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Optimizing Outdoor Thermal Comfort for Educational Buildings: Case Study in the City of Riyadh

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Abstract: In hot, arid climates, educational buildings often face the challenge of limited outdoor space usage. This research, through comprehensive simulation, aims to propose practical solutions to enhance outdoor thermal comfort, particularly during school break times and student dismissal periods, thereby fostering more comfortable and functional outdoor school environments. That will happen through achieving the main objective of the study, which is evaluating the suggested passive strategies. Riyadh was selected as the case study, and four representative schools were analyzed through simulation and optimization processes to identify key areas for improvement. The research leveraged simulation tools such as Ladybug and Grasshopper in Rhino, highlighting the practicality and impact of this approach. Simulations were performed to assess the existing outdoor thermal conditions using the universal thermal climate index (UTCI) and to pinpoint regions with elevated thermal discomfort. Passive design interventions, such as shading devices and vegetation, were explored and optimized using the Galapagos in Grasshopper. This methodology supports the originality of this research in its integration of simulation tools, such as Ladybug and Grasshopper, with optimization techniques using the Galapagos plugin, specifically applied to the unique site-specific context of educational outdoor environments in a hot, dry climate in Riyadh. Additionally, insights for urban planners and architects demonstrate the possibility of integrating passive design principles to improve the usability and sustainability of outdoor spaces. The findings indicated that fewer apertures in shade devices combined with greater tree canopies might double the effectivity in lowering UTCI values, thereby enhancing thermal comfort, especially during peak summer months.

Keywords: outdoor thermal comfort; educational building; simulation; optimization; shading; passive solutions; ladybug

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1. Introduction

Extreme temperatures present a challenge to the utilization of outdoor spaces, particularly in urban and educational settings. Urbanization has increased thermal discomfort, limited outdoor activities and affected sectors like education, where outdoor spaces are key to student well-being. Despite the known impacts of thermal discomfort, educational settings have received limited attention in this regard. Thermal comfort analysis is vital to identify strategies that enhance outdoor school environments, benefiting both student well-being and broader sustainability goals. This research addresses this issue by optimizing outdoor thermal comfort in schools through passive design and advanced simulation tools.

The desert environment of Riyadh, marked by elevated temperatures, poses considerable obstacles for several sectors, particularly education, during daytime hours and warmer seasons. The Köppen-Geiger climate classification designates arid regions according to their climatic traits, with Riyadh classified as BWh, a hot, arid, desert climate [1]. Outdoor activities in arid places are closely associated with climatic conditions and the adaptive methods used locally to manage climate fluctuation and change [2]. This study focuses primarily on educational facilities which operate mostly during the daytime when solar temperatures peak. Although children are shielded within interior temperatures, their exposure to the outdoors is restricted due to these climate conditions. The influence of outdoor environments on students transcends academic domains, affecting physical health and general well-being. Participating in open areas during school recess promotes students' physical fitness, enhancing their health and social interactions [3]. Moreover, integrating outside environments into education has been shown to improve students' cognitive functions, mental well-being, attention recovery, and overall educational experience [4]. Outdoor environments, including wilderness experiences and recreational activities, have had a beneficial effect on students' physical health and social responsibility [5].

Outdoor environments significantly influence children's physical, emotional, and cognitive growth, fostering cooperation and physical development [6]. Moreover, outdoor education has been shown to enhance knowledge retention and experiential learning, providing a more engaging and effective learning atmosphere [7]. Additionally, a comfortable outdoor environment enhances the overall school experience, making schools more attractive to students, parents, and teachers [8]. Furthermore, thermal comfort in outdoor spaces is not only a physical response but also significantly influenced by psychological factors. Research, including the work of Turhan and Özbey [9], has shown that factors such as mood, expectation, and perception of the environment can alter an individual's thermal sensation. For instance, a positive mood or association with an outdoor setting can lead individuals to perceive higher temperatures as more tolerable, while a negative mood or stressful environment can amplify discomfort.

Additionally, in the context of outdoor educational spaces, students and staff may experience varied thermal perceptions based on these psychological factors. Familiarity with the environment, visual appeal, and even social interactions within outdoor spaces can contribute to an increased tolerance for heat [10]. Conversely, exposure to direct sunlight in an unattractive or exposed area might heighten discomfort, regardless of the actual UTCI values [11]. Moreover, these psychological influences suggest that while optimizing physical aspects like shading and vegetation, design strategies should also consider elements that enhance positive environmental perception, such as aesthetic landscaping, comfortable seating, and interactive spaces. By fostering a pleasant atmosphere, it is possible to mitigate perceived thermal discomfort, making outdoor areas feel more comfortable even when temperatures remain high. This integrative approach aligns with findings that psychological factors can meaningfully impact thermal comfort outcomes [12], highlighting the importance of a holistic approach that considers both physical and psychological dimensions of comfort in outdoor educational settings.

From a sustainability perspective, addressing outdoor thermal comfort allows schools to serve as models for sustainable design and urban planning. Incorporating green spaces, shade structures, and heat-mitigating materials can reduce environmental impact. Furthermore, improving school outdoor spaces benefits the wider community by offering comfortable areas for community events and activities outside school hours. This holistic approach not only supports the health and education of students but also promotes broader environmental and social benefits [13].

Furthermore, the interplay of environmental factors such as temperature, humidity, and wind speed significantly affect thermal comfort levels. Research indicates that the design of urban spaces, including the geometry of buildings and the arrangement of outdoor areas, can exacerbate or alleviate heat exposure and enhance microclimatic conditions [14,15]. Moreover, López-Cabeza et al. [16] emphasize the importance of thermal inertia and natural ventilation in enhancing user comfort in courtyards, suggesting that thoughtful architectural design can significantly improve outdoor thermal conditions. As urbanization continues to expand, it becomes essential to promote outdoor comfort and reduce the urban heat island effect [17].

The key contribution of this research lies in its provision of practical solutions for school design, comprehensive guidelines for policy and implementation, and its role as an educational tool. By employing thoughtful simulations, the research analyzes various design interventions and offers evidence-based solutions to enhance outdoor thermal comfort in schools. It explores innovative strategies—such as optimized shading, green areas, and the use of reflective materials—tailored to the specific climatic conditions of the region. The findings can inform policymakers and educational authorities about effective measures to improve school environments, potentially leading to changes in building codes and construction standards. Furthermore, the research provides a step-by-step implementation framework for schools and communities to follow, ensuring that the proposed improvements can be effectively realized. Additionally, the study raises awareness among architects, urban planners, and educators about the importance of outdoor thermal comfort and its impact on students. It serves as an educational resource, demonstrating the application of simulations in solving real-world problems, and enhancing the knowledge and skills of professionals and students in architecture and urban planning.

