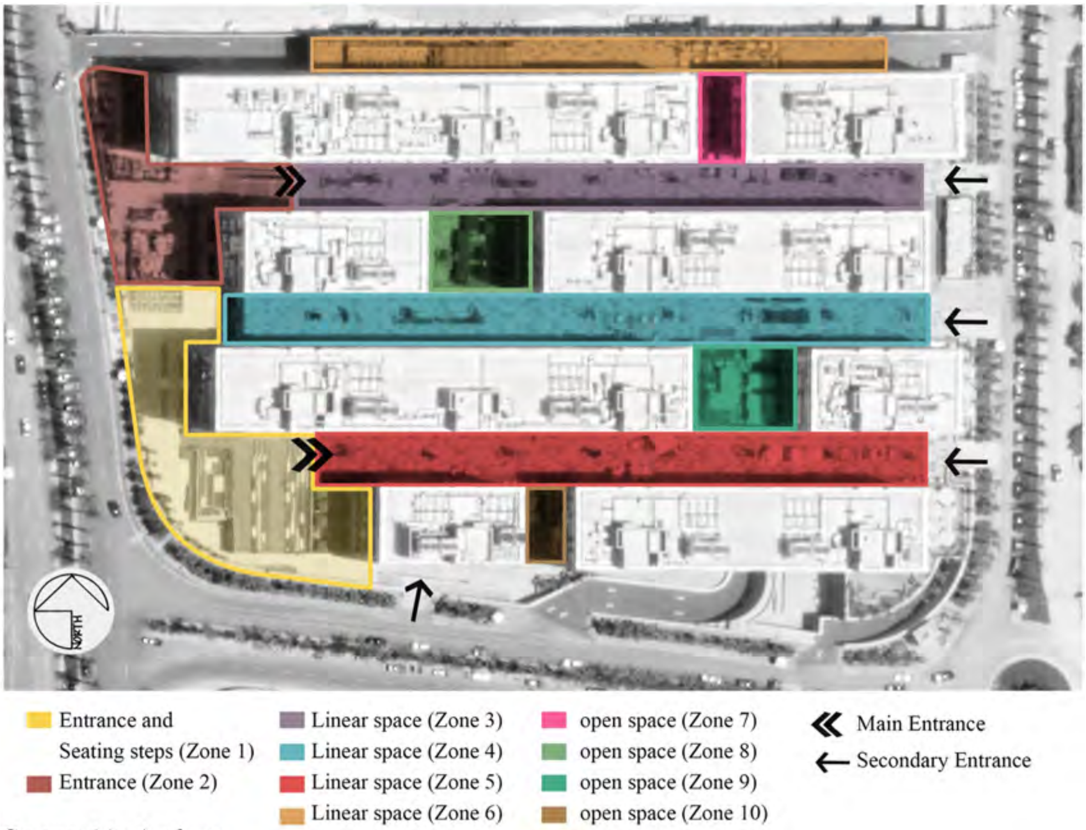

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Figure 5.
5A BP main zones and entrances

activities and prioritize high-usage sites. Carefully assess site nature and activities. The analysis of the shade priority checklist scores across all 10 zones revealed significant findings. Notably, zones 1, 3, 4, 5, 8 and 9 exhibited the highest scores, indicating a greater need for prioritized shade provisions in these areas.

4.2.2 5A BP space syntax analysis. Social evaluation of open spaces in the business park involved space syntax analysis. It included connectivity analysis and spaces integration analysis. The analysis objectively assessed outdoor spaces, examining relationships and attributes. Connectivity and visibility measured using Depth map software as indicators.

4.2.2.1 Connectivity and visibility analysis. Connectivity analysis examined spatial relationships between park zones. Zones 1, 2, 4, 5 and 9 showed high connectivity, indicating strong interaction and movement. Calculation considered direct paths and numerous connections. Map visualization represents varying levels of connectivity Figure 6. Using depth-map, a visibility map was created to analyze the integration and visibility of different zones in the BP. The results indicated that the main entrances were the most integrated and visible areas, serving as prominent gateways into the park. Additionally, the western side of the linear zones showed a high level of integration and visibility, making them favorable for social engagement. Zones 8 and 9, which connected the primary linear zones, also demonstrated significant integration and visibility, enhancing their potential for fostering social connections within the BP.

4.2.3 Social assessment conclusion. After combining the results of the shade audit and space syntax analysis, it has been determined that zones 1, 4, 5 and 9 hold the highest priority Table 2 These zones emerged as critical areas requiring immediate attention and focus due to the overlapping findings from multiple analyses. This prioritization ensures that resources

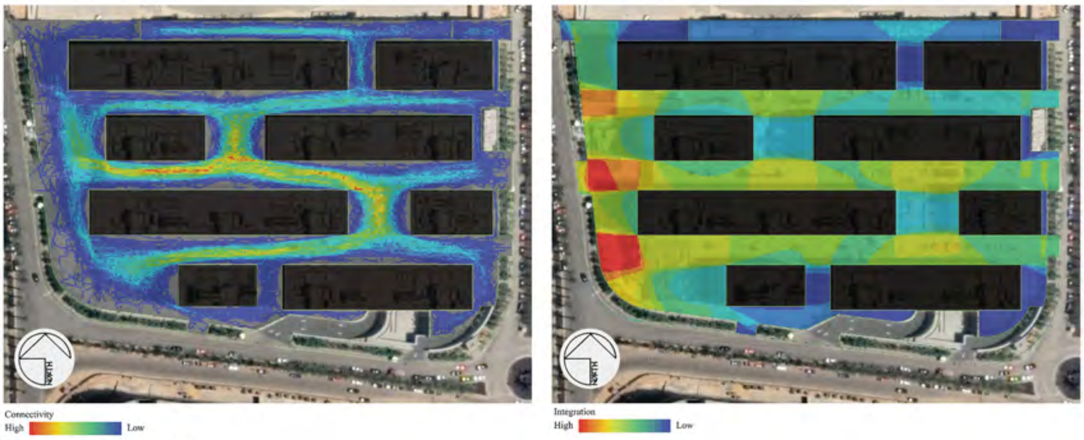

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Figure 6. Visibility analysis map on the left side and connectivity analysis on the right side

Table 2. Prioritized for shading based on the social assessment

Assessment tool	Zones 1	2	3	4	5	6	7	8	9	10
Shade audit	✓		✓	✓	✓			✓	✓	
Connectivity analysis	✓	✓		✓	✓				✓	
Integration analysis	✓	✓	✓	✓	✓			✓	✓	
Total	3	2	2	3	3	0	0	2	3	0

Source(s): Authors

and efforts can be efficiently directed towards these specific zones to address shade provision, spatial connectivity, geometry considerations and user needs effectively.

4.3 5A BP main outdoor zones analysis

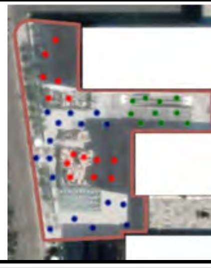
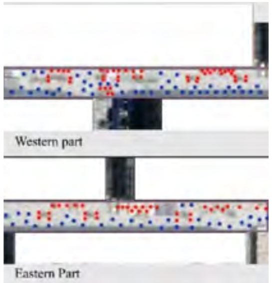
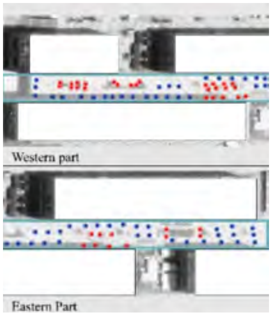
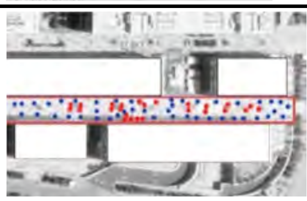
Several factors were considered when assessing the need for shade in the main zones and entrances. User movement analysis, including walking, sitting and transitions between spaces, was examined, along with the physical characteristics of the zones, such as their positioning, building height, space types and materials used Table 3. Considered entrances to buildings in 5A BP complex with uniform 18-m height. Buildings feature light grey cement tiles (albedo: 0.4). Linear zones are poorly oriented, facing east-west. Northern facades have stores/commercial zones, while southern facades house cafes/restaurants. These factors determined main zones and entrances. Table provides overview of key zones with high occupancy and poor orientation.

4.4 Social and geometrical assessment conclusion

After combining the results of the shade audit, space syntax analysis, geometry analysis and user behavior assessment, it has been determined that zones 1, 4, 5 and 9 hold the highest priority. These zones emerged as critical areas requiring immediate attention and focus due to the overlapping findings from multiple analyses. This prioritization ensures that resources and efforts can be efficiently directed towards these specific zones to address shade provision, spatial connectivity, geometry considerations and user needs effectively.

4.5 Case study environmental assessment

The process of making an environmental assessment involves several key steps. First, Ladybug, a plugin for Rhino software, is used to analyze thermal factors such as temperature,

Description	Analysis		Walking · Seating · Stepping
Zone 1: 1- Main Entrance 1 open space attached to main street 2- Entrance stairs and seating steps.	Space Orientation	N - S	
	Building Height	18 m	
	Space Type	1- Building at one side (E) 2- Building at two sides (N + E)	
	Hardscape	Light grey cement tiles with albedo 0.4	
Zone 2: 1- Main Entrance 2 open space attached to main street which have on both sides outdoor cafes shaded seating. 2- Entrance stairs and escalator - surrounding by buildings from both sides	Space Orientation	N - S	
	Building Height	18 m	
	Space Type	1- building at one side (E) 2- Building at two sides (N+S)	
	Hardscape	Light grey cement tiles with albedo 0.4 + Water Features with albedo 0.1	
Zone 3: Linear open space with mixed-use buildings on either side; the southern buildings feature retail, and the northern buildings have restaurants and cafes.	Space Orientation	E - W	
	Building Height	18 m	
	Space Type	Linear space, Building at two sides (N+S)	
	Hardscape	cement tiles with albedo 0.4 Fiberglass sculptures with albedo 0.4	
Zone 4: linear open space features mixed-use buildings (ground floor retail and upper floor offices.)	Space Orientation	E - W	
	Building Height	18 m	
	Space Type	Linear space, Building at two sides (N+S)	
	Hardscape	cement tiles with albedo 0.4 Fiberglass sculptures with albedo 0.4	
Zone 5: Linear open space with mixed-use buildings on either side. the southern buildings have retail, and the northern buildings have restaurants and cafes.	Space Orientation	E - W	
	Building Height	18 m	
	Space Type	Linear space, Building at two sides (N+S)	
	Hardscape	cement tiles with albedo 0.4 Fiberglass sculptures with albedo 0.4	

Source(s): Authors

Table 3.
5A BP main outdoor zones analysis

wind and humidity in different park zones. Next, solar irradiance levels are assessed to understand sunlight intensity throughout the day. Surveys or measurements are conducted to gather data on visitors' perception of thermal comfort. Finally, the findings are validated by comparing them with established thermal comfort standards and guidelines. These steps ensure a comprehensive evaluation of the park's environmental conditions.