2. Literature Review

2.1. Simulation

Outdoor thermal comfort is a critical factor in architecture and urban design, particularly in regions with extreme climates such as hot and arid environments. Researchers have utilized simulation to evaluate outdoor thermal comfort, and several studies have been conducted to assess and enhance thermal conditions in outdoor spaces. He and Hoyano [18], for example, utilized a coupled numerical simulation method involving computational fluid dynamics (CFD) and outdoor thermal simulation to evaluate microclimate and thermal comfort in outdoor living spaces. Abdallah and Mahmoud [19] proposed a coupled-simulation methodology to study the impact of outdoor and building passive strategies on outdoor thermal comfort in new desert Egyptian cities. Moreover, Musa et al. [20] concentrated on enhancing outdoor thermal comfort by simulating a specific urban region during the hottest summer day. They reported that environmental simulations in the holy city of Karbala during the hottest summer day showed that optimized vegetation could lower the universal thermal climate index (UTCI) by 4.2 °C compared to unoptimized urban areas. Finally, Binabid and Anteet [21] used simulation to test variations of passive solution scenarios to improve outdoor thermal comfort using Envi-met 5.5 software testing variation of strategies to improve outdoor thermal comfort.

Tools like Ladybug in Grasshopper conduct detailed simulations for assessing outdoor thermal comfort for pedestrians in outdoor settings. Khraiwesh [22] demonstrated the use of Ladybug and Honeybee plugins in Grasshopper to measure outdoor thermal comfort in urban street canyons, incorporating metrics like the universal thermal climate index (UTCI) based on the solar reflective index (SRI). Khraiwesh's study also emphasized the relationship between urban microclimate, building energy use, and outdoor thermal comfort, highlighting the importance of considering these factors in optimizing outdoor urban spaces. The use of the Ladybug plugin in Grasshopper has been significant in analyzing the effects of outdoor and urban planning techniques on enhancing outdoor settings. Xu et al. [23] used Ladybug within Rhino software to examine outdoor and urban block design in hot and arid climates, demonstrating substantial reductions in the UTCI during hot summer and cold winter days. Their study highlights the impact of urban shape on outdoor comfort, emphasizing the need to include thermal comfort in urban design.

The universal thermal climate index (UTCI) has emerged as a crucial parameter for assessing outdoor thermal comfort in several research studies. Karakounos et al. [24] emphasized the significance of the UTCI, established by the International Society of Biometeorology, in evaluating urban microclimate and outdoor thermal comfort. Similarly, Jiang et al. [25] used the UTCI as a thermal comfort index to evaluate the thermal environment, verifying its ability to accurately reflect individuals' physiological responses to environmental temperatures.

2.2. Optimization

Optimization for a single objective using Galapagos involves leveraging the capabilities of this algorithm component within Grasshopper software, as highlighted by Wang et al. [26]. Galapagos is specifically designed for single-objective optimization tasks, making it a valuable tool for refining solutions toward a specific goal. The integration of complex geometry calculations and optimization functions benefits from the algorithm's ability to iteratively improve designs [27]. This iterative process allows for the exploration of various design parameters to achieve the desired outcome efficiently. In the field of photovoltaic power forecasting and electric distribution network reconfiguration, the application of Galapagos with advanced optimization techniques enhances the accuracy and efficiency of predictive models and network management strategies. By utilizing Bayesian optimization and algorithms, researchers can improve the forecasting accuracy of renewable energy sources and optimize the operation of distribution networks. The adaptive nature of algorithms enables the dynamic adjustment of system parameters to achieve optimal performance under varying conditions [28].

The use of Galapagos in architectural design and computational form-finding tools demonstrates its effectiveness in achieving optimal solutions for building performance and energy efficiency. Yi et al. [29] and Chen et al. [30] employ hybrid metaheuristic algorithms and integrate evolutionary strategies into design processes; researchers can generate responsive building facades and innovative structural solutions. The iterative nature of the algorithms allows the examination of alternatives to design and the recognition of optimal configurations based on multiple objectives. Furthermore, the use of Galapagos in daylight design and dynamic shading systems demonstrates its adaptability in tackling various optimization issues, as shown by the research of González and Fiorito [31]. Researchers may optimize exterior solar shadings or dynamic geometries to improve building efficiency and occupant comfort by integrating simulation tools with optimization methodologies. The iterative characteristics of algorithms enable the enhancement of design parameters according to performance metrics, resulting in optimum solutions [32]. Moreover, the use of Galapagos, an algorithmic element, in optimization tasks for singular objectives provides a systematic and effective means of enhancing designs, addressing intricate issues, and attaining optimum solutions across diverse fields. Integrating Galapagos with simulation tools, heuristic algorithms, and sophisticated optimization approaches enables researchers to investigate solution space, refine design parameters, and determine the most appropriate configurations according to particular goals. The iterative characteristics of genetic algorithms facilitate the ongoing enhancement of solutions, rendering them exceptionally effective for a myriad of optimization challenges.

2.3. Passive Solutions

Transitional spaces have been studied extensively for their ability to create comfortable outdoor conditions through a combination of shading, vegetation, and natural ventilation. For example, Sun et al. [33] conducted a numerical investigation on the use of vegetation and high-albedo materials in urban courtyards in hot, arid regions, finding that increased vegetation cover significantly improved thermal comfort. Similarly, Mirrahimi et al. [34] explored the effectiveness of integrating water features and vegetation in transitional courtyard spaces to mitigate extreme heat, showing a notable improvement in perceived comfort. Another study by Diz-Mellado et al. [35], examined courtyard microclimates and demonstrated how the strategic use of passive systems can lead to a substantial reduction in mean radiant temperatures reaching 11.7 °C below reference points.

Moreover, several research studies have been conducted in various cities worldwide to investigate nature-based solutions (NBS) such as vegetation as passive solutions to reduce outdoor thermal comfort in hot, arid climates. One such study by Zheng et al. [36] focused on high-density neighborhoods in Shenzhen, highlighting the positive cooling effects of vegetation and shade trees in tropical and subtropical climates. The addition of green roofs and facades was also found to significantly impact cooling. Ali et al. [37]

studied the role of green infrastructure in Abu Dhabi, showcasing how local NBS, like trees and landscaping, can enhance microclimate conditions in desert areas. Additionally. El Deeb et al. [38] explored the use of green design strategies with trees, applying the predicted mean vote (PMV) as a measurement tool to achieve thermal comfort in hot, arid regions. They highlighted the challenges of controlling microclimates in such climates and the importance of green design strategies in achieving thermal comfort. Studies in cities like Seville, Spain, by Ramos et al. [39], and Aswan, Egypt, by Ayoub and Elseragy [40] have assessed thermal resilience and traditional domed-roofs insolation, respectively, to optimize outdoor thermal comfort in hot arid climates. Sun et al. [33] demonstrated that increasing vegetation coverage by 30% in courtyard spaces led to a decrease in ambient temperatures by an average of 3.8 °C. The effectiveness was especially pronounced during the hottest hours of the day. Similarly, Gomaa [41] highlighted the significant role of vegetation in enhancing thermal comfort in low-density residential areas of hot, arid regions. These studies underscore the importance of vegetation in mitigating thermal discomfort in urban environments exposed to hot, arid conditions. Other research by Mahmoud and Ghanem [42] focused on formulating guidelines for urban heat island mitigation strategies in Egyptian new, hot, arid cities, exploring the impact of urban geometry on outdoor thermal performance. Their work provides valuable insights into improving the thermal performance of outdoor spaces through urban design interventions. Additionally, Sadeghi and Bahadori's [43] study in Shiraz, Iran, demonstrated that trees with larger crown widths can enhance thermal comfort in hot, semi-arid climates by providing shade.

Weerakoon and Perera [44] investigated the effects of vegetation cover on outdoor thermal comfort around high-rise developments in Colombo, Sri Lanka, highlighting the viability of increasing urban vegetation to reduce urban heat stress. In studying the impact of urban design elements on microclimate in Al Ain City, UAE, Hamdan and de Oliveira [45] confirmed the critical role of microclimate improvement in enhancing human comfort and reducing indoor air conditioning demand in hot, arid climates. Sedira and Mazouz [14] delved into the influence of urban geometry on outdoor thermal comfort in hot and arid climates, focusing on the application of the UTCI index. Their research sheds light on the relationship between urban form and thermal comfort in outdoor spaces, providing valuable insights for urban planners and designers. Mutani et al. [46] evaluated the impact of urban morphology and green surfaces on outdoor thermal comfort, noting the importance of green spaces in enhancing thermal conditions. These studies underscore the multifaceted role of urban design elements and vegetation in improving outdoor thermal comfort in hot, arid climates.

Gaxiola et al. [47] explored the architectural implementation of vegetated cover for restoring human thermal comfort and mitigating the urban heat island effect in arid regions, focusing on integrating vegetated surfaces into building envelopes. Their findings demonstrate the potential of incorporating vegetation from urban agriculture systems to enhance outdoor thermal comfort in arid regions. Mirrahimi et al. [34], found that the integration of water features along with vegetation in courtyards reduced mean radiant temperature (MRT) by 5.2 °C, providing significant thermal comfort during peak summer hours. These studies collectively emphasize the significance of urban design and vegetation in creating comfortable outdoor environments in hot, arid regions.

In addition to vegetation, shading plays a crucial role in reducing outdoor thermal discomfort in hot, arid climates. Darbani and Parapari [48] discussed the use of indigenous materials and shading in pedestrian walkways to decrease sunlight absorption and improve outdoor thermal comfort. Athmani and Sriti [49] conducted an experimental study on the impact of passive cooling techniques, such as the 'cool roof' technique, on the thermal behavior of residential buildings in hot and arid regions. Their results confirmed the effectiveness of passive cooling techniques in achieving comfort conditions in such climates by reducing heat gains through the roof. Djekic et al. [50], exploring the influence of pavement materials on pedestrian thermal comfort during summer, determined the importance of appropriate materials in enhancing comfort and reducing energy consumption.

A hybrid approach combining vegetation and materials has shown promise in enhancing outdoor thermal comfort as Bande et al. [51] studied outdoor thermal comfort on a district level in Abu Dhabi and Al Ain, UAE, demonstrating the effectiveness of shading structures combined with local vegetation for enhancing microclimate conditions. Investigating the effect of shading patterns and greenery strategies on outdoor thermal comfort, Ridha et al. [52] confirmed the influence of pedestrian perception and satisfaction in hot and arid climates. Finally, indices such as the UTCI have been employed to evaluate outdoor thermal comfort conditions in various climatic regions, as highlighted by Huang et al. [53] and Zafarmandi et al. [54]. These tools provide valuable insights for urban planners and designers to optimize outdoor thermal comfort and create healthier living environments in urban areas.

Overall, the research gap in studying vegetation and shading as solutions to enhance outdoor thermal comfort in hot to arid climates is significant. While existing literature emphasizes the importance of these elements, many studies focus on general strategies without site-specific simulations that account for local microclimatic conditions. For instance, Liu highlights the need for standardized thermal comfort evaluation models tailored to specific climates and cultural contexts [55]. Moreover, while several studies advocate for vegetation and shading as effective mitigation strategies, there is a lack of comprehensive optimization frameworks that integrate these elements into urban design [56]. The necessity for site-specific simulations is underscored by findings from Sayad et al. and Weerakoon and Perera, which demonstrate that varying vegetation configurations can significantly influence thermal comfort outcomes [44,57]. Thus, advancing research in this area requires a focused approach to localized simulations and optimization techniques to effectively bridge the existing gaps.

Finally, the main objective of this research is to develop and propose practical, data-driven solutions to enhance outdoor thermal comfort in educational settings located in hot, arid climates, with a specific focus on Riyadh. The study aims to identify effective passive design strategies that can optimize the usability of outdoor spaces in schools, ultimately improving the well-being and learning environment for students. Furthermore, to achieve this objective, the research utilizes comprehensive simulations to assess outdoor thermal conditions across five representative schools in Riyadh. The study then optimizes passive design interventions, including shading devices and vegetation, to enhance outdoor thermal comfort during critical times, such as school breaks and dismissal periods.

Unlike previous studies that often focus on isolated design interventions, this work utilizes an iterative and optimization process to refine combinations of shading and vegetation tailored to the extreme climatic conditions of Riyadh. By employing advanced simulation tools such as Ladybug and Galapagos within Rhino's parametric environment, this study not only enhances existing knowledge on passive cooling strategies but also provides a scalable framework for architects and urban planners in similar climates. The results demonstrate how integrating passive strategies and computational tools can lead to significant improvements in thermal comfort, offering valuable insights for urban planners and architects working in similar hot, arid environments.

3. Methodology

This study applies a multi-step computational workflow (as shown in Figure 1) to assess and optimize the outdoor thermal comfort of school outdoor spaces using the universal thermal climate index (UTCI). Moreover, Rhino 3D was chosen for this study due to its powerful parametric design capabilities and seamless integration with environmental analysis tools like Ladybug and optimization tools such as Galapagos. Its versatility makes it ideal for analyzing and optimizing outdoor thermal comfort in architecture. Rhino has been effectively used in similar studies, such as by Xu et al. [23] for urban block design in hot climates and by Khraiwesh [22] for optimizing thermal comfort in urban street canyons, demonstrating its adaptability for environmental research. Overall, the methodology involves multiple steps: first, creating geometric models of school buildings and their surroundings; next, conducting a thermal comfort analysis; then, applying evolutionary computing for optimization; and finally, comparing the optimized results against the baseline to assess improvement.

Figure 1. Computational workflow.