4.5.1 Dry and dew bulb temperature. The dry bulb temperature in Cairo represents the ambient air temperature without accounting for moisture content. It is evident that Cairo experiences significant variations in dry bulb temperature throughout the year Figure 7. Monthly averages range from around 5 °C in the cooler months to approximately 45 °C during the hotter periods. The data indicates a clear distinction between the winter and summer seasons in terms of temperature. These fluctuations in dry bulb temperature highlight the contrasting climate conditions experienced in Cairo and play a crucial role in understanding the local weather patterns and planning for appropriate measures to mitigate the effects of extreme temperatures. The dew point temperature in Cairo reflects the moisture content in the air and provides insights into the level of atmospheric humidity. Analyzing the available data, it is observed that the dew point temperature exhibits fluctuations throughout the year. In general, Cairo experiences a range of dew point temperatures, with monthly averages varying from as low as −14 °C to as high as 23.1 °C as shown in Figure 7. These fluctuations indicate the dynamic nature of humidity levels in the region. Understanding the dew point temperature is crucial for assessing the likelihood of condensation and the potential for moisture-related phenomena in Cairo's climate.

4.5.2 Relative humidity (RH). The RH exhibits monthly variations, as evidenced by the data presented in Figure 8. On average, the relative humidity stands at 57.75%. Notably, the highest monthly average of 68% is observed in January, indicating a relatively more humid period. On the other hand, may records the lowest monthly average of 44%, representing a drier period with reduced moisture content in the air. These fluctuations in RH throughout the year highlight the dynamic nature of Cairo's atmospheric conditions.

4.5.3 Wind velocity and direction. In Cairo, there is an average range of maximum wind speed ranging from 6.58 to 9.4 m/sec. The monthly mean maximum wind speed occurs specifically during winter days, as shown in Figure 9. Prevailing wind: (summer: N), (winter:

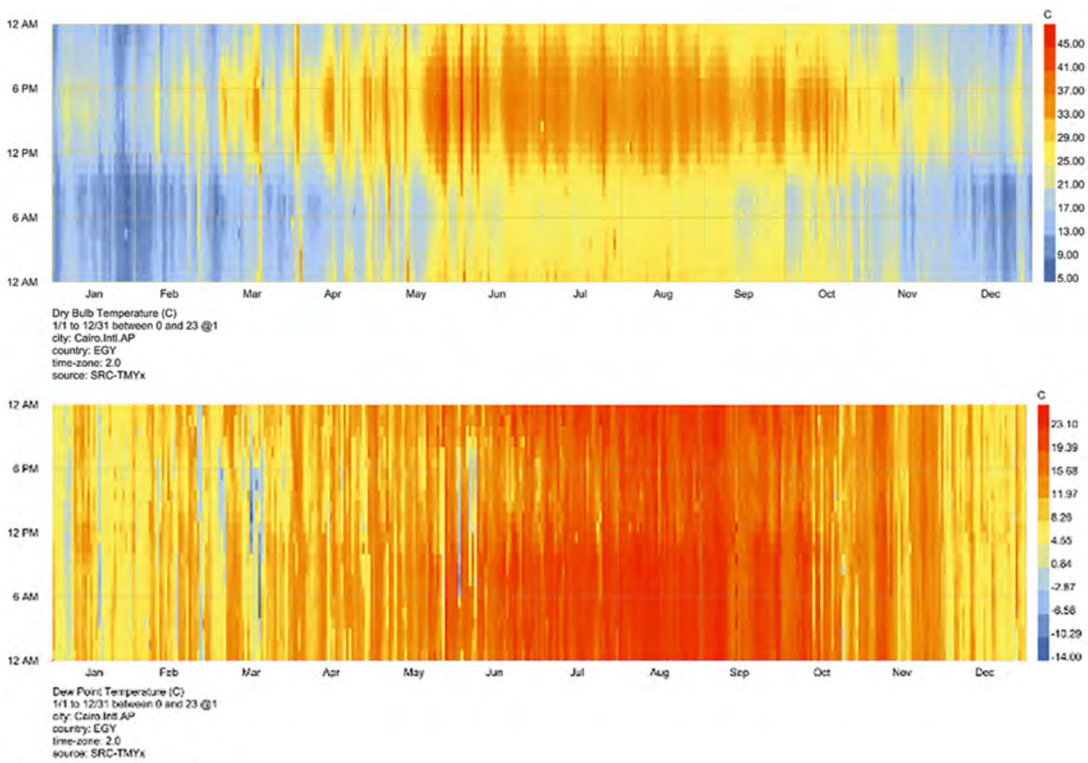


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Figure 7. Dry bulb temperature and dew bulb temperature during the year in Cairo

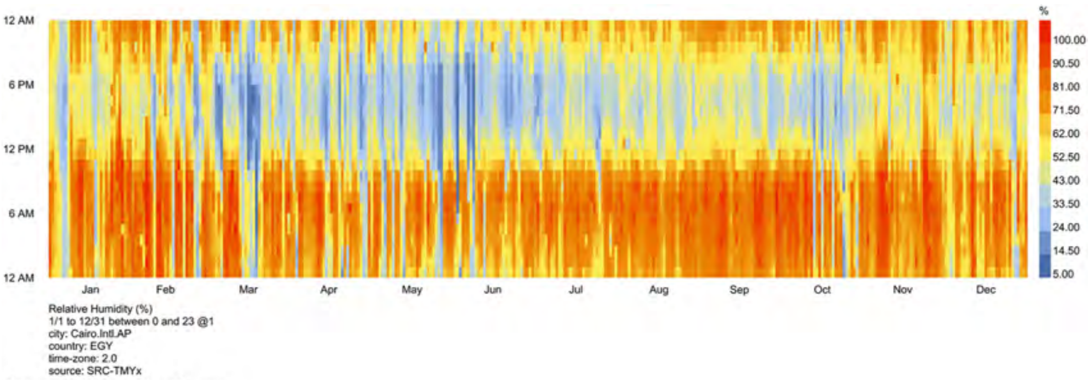

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Figure 8.
Relative humidity during the year in Cairo

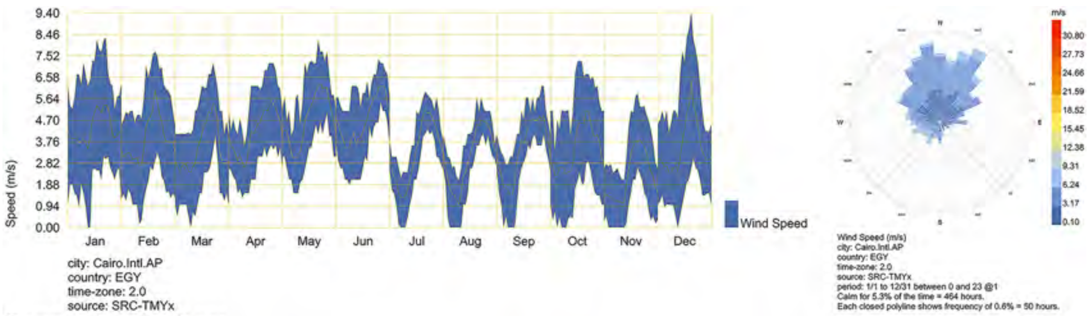

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Figure 9.
Wind speed and direction during the year in Cairo

SW). Secondary wind through (summer: NW), (winter: S). The khamsin wind hit Cairo in springtime which are southern hot winds accompanied by sand and dust whereas the preferable wind below due Northwest Figure 9.

4.5.4 Solar radiation. Being classified as hot and arid, Sky Dome Representation of Total Radiation in Cairo: Depicting the Sun's Path from East to South to West. The chart showcases the range of total radiation values, with a maximum recorded value of approximately 74.58 kWh/m^2 Figure 10.

4.5.5 Field and simulated measurement. Field measurements were carried out to give an idea of the accuracy of the Grasshopper – Rhino and its plugins and to help set the boundary conditions, Field measurements were conducted at Entrance space and at the most connected and integrated spaces (zone 1, 4, 5 and 9) in winter from 27 January to 2nd February and in summer 20 July to 26 July. The meteorological parameters such as air temperature, relative humidity and wind speed and globe temperature were measured during daytime from 11 a.m. to 4 p.m. Figure 11. A comparison between the simulated and measured results for microclimatic parameters, such as dry bulb temperature, dew point temperature, relative humidity and wind speed at specific points, is depicted in Table 4. The simulation study was conducted during the most extreme hot and cold weeks, as shown in Figure 11, which were identified based on the meteorological data (epw. file) obtained from the weather stations. The model was simulated for a duration of 5 h, from 11 a.m. to 4 p.m., taking into consideration the period with the highest risk of sun exposure. This carefully chosen time period allowed for a more accurate representation of the impact of extreme weather conditions on the simulation outcomes.