Stage 1: Geometrical Modelling: The first step focuses on the accurate geometrical modeling of school environments, including the buildings, open spaces, and areas where outdoor activities take place. Rhinoceros (Rhino) 3D is employed for this purpose alongside Grasshopper, a parametric design tool integrated with Rhino. These tools facilitate the creation of precise, adaptable models of case studies critical for the subsequent thermal analysis and optimization processes. The geometric model serves as the foundation for the outdoor thermal comfort evaluation by providing a spatially accurate representation of the school environment.

Stage 2: Baseline Thermal Comfort Analysis: In the second step, the study conducts a baseline assessment of outdoor thermal comfort using the UTCI. The simulation uses weather data spanning the entire year from January to December, and it is carried out using environmental analysis tools such as Ladybug, both of which are integrated with Grasshopper. These plugins simulate the UTCI by factoring in variables like air temperature, wind speed, humidity, and solar radiation. Moreover, the simulations were conducted over a full calendar year, starting from 1 January and concluding on 31 December. This annual timeframe allowed for a comprehensive analysis of thermal comfort across different seasons. Simulations were run on an hourly basis to capture diurnal variations, particularly during the critical hours from 9:00 a.m. to 1:00 p.m., which align with the highest outdoor activity levels in school settings. Finally, the resulting UTCI maps reveal areas within the school environments that experience the highest levels of thermal discomfort. These baseline results are crucial for identifying zones that need to be addressed through design interventions.

Stage 3: Optimization of Design Solutions: To improve outdoor thermal comfort, the third step applies evolutionary computing techniques to optimize the placement and design of shading devices and vegetation. Using the Galapagos plugin for Grasshopper, the study explores various configurations of shading and tree placement through an algorithm. This process iteratively refines the size and position of shading devices, as well as the width of each tree canopy. The optimization aims to reduce UTCI values in the areas experiencing the greatest thermal discomfort, enhancing overall outdoor comfort. Galapagos uses fitness criteria to guide the optimization, focusing on minimizing UTCI values while maximizing the effectiveness of the proposed shading and vegetation configurations.

Stage 4: Evaluation of Optimized Interventions: Once the optimal shading and tree layouts are determined, the study performs a second UTCI analysis to evaluate the effectiveness of the interventions. The enhanced UTCI simulation, carried out again using Ladybug, examines how the optimized shading and vegetation impact on thermal comfort conditions throughout the year. The results, visualized in enhanced UTCI maps, allow for a direct comparison with the baseline scenario, showing the improvement in thermal comfort across the outdoor spaces of the school buildings. This analysis generates a clear visualization of the reduction in thermal discomfort achieved by the proposed strategies.

Stage 5: Comparison: In the final stage, the study compares the baseline UTCI analysis with the enhanced results, focusing on key metrics such as the change in UTCI values and the spatial distribution of comfortable zones. The optimal solution is selected based on its ability to provide the most significant reduction in thermal discomfort while maintaining a balance between the number of shading devices and trees used. By comparing the baseline and optimized scenarios, the study quantifies the improvement in outdoor thermal comfort, demonstrating the effectiveness of the proposed interventions in enhancing the thermal environment of school spaces throughout the year.

3.1. Validation

The climatical data used in this study was previously validated for Case A by Binabid and Anteet [21], wherein the effects of vegetation on outdoor thermal comfort were demonstrated through onsite measurements. Measurements were conducted using a Wintact digital monitor, model WT83, mounted on a tripod. This monitor is capable of measuring temperatures ranging from −20 °C to 70 °C and relative humidity levels ranging from 0%

to 100%, with a resolution of 0.1% and an accuracy level of ±0.5, ±2%. The validation showed a high correlation between actual data and simulation results, with a Coefficient of Determination (R^2) recorded at 0.97 for Ta and 0.94 for RH. This indicates that the simulation closely replicated real-world conditions, confirming the reliability and accuracy of the model. Furthermore, this confirmed the validation, and so on proceeded with cases B, C, and D.

3.2. Case Study and Simulation Settings

This section outlines the simulation settings and parameters employed to calculate the universal thermal climate index (UTCI) that is selected for its comprehensive approach to evaluating outdoor thermal comfort, particularly in complex urban environments. The UTCI is recognized for its ability to integrate multiple environmental parameters, including air temperature, wind speed, humidity, and mean radiant temperature, providing a more holistic assessment of thermal stress. Then, the analysis used Ladybug tools in Grasshopper, incorporating meteorological data for Riyadh that is classified within the Köppen-Geiger climate classification as BWh, an arid desert climate, and also, human parameters, geometric parameters, and context-specific environmental elements. The simulation seeks to assess thermal comfort across varying tree canopy diameters and shading coverage percentages, with the objective of enhancing outdoor thermal conditions for children during school hours. A weather file (EPW) for Riyadh was imported into Ladybug to precisely recreate the external heat environment. This EPW file included the hourly meteorological data, encompassing air temperature, relative humidity, wind speed, and solar radiation. These inputs were crucial for computing the mean radiant temperature (MRT) and, subsequently, the UTCI. The research space, an outdoor playground, was modelled in Rhino, with grid points generated in Grasshopper to evaluate outdoor thermal comfort at different locations. Each grid point corresponded to the position of a human subject, positioned at an average height of 128.5 cm to simulate a standing child [58,59]. Components including building shading, and trees were included as context geometry to replicate the effects of shade and sky exposure on the playground. The correlation between human geometry and the surrounding environment was evaluated via the Ladybug human-to-sky relationship component, replicating human location and calculating the proportion of the body exposed to direct sunlight as well as the exposure to the sky.

The mean radiant temperature (MRT) is an essential factor of thermal comfort, calculated using both shortwave solar radiation and longwave radiation shown in Equation (1), as per the Stefan-Boltzmann Law and SolarCal's method for incorporating the delta from solar radiation. The Ladybug Outdoor Solar MRT component evaluates factors like solar radiation, surface temperature, and sky exposure to determine the mean radiant temperature (MRT) encountered by a human in an outdoor environment. The SolarCal model, described in ASHRAE Standard 55, was utilized to calculate the MRT delta in Equation (2), considering the human body's position and solar exposure [60,61]. The following formula was employed to calculate MRT:

$$MRT_{solar} = MRT_{base} + \Delta\, MRT_{solar} \tag{1}$$

where:

- MRT_{solar} = adjusted mean radiant temperature accounting for both longwave and solar radiation (°C);
- MRT_{base} = mean radiant temperature from longwave radiation exchanges (sky and surrounding surfaces; and
- $\Delta\, MRT_{solar}$ = solar MRT delta, which accounts for the increase in MRT due to shortwave solar radiation absorbed by the human body.

The SolarCal model calculates ΔMRT_{solar} as:

$$\Delta MRT_{solar} = \frac{(SHARP \cdot A_{sol} \cdot DNI + DHI \cdot f_{exp}}{\varepsilon \cdot \sigma \cdot F} \tag{2}$$

where:

- $SHARP$ = solar horizontal angle relative to person, which defines the angle between the person's orientation and the sun (=135° for human back/side facing the sun);
- A_{sol} = absorptivity of the body for shortwave solar radiation (=0.7, can vary depending on skin tone and clothing);
- DNI = direct normal irradiance (W/m^2);
- DHI = diffuse horizontal irradiance (W/m^2);
- f_{exp} = fraction of the body exposed to direct sunlight;
- E = emissivity of the body (typically 0.95);
- σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4); and
- F = view factor from the person to the sky or other surrounding surfaces.

The SolarCal model effectively integrates these variables to assess the increase in perceived temperature (MRT) resulting from sun exposure. The MRT delta (ΔMRT_{solar}) is incorporated into the base MRT (longwave radiation from the surrounding environment) to provide a more accurate representation of the thermal environment, including the influence of solar radiation on the human body. The UTCI was calculated utilizing Ladybug's UTCI comfort component, which integrates air temperature, mean radiant temperature, wind speed, and relative humidity to evaluate thermal stress. The UTCI equation is based on the Fiala model, shown in Equation (3), which models heat exchange between the human body and its surroundings [62]. The equation employed in the Ladybug component is based on a sophisticated regression model rather than a single formula. This is why Ladybug utilizes precompiled algorithms to calculate the UTCI based on user-provided inputs. The equation for UTCI employed in this investigation is as follows:

$$UTCI = T_{air} + a\ regression\ function\ (T_{air},\ MRT,\ v,\ RH) \tag{3}$$

where:

- T_{air} = air temperature (°C);
- MRT = mean radiant temperature (°C), which accounts for solar radiation and radiant heat exchange from surrounding surfaces;
- v = wind speed (m/s), which affects convective heat loss; and
- RH = relative humidity (%), which impacts evaporative cooling.

Finally, the fixed and dynamic inputs for the simulation were categorized into building geometry, playground study area, hours, days, and varying environmental parameters such as tree canopy diameters and shading coverage (Table 1). The outdoor space area was modeled as specified in Figure 2 to reflect a typical school environment in Riyadh. The study period was set from 9:00 a.m. to 1:00 p.m., with daily data over a month. The simulation assessed outdoor thermal comfort by varying tree canopy diameters (2, 3, 4, and 5 m) and shading coverage percentages (20%, 30%, and 40%) across the months of January to December. With these dynamic inputs, a total of 576 iterations were conducted across different months and scenarios to assess thermal comfort under various conditions. Each iteration represented a unique combination of tree canopy size and shading percentage to optimize outdoor thermal comfort.

Table 1. Fixed and dynamic inputs used in the simulation.

Fixed Inputs	Assigned Values
School geometry (width, length, height)	Fixed per school site, specified in Figure 2
Surrounding context (width, length, height)	Fixed per location, specified in section Figure 2
Playground study area (width, length)	Fixed area dimensions, specified in Figure 2
Hours	9 a.m. to 1 p.m.
Days	1st to 31st
Tree height	3, 4, 5 m
Shading height	Small, medium, large

Table 1. *Cont.*

Dynamic Inputs	Assigned Values
Months	January to December
Tree canopy diameter	2, 3, 4, 5 m
Shading coverage	20%, 30%, 40%

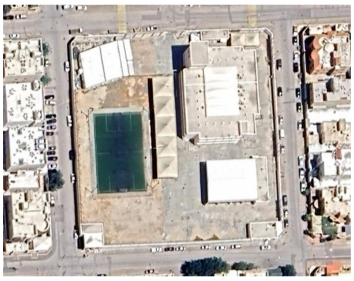
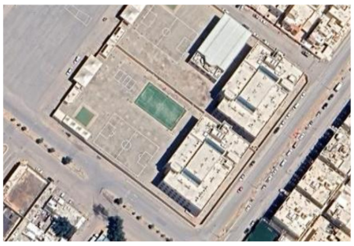
Case Study	Total area of school	Total study area	Percentage of study area to total area of school	Study area dimension
Case Study A	100 m × 60 m 6000 m²	1280 m²	21.3%	32 m × 40 m
Primary school for girls, located in the northern part of Riyadh in the Alyasmin district				N
Case Study B	90 m × 50 m 4500 m²	960 m²	21.3%	24 m × 40 m
Primary school for girls, located in the eastern part of Riyadh in the An Nahdah district				N
Case Study C	100 m × 100 m 10000 m²	2176 m²	24.7%	32 m × 64 m
Primary school for boys, located in the central part of Riyadh in the Al Malaz district				N
Case Study D	120 m × 60 m 7200 m²	1536 m²	21.3%	32 m × 48 m
Primary school for boys, located in the southern part of Riyadh, in the Badr district				N

Figure 2. All case studies and corresponding details.

4. Results

The results of the study are organized to provide a comprehensive understanding of the impact of passive design interventions on outdoor thermal comfort in outdoor educational settings. It begins with an analysis of the temperature reduction achieved through shading devices, followed by the effects of vegetation on reducing thermal discomfort. Subsequently, the combined impact of these interventions is discussed, highlighting seasonal variations and the effectiveness of different strategies during peak summer and cooler months. This structured presentation aims to clearly convey how each intervention contributes to improving outdoor thermal comfort in hot, arid climates.

4.1. Base Model

In this study, four base model cases (A, B, C, and D) representing typical elementary school designs in Riyadh were examined to evaluate outdoor thermal comfort and explore potential improvements through passive design strategies. The base models represent current conditions without intervention, serving as benchmarks for comparison after implementing proposed strategies such as varying tree canopy diameters and shading coverage. The selection of school playgrounds as the focus of the study stems from the importance of outdoor spaces for children's physical activity, socialization, and learning [63].

The simulation of these base model cases fulfills two primary objectives. Initially, it seeks to determine the months with the most thermal stress. This is essential for identifying the intervals during which passive cooling techniques would be most effective. The simulations seek to quantify the improvements in thermal comfort attainable via interventions, facilitating an evidence-based methodology for school design in hot areas. This research aims to provide insight into the efficacy of passive design solutions for enhancing outdoor thermal comfort by modeling and comparing various scenarios, thereby aiding in the creation of more robust and sustainable school settings in Riyadh's harsh climate. This prolongs the duration students may safely and pleasantly engage in outdoor activities. The simulation results of the basic model scenarios for primary schools in Riyadh demonstrate a uniform trend of external thermal stress across all four examined instances (A, B, C, and D). In Case A, Figure 3 indicates that the UTCI reaches a maximum of 43.30 °C during the peak months of July and August. The elevated thermal discomfort progressively decreases to 26.05 °C in November and 22.45 °C in December, indicating the seasonal shift from summer to autumn. Similarly, Case B (Figure 4) demonstrates that the most significant time for thermal stress transpires from May to October, characterized by persistently high UTCI values due to the city's severe summer temperatures.