4.5.6 Validation. To validate the accuracy and reliability of the simulation results, a comprehensive instrumentation setup was employed. The measurements were conducted

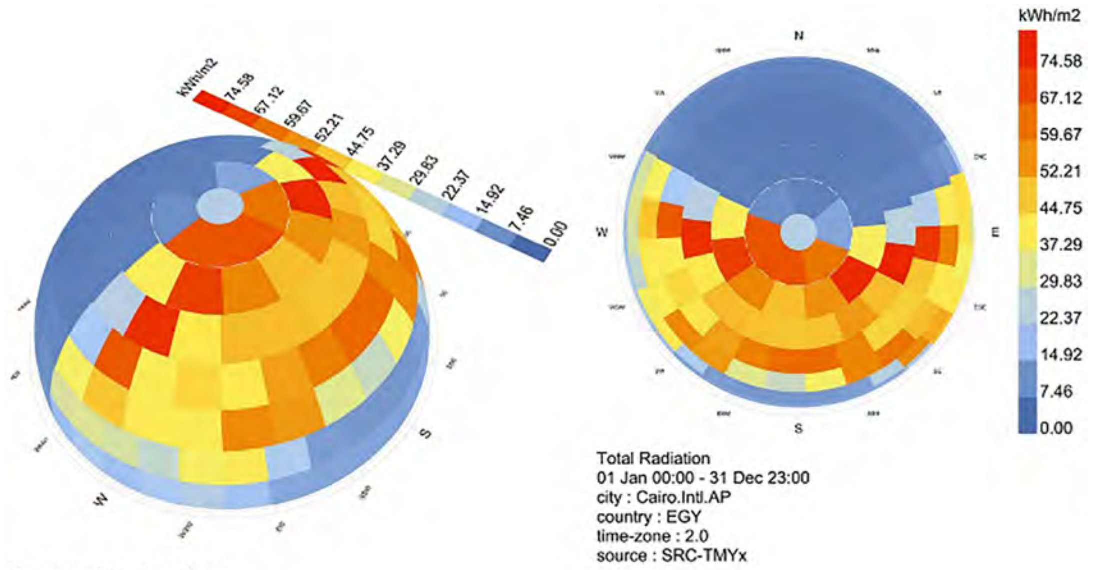

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Figure 10. Total radiation during the year in Cairo

using a Heat Stress WBGT (Wet Bulb Globe Temperature) Meter, positioned at a height of 1.8 meters. This instrument is widely recognized for assessing thermal comfort and heat stress levels in outdoor environments. The measurements were specifically taken during the coldest week and hottest week, between 11 a.m. and 4 p.m., which coincides with the period of the day when individuals are at the highest risk of sun exposure. Despite some discrepancies between the measured and simulated results, the validation process justifies the use of Rhino, Grasshopper and Ladybug for simulating the outdoor microclimate in the study area. These software tools provide a robust framework for analyzing the impact of design parameters and optimizing outdoor environments.

4.5.7 Base case solar irradiance assessment. The following analysis of sun hours in summer using the Ladybug plugin in Rhino revealed that all east-west (EW) spaces in the business park experienced the highest exposure to sunlight throughout the day Figure 20. This presents an opportunity to implement effective strategies for outdoor shading. By incorporating shading structures, park visitors can enjoy the outdoors while staying protected from the intense sunlight. On the other side, the analysis of direct sun hours in winter using the Ladybug plugin in Rhino, the results revealed that the outdoor seating areas and main entrances of the business park were the most exposed to direct sun hours Figure 20. This finding carries significant implications, particularly during the winter months when sunlight is scarce. The analysis provided valuable insights into the sun's trajectory and its influence on different areas of the park. Interestingly, all the linear spaces exhibited self-shading properties, resulting in the minimum direct sun hours received.

The simulation of solar irradiance in outdoor spaces during the summer months, as illustrated in Figure 21, has yielded important findings regarding solar energy distribution. Notably, the cumulative solar irradiance recorded during the hottest week was approximately 160 kWh/m^2. It is worth mentioning that the spaces attached to northern faces of the buildings received less solar irradiance compared to the spaces oriented in the north-south direction. Furthermore, the spaces oriented in the east-west direction experienced the highest solar gain. These observations highlight the impact of building orientation on solar exposure. The cumulative solar irradiance recorded during the coldest week amounts to approximately 93 kWh/m^2. It is worth noting that the linear outdoor spaces, due to HW ratio,

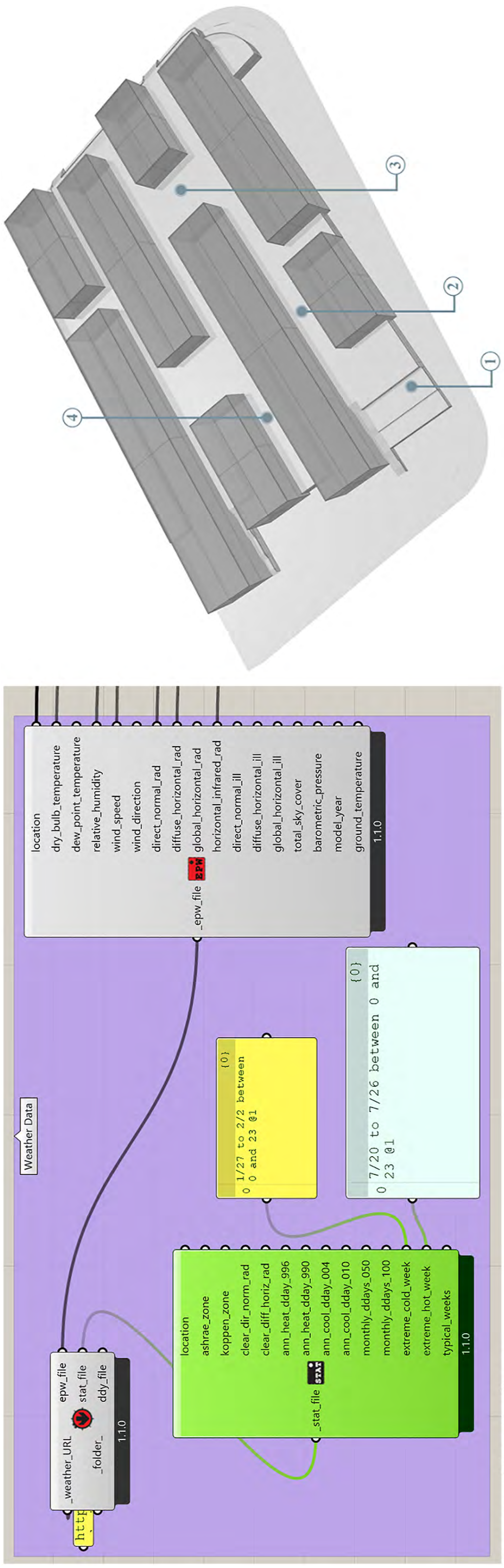

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Figure 11.
Extreme cold and hot week due to ladybug analysis and rhino model with receptors for the study area

Table 4. Comparison between measured and simulated microclimatic parameters

Dry Bulb Temperature (DBT)

In Figure 13, a comparison is presented between the average dry bulb air temperature simulated by Ladybug, as displayed in Figure 12, and the corresponding measurements for the main four points in the study area. The results reveal a consistent tendency of Ladybug to underestimate the daytime dry bulb temperature during both winter and summer seasons. However, it is worth noting that the variations between the measured and simulated dry bulb temperatures remain below 2 °C, indicating a relatively small deviation between the two.

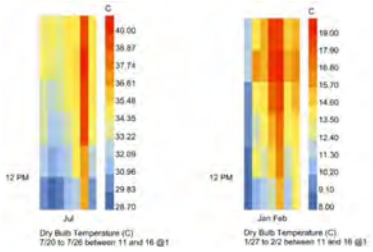

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Figure 12. DBT °C at extreme cold and hot week in Cairo

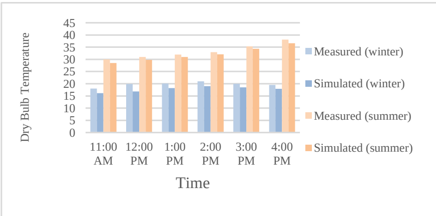

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Figure13. Measured and Simulated DBT

Relative Humidity (RH)

Figure 15 presents a comparison between Ladybug's simulated average relative humidity (as shown in Figure 14) and the measured values for the main four points in the study area. The results indicate that Ladybug consistently overestimates daytime relative humidity in both winter and summer seasons, with differences surpassing 8% in winter and 4% in summer.

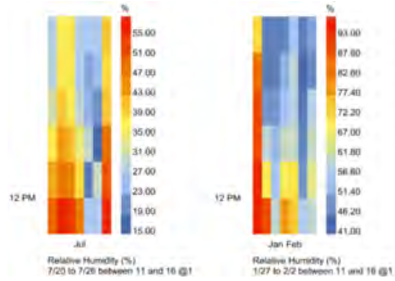

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Figure 14. RH % at extreme cold and hot week in Cairo

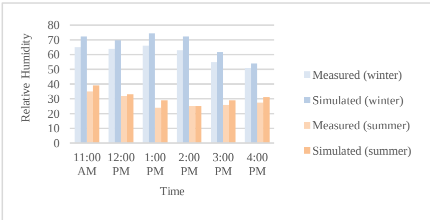

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Figure 15. Measured and Simulated Relative Humidity

Dew Point Temperature (DPT)

In Figure 17, a comparison is made between the average dew point temperature simulated by Ladybug Figure 16 and the corresponding measurements for the main four points in the study area, revealing Ladybug's consistent tendency to overestimate daytime dew point temperature in both winter and summer seasons, with variations exceeding 4 °C in winter and 9 °C in summer.

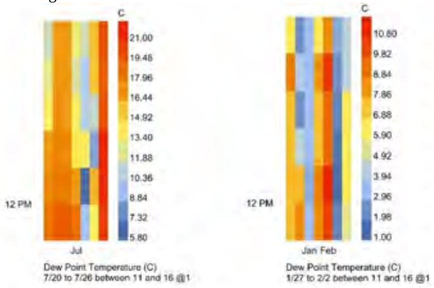

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Figure 16. DPT °C at extreme cold and hot week in Cairo

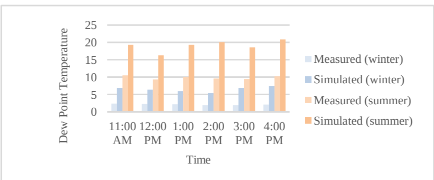

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Figure 17. Measured and Simulated Dew Point Temperature

Wet Bulb Globe Temperature (WBGT)

In Figure 19, a comparison is presented between the average WBGT simulated by Ladybug, as displayed in Figure 18, and the corresponding measurements for the main four points in the study area. The results reveal a consistent tendency of Ladybug to underestimate the WBGT during both winter and summer seasons. the variations between the measured and simulated WBGT is below 6 °C.

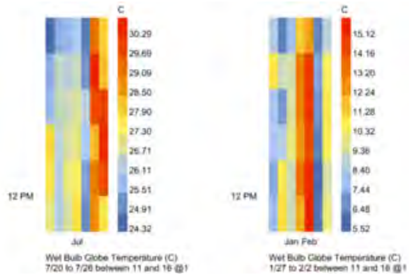

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Figure 18. WBGT °C at extreme cold and hot week in Cairo

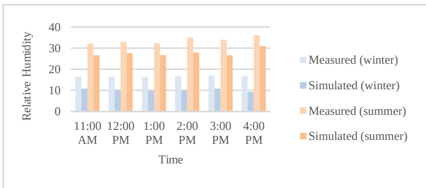

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Figure 19. Measured and Simulated WBGT

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experience more self-shading, resulting in lower solar irradiance compared to other outdoor spaces. This analysis highlights the importance of considering the geometry and orientation of outdoor spaces when designing for shading elements in winter.

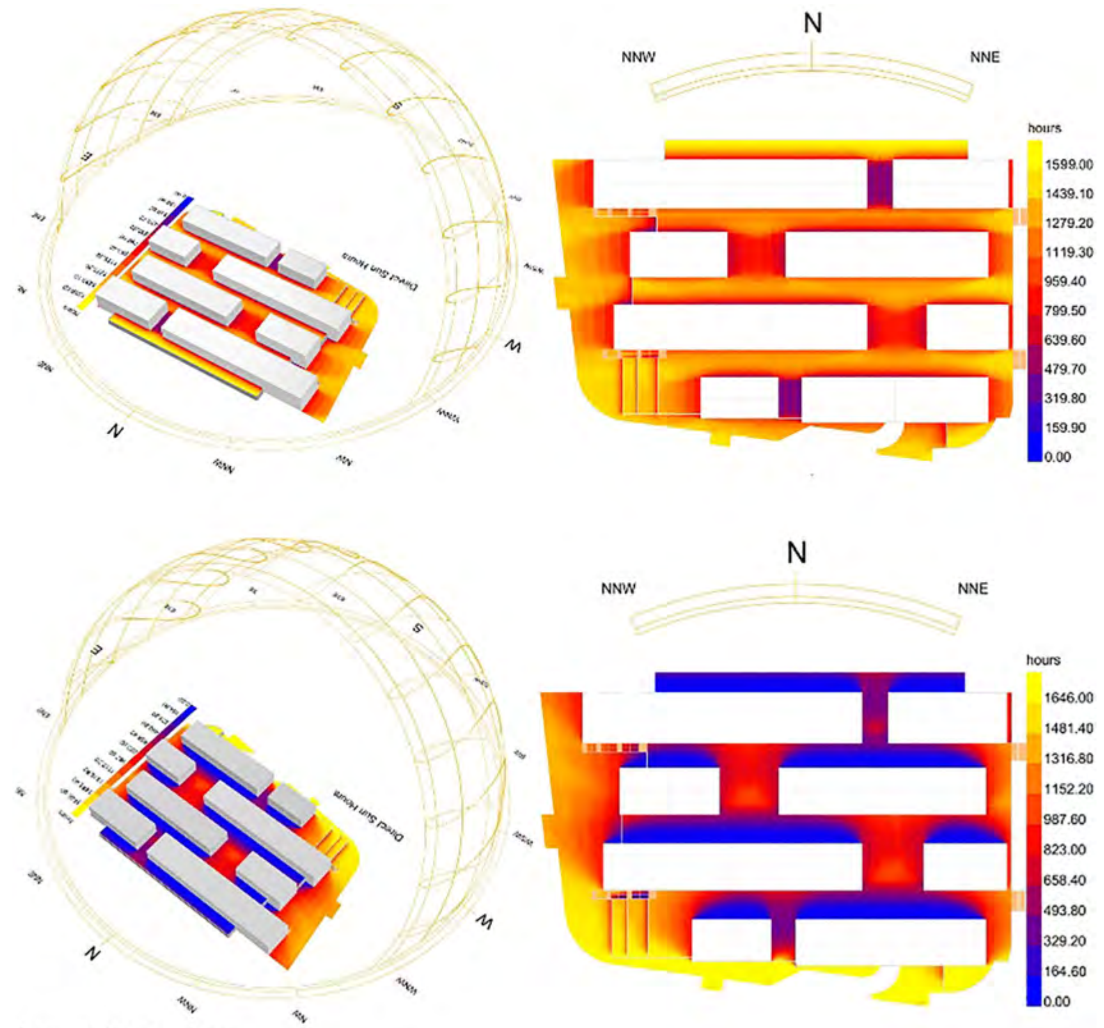

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Figure 20.
Direct sun hours analysis during the summer and winter in 5A BP

It is worth noting that the linear outdoor spaces, due to HW ratio, experience more self-shading, resulting in lower solar irradiance compared to other outdoor spaces. This analysis highlights the importance of considering the geometry and orientation of outdoor spaces when designing for shading elements in winter.

4.5.8 Base case OTC perception. After building base case model based on its parameters, outdoor thermal comfort parameters in 5A BP have been investigated considering the parameters of Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI). These parameters are crucial for understanding and improving the comfort levels experienced in outdoor spaces. Based on the analysis of outdoor thermal comfort parameters, specifically the Physiological Equivalent Temperature (PET), the chart reveals Figure 22. That during the summer days in 5A BP specially in the period from July 20th to 26th, the thermal conditions are consistently uncomfortable, particularly during the daytime. Furthermore, the chart indicates that even during the winter months, especially in the period January 27th to February 2nd in the daytime discomfort persists in outdoor spaces moreover it is uncomfortable during the nighttime in all winter months.

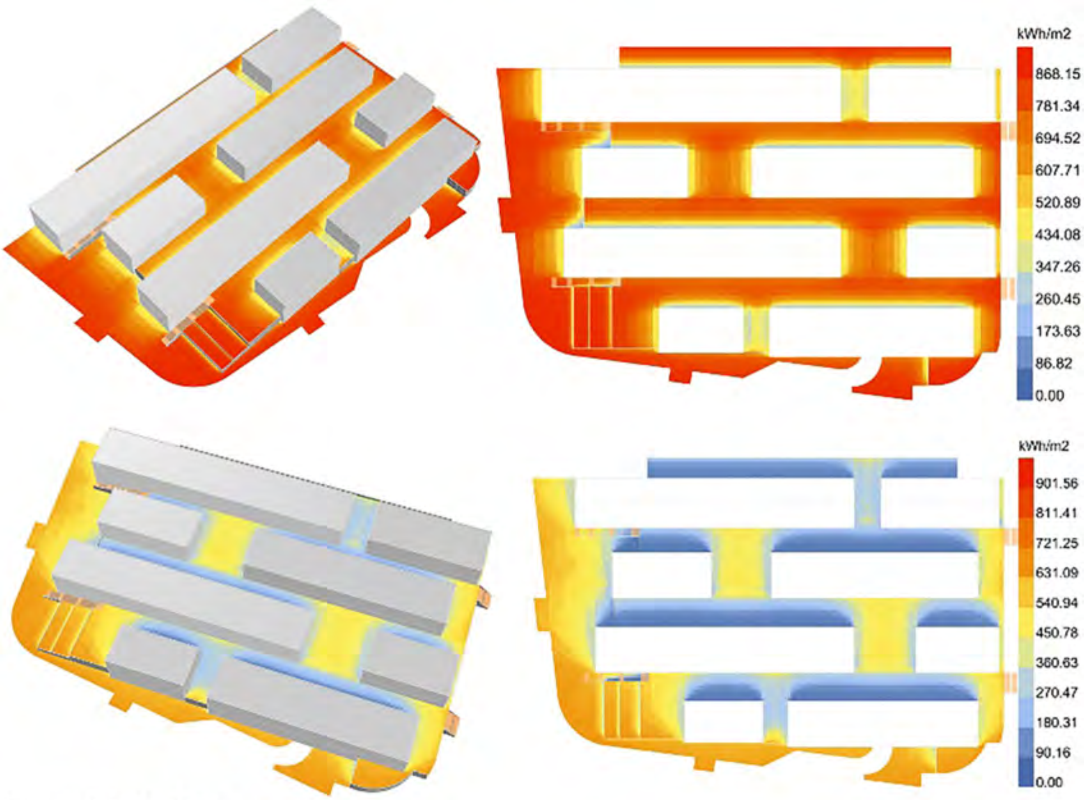

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Figure 21.
Base case solar irradiation analysis/m^2 during summer and winter months for outdoor open spaces in 5A BP

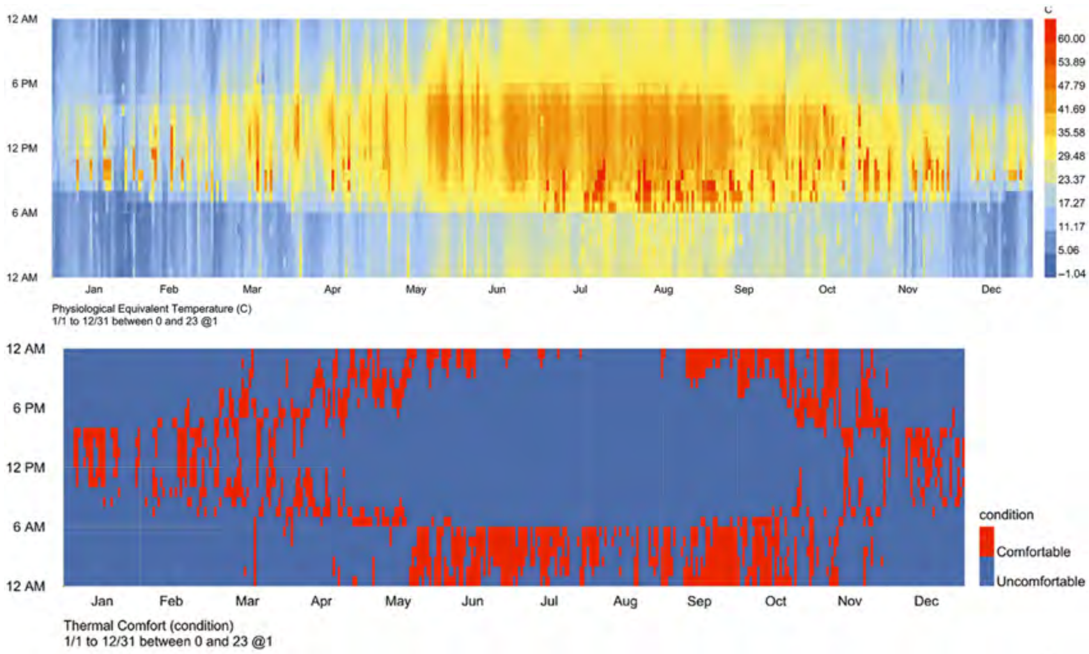

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Figure 22.
PET during the year and outdoor thermal comfort based on PET model in Cairo

The PMV (Predicted Mean Vote) model provides insights into the relationship between human thermal sensation and thermal load, considering factors such as the average skin temperature and sweat rate of the human body. In the model at ladybug, the assumed values for metabolic rate are 1.2, while the values for clothing insulation (clo) are 0.5 in summer and 1 in winter. The results of the study indicate that during the summer months, the PMV values range from warm to hot, typically falling between 1 and 3. Conversely, in the winter months, the PMV values tend to range from neutral to cold, typically falling between −3 and 0. Based on the analysis of Predicted Mean Vote (PMV) parameter, Figure 23. Indicates that during the study period from July 20th to 26th and January 27th to February 2nd, the outdoor thermal conditions in 5A BP are deemed uncomfortable. The PMV values suggest that individuals may experience thermal sensations that deviate from the desired comfort range during these specific timeframes.