In Case C, Figure 5 illustrates a similar pattern, with UTCI levels exhibiting the same seasonal peaks and troughs as found in Cases A and B. The findings from example Case D in Figure 6 corroborate these trends, indicating that July and August are the months with the highest thermal stress, while January and February exhibit the lowest UTCI values of 17.86 °C and 21.19 °C, respectively. Across all cases, the months from May to October emerge as the most critical for outdoor thermal comfort (Figure 7), emphasizing the need for targeted passive design interventions during this period to mitigate extreme heat. The consistency of these results reinforces the necessity of addressing summer thermal conditions through design strategies—such as increasing shading and optimizing green cover—to improve the outdoor thermal comfort in school environments.

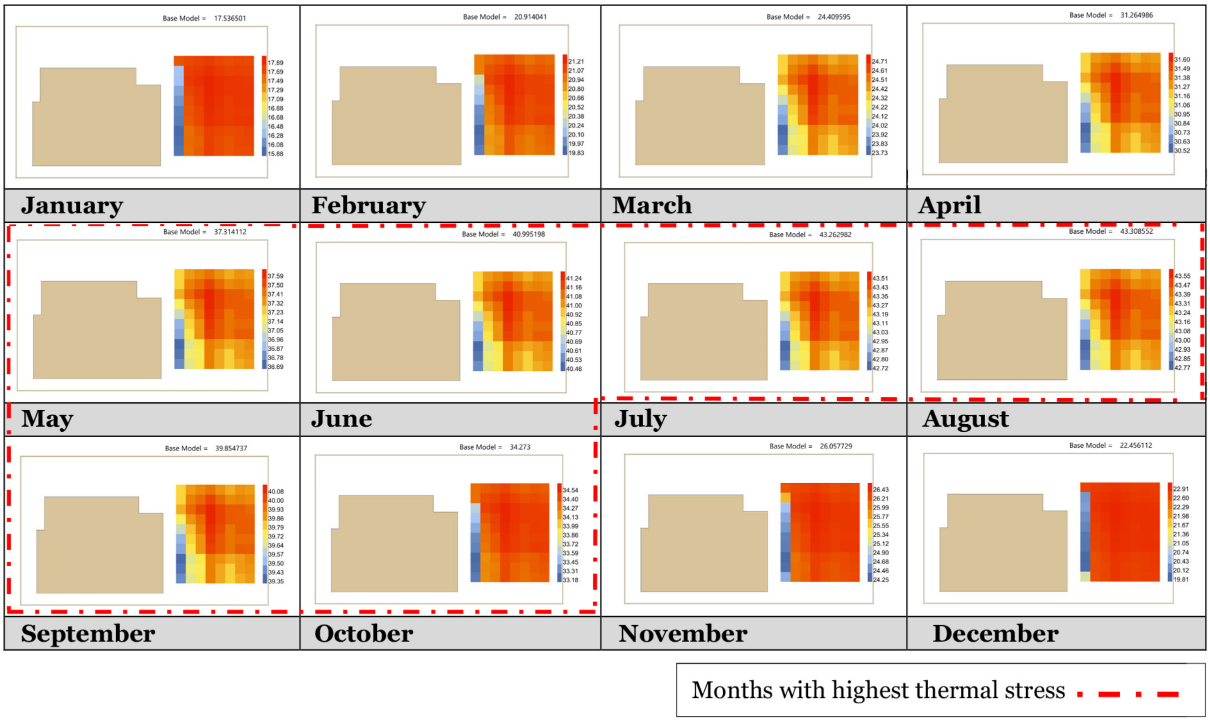


Figure 3. Base model Case Study A.

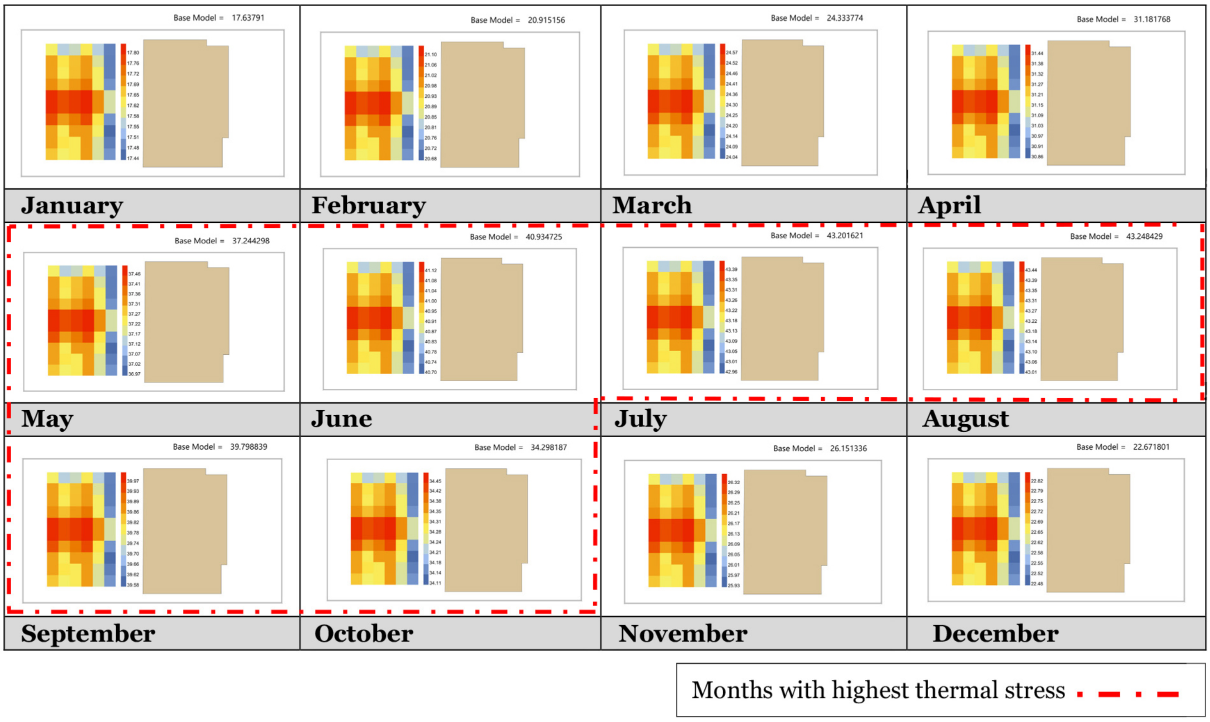


Figure 4. Base model Case Study B.