4.6 5A BP base case UTCI analysis

The UTCI is a temperature scale index used to measure the level of thermal comfort. It considers not only environmental factors like air temperature, mean radiant temperature, relative humidity and wind speed, but also human parameters like metabolic rate and clothing ratio and MRT parameter as shown in Figure 24. Results show that all summer months during the noon is uncomfortable. UTCI differentiates itself from PMV and PET by employing an unsteady model that considers the human body's thermal adaptation.

In this study, the simulation conducted using Universal Thermal Climate Index (UTCI) reveals notable variations compared to Predicted Mean Vote (PMV) and Physiological Equivalent Temperature (PET). The results indicate that, considering the scale of UTCI, the linear spaces experienced a moderate level of heat stress, while the main entrances exhibited a stronger level of heat stress. In contrast, the attached spaces located along the northern facades demonstrated only a slight level of heat stress during the extreme hot week's noon period of the summer simulation. During the winter season, particularly the extreme cold

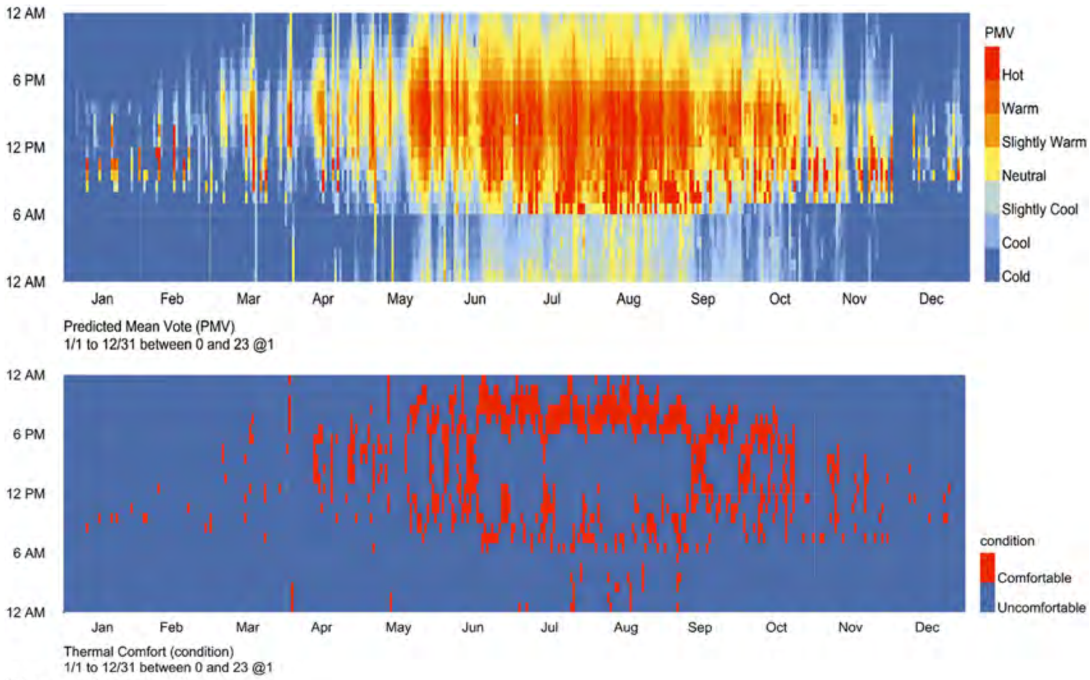

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Figure 23.
PMV during the year and outdoor thermal comfort based on PMV in Cairo

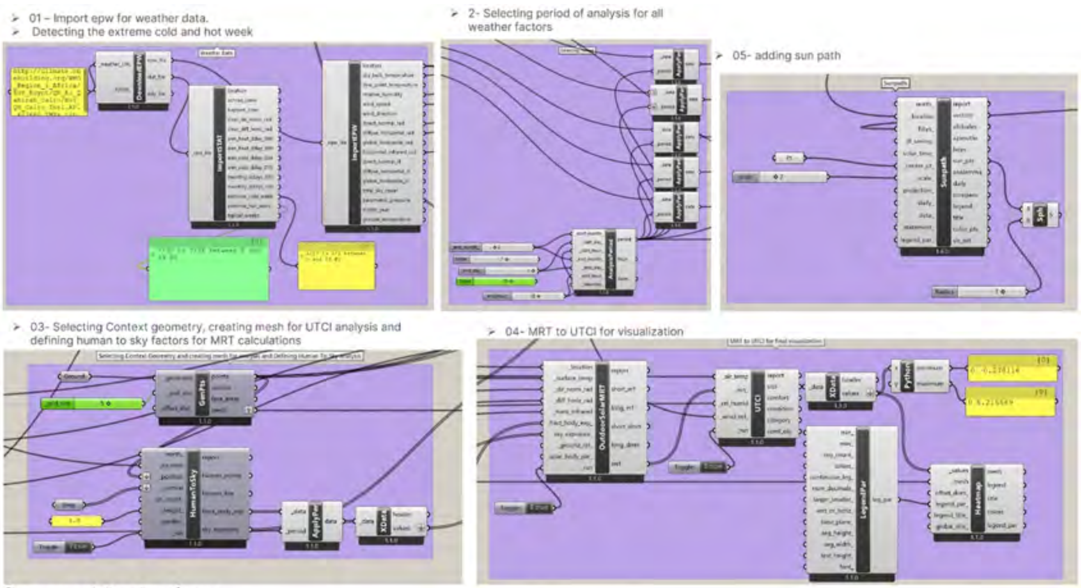

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Figure 24.
UTCI algorithm

week in February, the simulation results indicate distinct thermal conditions Figure 25. In this period, the study demonstrates that all linear spaces experience a moderate level of cold stress, suggesting potential discomfort due to the low temperatures. However, the main

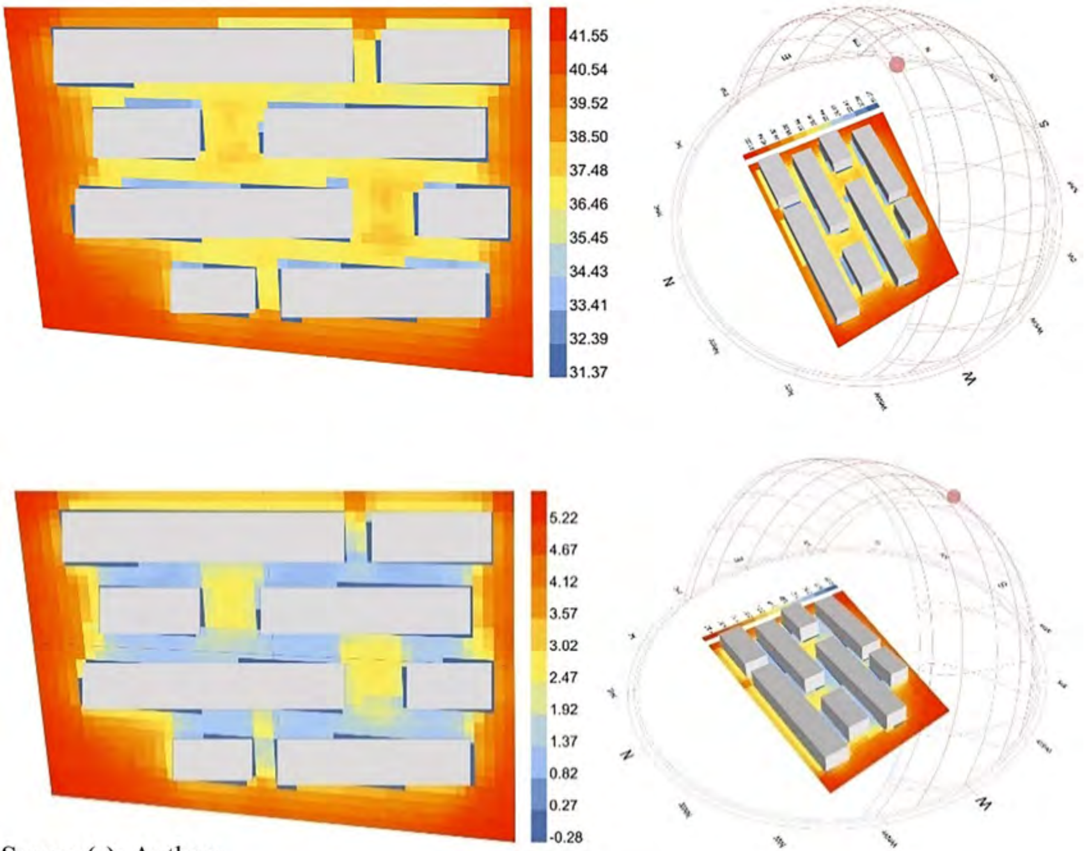

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Figure 25.
UTCI calculations for 5A BP at the extreme hot and cold week

entrances exhibit a range from slight cold stress to a neutral thermal sensation, indicating a relatively milder thermal experience.

5. Testing shading strategies

By overlaying the results of social assessment, environmental assessment and outdoor thermal comfort assessment, a clear prioritization of zones for shading design emerges. The findings indicate that the outdoor seating in Zone 1 and the western sides of Zones 4, 5 and 9 are high-priority areas due to their alignment with user needs and preferences. The assessment of environmental factors, including solar irradiance, PET, PMV and UTCI, further supports the significance of these zones. Additionally, the emphasis on the importance of linear spaces in the outdoor thermal comfort assessment reinforces the prioritization of these specific areas. By combining these results, the overlapping findings guide the design of shading strategies in these prioritized zones, ensuring a positive impact on social well-being and enhancing outdoor thermal comfort Figure 26.

5.1 Selecting shading elements

The research investigates the significance of employing portable and dynamic shading elements as the optimal choice for shading strategies. These elements offer the flexibility to adapt to a variety of situations, making them highly versatile. Their suitability for linear zones stems from their ability to cover relatively small areas efficiently. What sets them apart is their capacity to be modified dynamically, effectively providing shade as the sun moves throughout the day and during different seasons. Moreover, in the event of inclement weather, such as strong winds, these shading systems can be swiftly taken down or closed to

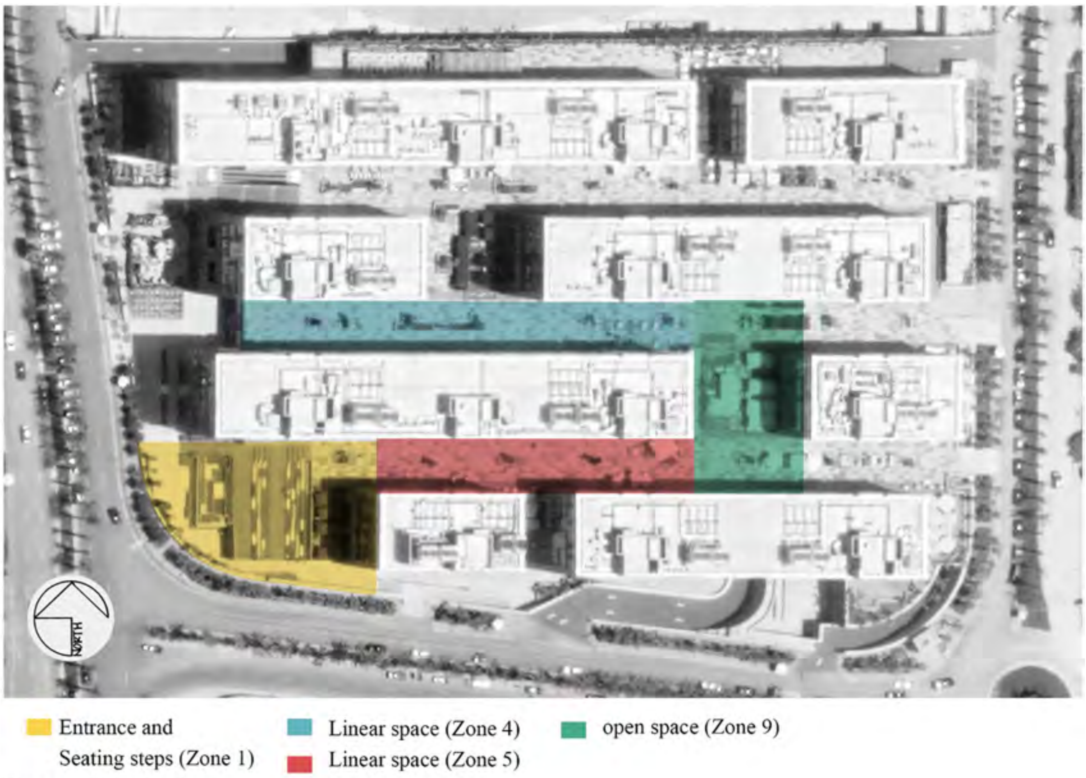

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Figure 26.
Prioritized zones for shading design

ensure safety and prevent damage. The research underscores the value of portable and dynamic shading elements as they offer adaptability, efficiency and responsiveness to varying environmental conditions. Shading elements are selected based on their function and size to suit specific activities and areas. Retractable shades are chosen for shops to prevent obstruction of the view while still providing shade Figure 27.

The size of these shades is chosen to match the module of the building, ensuring seamless integration with the architectural design. Shading parasols, on the other hand, are ideal for restaurants and outdoor seating areas. The size of the parasols is carefully considered to cover the seating area while maintaining a visually appealing and proportional aesthetic. By selecting shading elements with appropriate functions and sizes, both shops and restaurants can optimize their environments for the comfort Table 5. Larger shading elements (Type B) were strategically deployed in the larger zones, such as the seating steps in

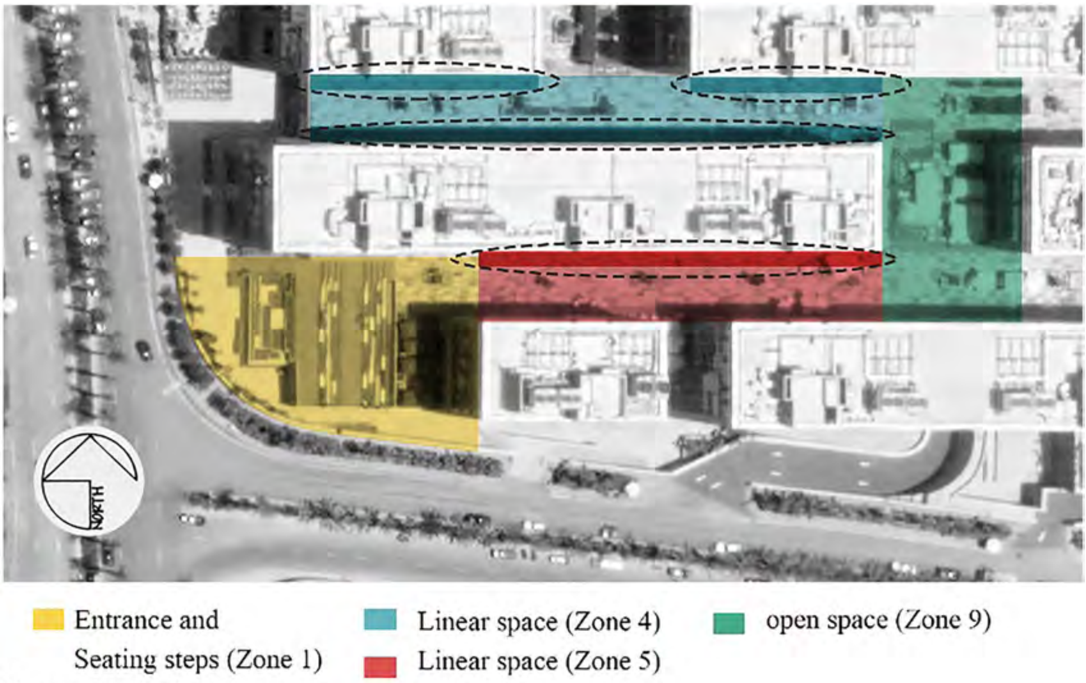

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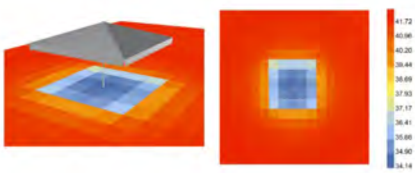
Figure 27. Suggested zone for retractable shading

Table 5. Selected shading elements specifications

Selected Shading devices	Zone & Function	Size	Material	Effect of using one shade parasol of Type B on UTCI
Type A: Retractable Shade 	Attached to all shops for the linear zones.	= Building module = 4.00 * 2.70 m	Canvas or other tightly woven fabric	
Type B: Squared Parasol Shade	Suitable for cafes and restaurants	Suitable for cafes and restaurants		
	Suitable for larger zones as outdoor seatings and outdoor circulation	Suitable for larger zones as outdoor seatings and outdoor circulation		

Source(s): Authors

zone 1, the open space in zone 2 and the circulation space in zone 4. These elements provide ample coverage to ensure a comfortable environment for individuals utilizing these areas. Conversely, smaller shading elements were chosen for linear zone 5, which accommodates restaurants. This selection caters to the specific needs of the dining establishments, offering targeted shade to individual seating areas. By carefully matching the shading elements to each zone's purpose, the overall design optimizes functionality and enhances the overall experience. The implementation of a single shading element showcased a remarkable impact on the Universal Thermal Climate Index (UTCI) value, reducing it by a significant 5–8°.

5.2 Parameterize 3D model's elements

The input parameters for shading optimization, utilizing the Grasshopper program, can be divided into three categories. Firstly, the meteorological parameters are extracted from Energy Plus weather files (EPW). Secondly, the geometric model parameters encompass urban elements such as buildings, existing shading elements and surfaces. Lastly, the shading design variables and parameters directly influence the shading outcome.

5.3 Shade arrangement

The best spatial location of shading elements: Because infinite potential shading element's locations exist, the simplification of potential shading device location set is necessary, Linear, group and random are common arrangements from previous studies which were used to investigate shading variation in different arrangements.

(1) . *Distance between Shading elements (DS)*

To avoid shading elements intersection with buildings facades and emphasize the complete shading of the single shading without overlapping which generated by LUNCHBOX plugin Figure 28, the following common distances were studied:

(1) Seating Steps 1 and open space 9: shading elements (Type B) were strategically positioned at grid points with minimum grid size 5 meters, aligning shading elements centers with grid points to create efficiently shaded environment thus minimum DS were 5 m from center to center to avoid intersecting shading elements.

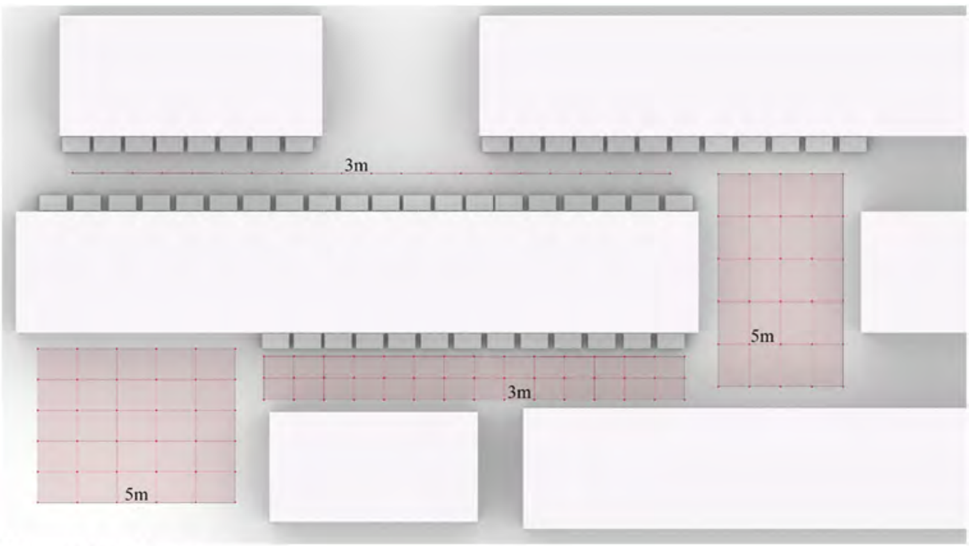


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Figure 28. Grid size parameterization for testing the optimization of shading element arrangement

(2) Linear Space 4: retractable shading elements were strategically employed to serve both the north and south parts. These retractable shades had a projection of 2.7 meters, effectively providing coverage and protection from the sun. Additionally, the center of the linear space was evenly divided into points, minimum spaces between them is 3-m intervals, to accommodate shading elements of Type B.

(3) Linear Space 5: shading elements (Type A) were positioned at grid points every 5 meters. Aligning their centers with precision to create an efficient shaded environment thus minimum DS were 5 m from center to center to avoid intersecting shading elements.