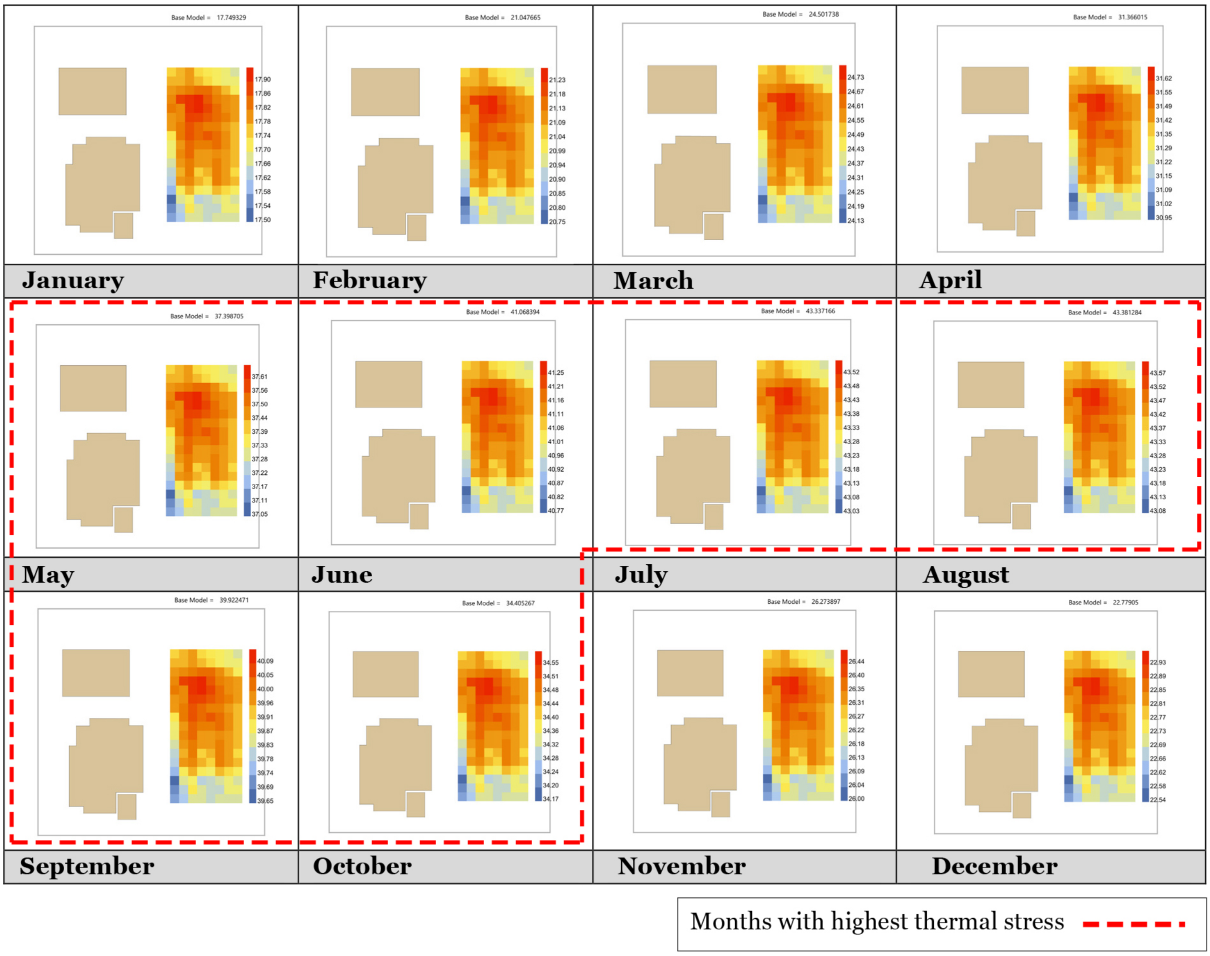


Figure 5. Base model Case Study C.

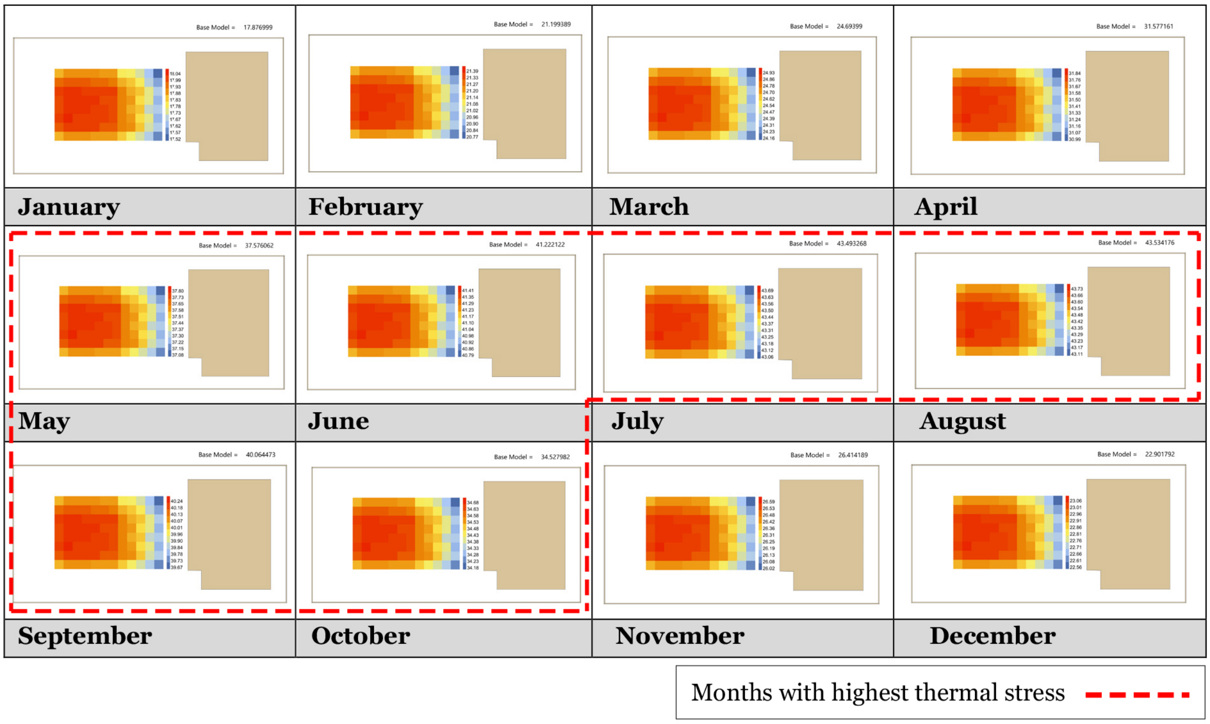


Figure 6. Base model Case Study D.