5.4 Optimization objective

The optimization process was done based on achieving one objective, minimum sun irradiation on ground. Owing to the infinite possible alternatives, each optimization process time was set to be 1 h. As mentioned, the most common arrangements were previously studied; Linear, Group and random. To assure that the optimization process would include all the common arrangement types, each arrangement optimization was governed by the following variables:

(1) Linear arrangement: distance between shading elements, maximum number of shading due to shading size.

(2) Cluster arrangement: distance between shading cluster and Shading element size and compared based on it.

(3) Random arrangement: shading element size.

5.5 Defining optimization algorithm

Optimization process objectives were to obtain minimum solar irradiation on ground in addition to enhance outdoor thermal comfort for adequate percentage of users on operation time. The process was applied as a generative design through two phases; First, minimize solar irradiation to support shading on ground utilizing the raytracing approach via Ladybug which is plug-in for Rhinoceros 3D software. It simulates and analyzes environmental performance fast and accurately. The second phase is defining optimization algorithm and alternatives modeling. The optimization algorithm chart in Galapagos as shown in Figure 29. Depends on defining two inputs.

(1) Genomes (studied variables): were shading parasols number, distance between them and arrangement. Shade types and sizes (constraints) were selected due to functions need and arrangements were varied manually as categorical variables.

(2) Fitness (optimization objective): was defined as a single-objective process to target minimum solar irradiance on ground.

6. Results

6.1 Linear arrangement

Figure 30 depicts the interface of the Galapagos solver in Grasshopper in linear arrangement, illustrating the rapid convergence of the Genetic Algorithms (GAs) towards near-optimal solutions starting from the second iteration. The average performance of the selected solutions steadily improved until generation 19, after which it consistently declined, deviating further from the optimal solutions. Subsequently, the average performance

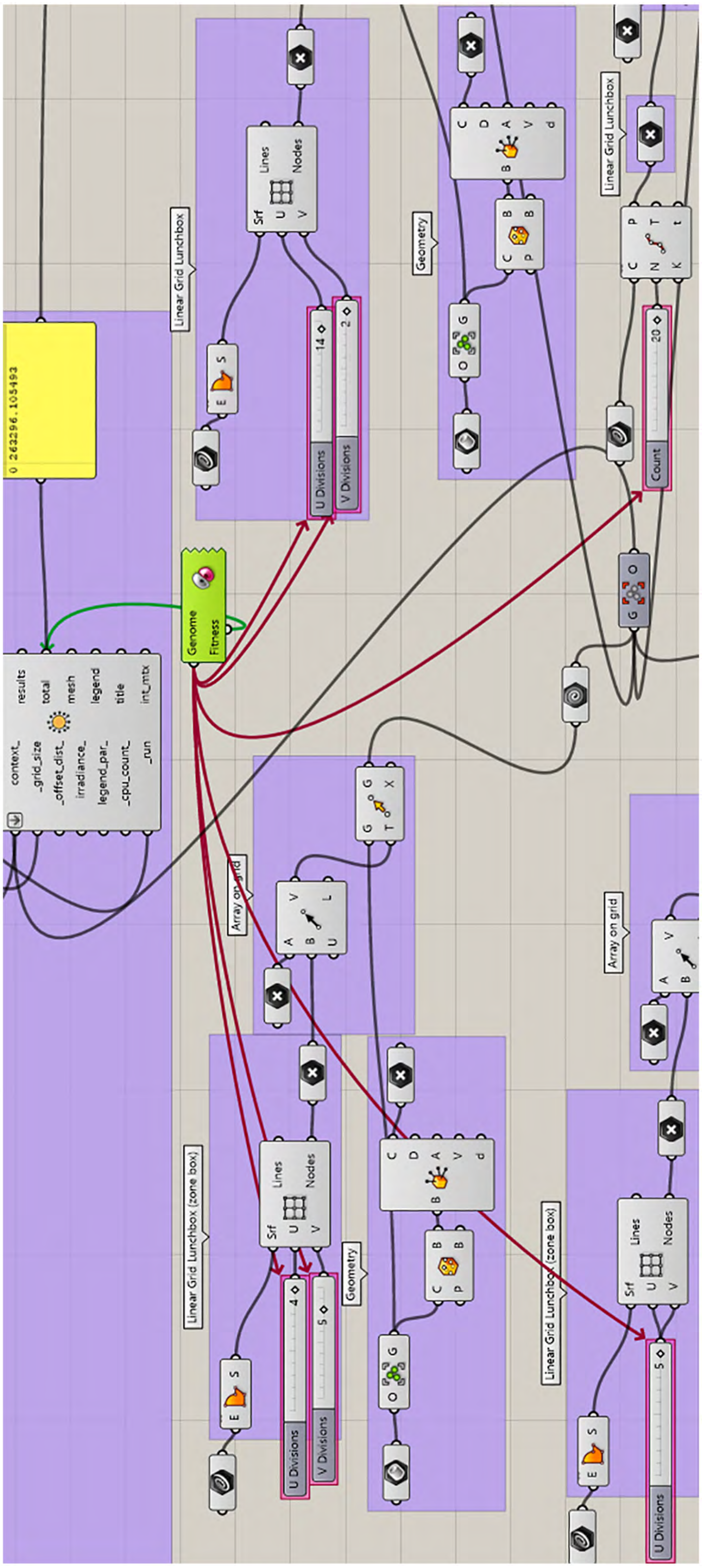

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Figure 29.
Fitness and genomes of different scenarios

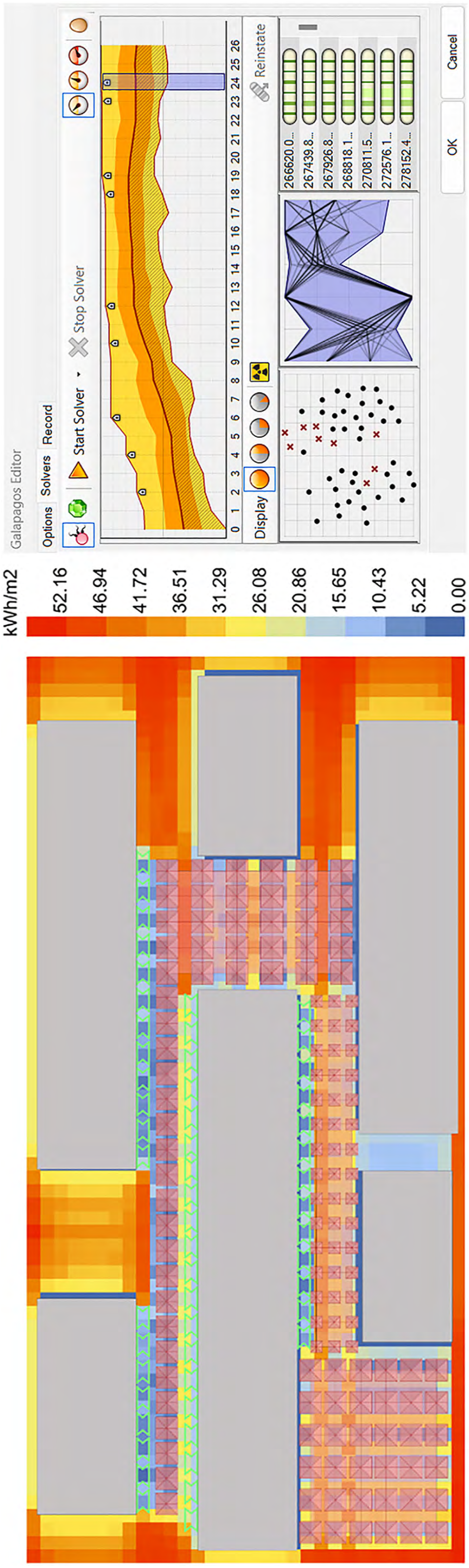

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Figure 30.
Left- optimized SIR simulation for linear arrangement kWh/m^2, right- Galapagos solver optimization process utilizes diverse individuals and generations to minimize solar irradiation in a linear arrangement

fluctuated without surpassing the solutions found in generation 19, although satisfactory solutions remained attainable. Figure 30 showcases the fitness of all solutions across the 26 generations in terms of minimizing solar irradiation, highlighting the lower solutions that fulfill the objective.

6.2 Cluster arrangement

The interface of GAs solver in Grasshopper (Galapagos) was represented in Figure 31. Showing the fast convergence of GAs in reaching near optimal solutions for cluster arrangement starting from iteration 6. Average performance of selected solutions continued to increase till generation number 16, then it decreased constantly away from optimal till generation 25. Afterwards, average performance fluctuates, but couldn't reach better solutions than what was found in generation 16. However, good solutions can still be found. The fitness of all solutions in the 16 generations regarding minimize solar irradiation and its simulation represented in Figure 31.

6.3 Random arrangement

Figure 32 presents a visual representation of the Galapagos solver interface within Grasshopper, where the elements are arranged randomly. This arrangement visually demonstrates the swift convergence of Genetic Algorithms (GAs) towards solutions that are close to optimal, beginning from the third iteration. The average performance of the chosen solutions exhibited a consistent improvement up to generation 21, where it reached a peak. From generation 21 to generation 28, the solutions obtained were remarkably close to those achieved in generation 21.

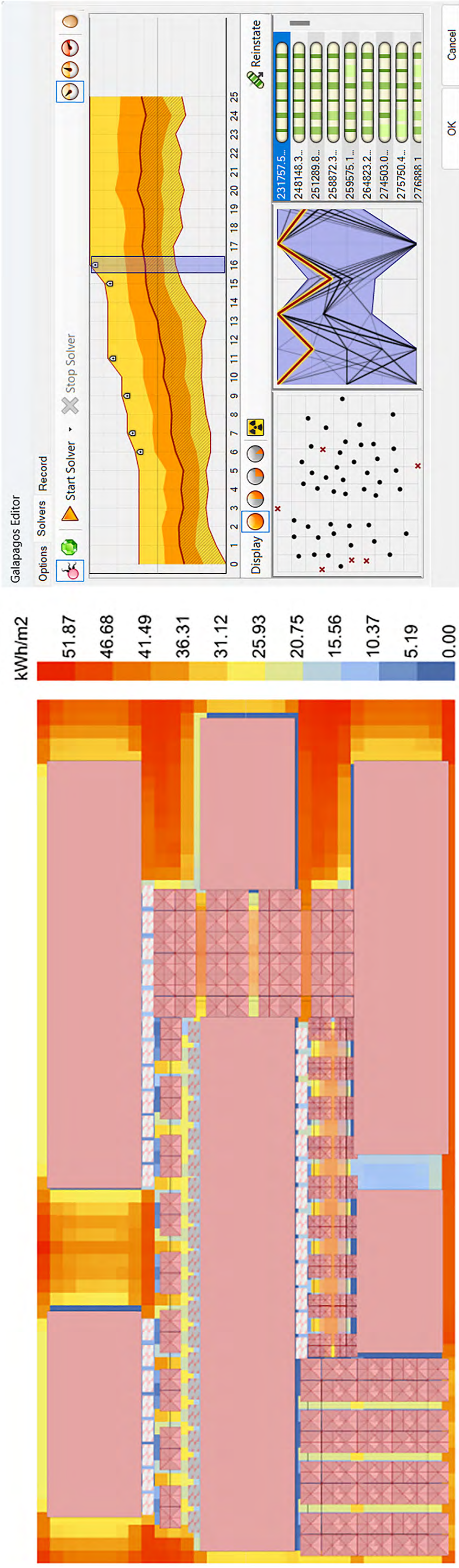
However, beyond generation 28, the solutions started to deviate further away from the optimal ones Figure 32 provides a graphical representation of the fitness levels of all solutions throughout the 28 generations, emphasizing the objective of minimizing solar irradiation.

6.4 Solar irradiation analysis

In every generation, a total of 5 solutions, which account for a mere 0.008% of all possible solutions, were generated. This implies that approximately 7% of the potential solutions were simulated after 25 generations. The ability of the Genetic Algorithms (GAs) to attain near-optimal solutions from the early generations demonstrates their robustness in finding good solutions with a satisfactory convergence rate. In similar scenarios, a smaller number of generations may be sufficient to achieve desirable solutions. The Galapagos solver effectively optimized the fitness value, measured as solar irradiation (SIR), for different arrangement strategies. The linear arrangement resulted in a SIR value of 267 KWh/m^2, while the cluster arrangement achieved a significantly lower value of 231 KWh/m^2. In contrast, the random arrangement yielded a higher SIR value of approximately 306 KWh/m^2. The comparative Figure 33 clearly illustrates that the cluster arrangement achieved the lowest SIR value, which is nearly half of the SIR value observed in the base case without any shading elements.

6.5 Conclusions and recommendations

In multiple instances within similar projects, it has been observed that shading devices are distributed in a random manner that may lead to both errors and successes. The objective of this research is to establish a methodology that exhibits a significant degree of predictability in achieving optimal distribution, maximizing user comfort in the process. Generative design systems have contributed in liberating the limits of design exploration, allowing designers to explore various design solutions. The utilization of shading elements based on multiple assessment tools in various design cases consistently resulted in lower solar irradiation (SIR)



Source(s): Authors

Figure 31.
Left- optimized SIR simulation for cluster arrangement KWh/m^2, right- Galapagos solver optimization process utilizes diverse individuals and generations to minimize solar irradiation in a cluster arrangement

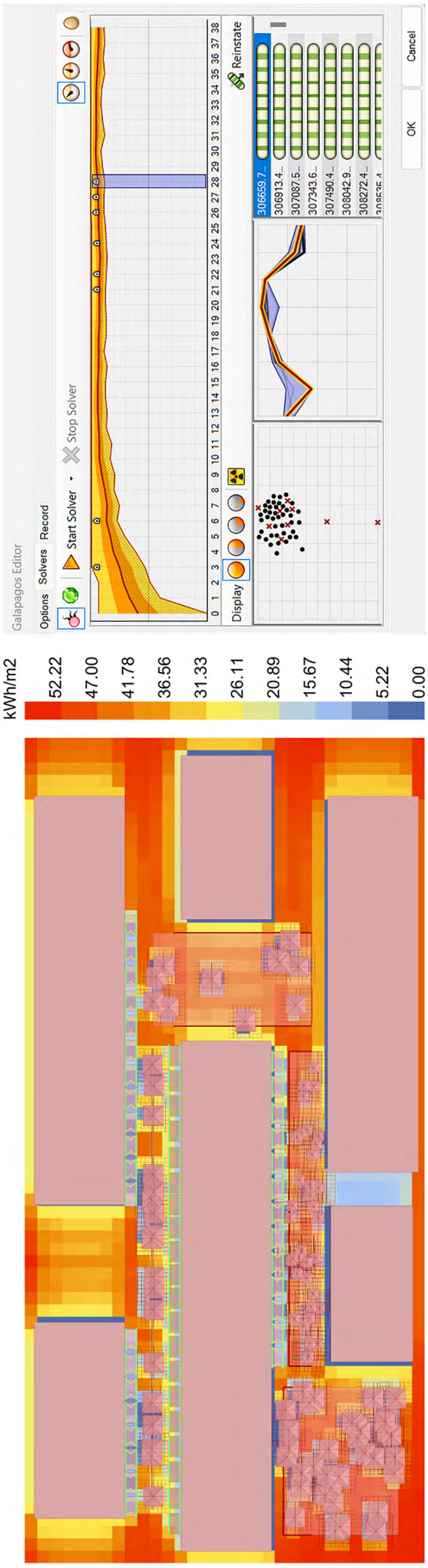


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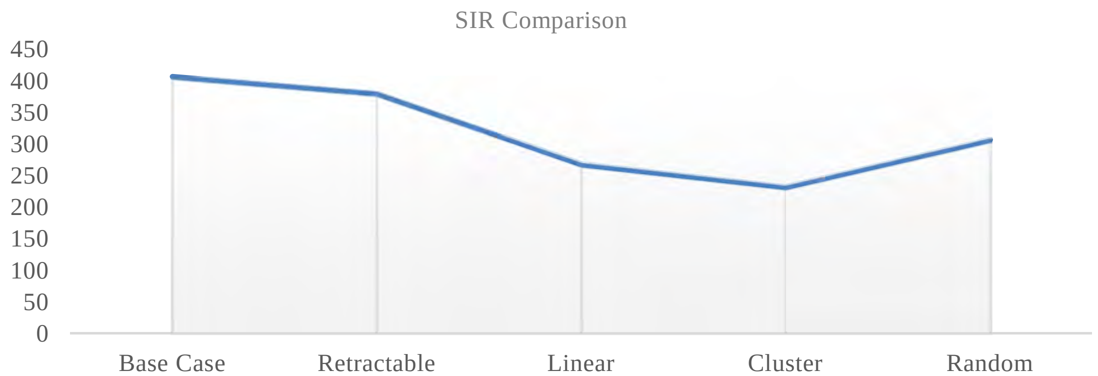
Figure 32.
Left – optimized SIR simulation for random arrangement (KWh/m^2), right - Galapagos solver optimization process

values compared to the base case. While generative design systems have transformed the way designers explore various design solutions, there is still limited research focused on dynamic shading elements in the built environment. This research gap presents an opportunity to delve deeper into the potential benefits and applications of dynamic shading systems, leading to advancements in sustainable and efficient architectural design. Dynamic and portable shading elements provide multiple advantages for outdoor thermal comfort. They offer adjustable shade levels, protect against direct sunlight, reduce heat gain and act as windbreaks against strong winds. Parametric design and computational optimization enhance shading design by generating diverse alternatives and allowing for efficient evaluation and comparison of different shading element types and placements. This evidence-based approach leads to informed decisions, optimizing the balance between aesthetics and functionality in shading design. The validation of Ladybug results in a hot arid climate, despite minor discrepancies, reinforces the use of Rhino, Grasshopper and Ladybug for simulating the outdoor microclimate. These software tools offer a robust framework for analyzing design parameters and optimizing outdoor environments. We suggest their continued application in similar climates to advance our understanding of outdoor thermal comfort and design strategies. It is crucial to recognize the significance of empirical validation alongside simulation results in our research endeavors. The incorporation of on-site measurements offers a valuable opportunity to authenticate the accuracy of our computational models with real-world data. This verification process not only enhances the credibility of our findings but also provides a more comprehensive understanding of the practical implications of our study. This case study has demonstrated the potential of generative design using the grasshopper method and genetic algorithms. Parametric design support decision making in early design stages, as it relies on computational techniques of programing, which facilitate integrating the design parameters and algorithms with optimization algorithms for an automated search to find the near optimum solution based on the design goals. By running hybrid simulations, a wide possible solution was generated, offering designers an expanded range of innovative options. However, it is essential to acknowledge that the findings and conclusions of the study may benefit from further clarification regarding the adaptability of this parametric approach to different locations and their respective climatic conditions. To enhance the research implications, future investigations could focus on exploring how this tested concept can be effectively applied and modified to suit other geographical areas and their unique environmental contexts. In order to efficiently design and allocate shade elements in open spaces to enhance outdoor thermal comfort, designers should adopt a comprehensive procedure that encompasses three essential assessment tools: social, environmental and geometrical factors. These tools collectively ensure the proper positioning and suitability of



Source(s): Authors

Figure 33.
Sir comparison KWh/m^2 between different scenarios and base case

shade elements, ultimately contributing to the achievement of optimum comfort for users. By considering the social preferences, environmental conditions, and geometric characteristics, designers can improve the quality and effectiveness of shade elements, leading to a more pleasant and comfortable outdoor experience for individuals.

7. Research limitation and further studies

While conducting this research, it is important to acknowledge certain limitations that may affect the generalizability and scope of the findings. One significant limitation lies in the use of the shade audit method as a tool to prioritize zones for shading. Although the shade audit approach offers practical benefits for designers compared to using questionnaires, it may have its own inherent biases or may not capture the full complexity of human preferences and needs. Given that our study primarily investigates outdoor thermal comfort in the specific context of the 5A Business Park located in the hot arid climate of Cairo, it is important to acknowledge the potential limitations in generalizing our findings to different geographic locations and climates. It is well-recognized that various regions may have unique requirements and climatic conditions that influence the effectiveness of shading solutions. While our research offers valuable insights tailored to the Cairo setting, we recognize the need for caution when applying our specific recommendations to other contexts. Future research endeavors should consider the adaptability and modification of our parametric design framework to accommodate the diverse requirements of varying geographic locations and climates, ensuring that shading solutions are appropriately tailored to the specific needs of each region. Future research endeavors can delve deeper into the environmental aspects associated with shading strategies. This may involve conducting life cycle assessments to evaluate the environmental impact of materials used in shading installations, considering energy consumption patterns and assessing the long-term sustainability of the proposed design solutions. Incorporating Arduino, an open-source electronics platform, offers opportunities to explore the design of adaptive shade elements. Arduino's programmable microcontrollers enable the creation of responsive and dynamic shading systems capable of adapting to changing environmental conditions. This integration into the shade design process could unlock the potential for real-time adjustments and optimizations, ultimately enhancing the shading system's overall performance and effectiveness.

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