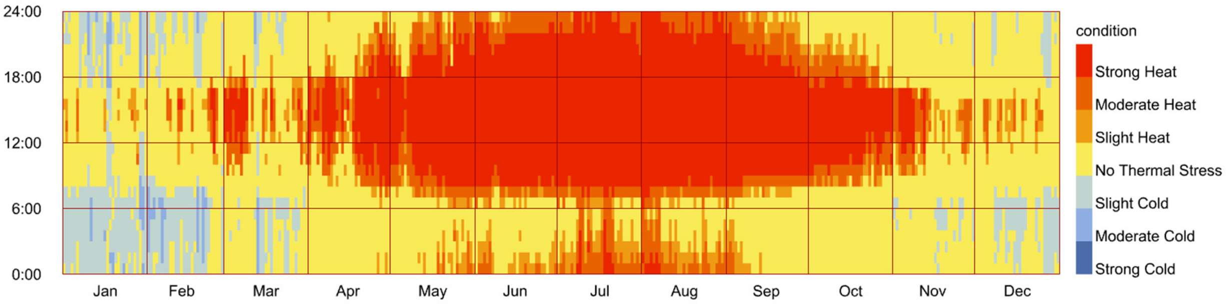


Figure 7. Hourly current conditions highlighting months with highest thermal stress.

4.2. UTCI Scenarios

The universal thermal climate index (UTCI) is a chosen measure for assessing outdoor thermal comfort in school outdoor spaces for this research. By analyzing the UTCI as an average across all study points during the critical hours of 9 a.m. to 1 p.m., we can gauge the effectiveness of various urban strategies aimed at mitigating heat stress throughout the year, that could be found as raw data in Supplementary Materials. The proposed techniques include the implementation of shade devices with varied aperture sizes (0.2, 0.4, and 0.6) and the cultivation of trees with canopies of differing diameters (3 m, 4 m, and 5 m). This investigation included four independent case studies (A, B, C, and D), each offering a unique viewpoint on the influence of these tactics on thermal comfort during various months of the year.

4.2.1. Case Study A: Seasonal Variations and Strategic Interventions

For Case Study A, Figure 8 illustrates the diversity of methods and months, whereas the baseline UTCI exhibited a consistent seasonal pattern, with values progressively rising from January, reaching a high in July and thereafter declining towards December. This pattern corresponds with standard urban thermal dynamics, whereby heat buildup in spring and early summer results in peak thermal discomfort at mid-year. The base model, depicting settings devoid of interventions, underscored the intrinsic susceptibility of the urban environment to seasonal temperature variations, especially in the summer months when the UTCI peaked.

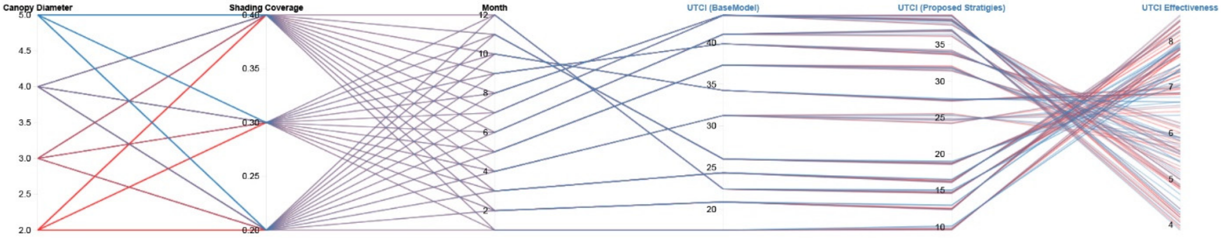


Figure 8. Variation of strategies by month for Case Study A.

In February, as seen in Figure 9, the basic model exhibits a UTCI of 17.54 °C, but the implementation of the recommended techniques results in a UTCI reduction of 9.81 °C, signifying a substantial drop in thermal stress of 7.73 °C. The efficacy of these measures is apparent, as the UTCI decreases to 7.73 °C, resulting in a significant enhancement. In August, the basic model has a maximum UTCI of 43.31 °C. The recommended techniques lower it to 38.53 °C, achieving an efficacy of 4.78 °C, which results in a significant decrease, but less noticeable than during winter months.

Shading devices with different opening sizes were introduced as a primary mitigation strategy. The analysis revealed that smaller openings (0.2) were particularly effective in reducing UTCI across all months, with the most significant impact observed during the peak summer months of June, July, and August. Smaller openings effectively limit solar radiation, reducing the ambient temperature and, consequently, the UTCI. On the other hand, larger openings (0.6) were less effective but still contributed to a noticeable reduction in UTCI compared to the base model. The larger openings allowed more sunlight to penetrate, which, while still beneficial in providing some shading, did not reduce temperatures as effectively as the smaller openings.

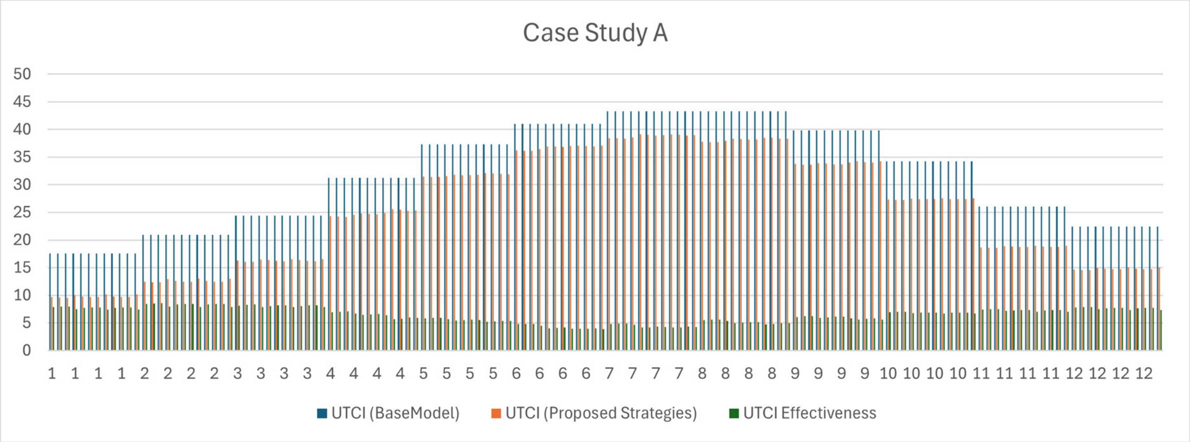


Figure 9. UTCI effectiveness.

In addition to shading, the introduction of trees with varying canopy diameters was explored as a complementary strategy. Trees with larger canopies, mainly those measuring 4 and 5 m, had a pronounced cooling effect, especially during the hottest months. These trees provide substantial shade, reducing direct solar exposure and decreasing the ambient air temperature via evapotranspiration. The integration of good shade with huge canopy trees produced the most substantial decrease in thermal discomfort, highlighting the necessity of these measures during severe heat events. This combination was successful during the peak summer months, as the UTCI was much lower than the baseline, illustrating the critical role of both shade and vegetation in urban thermal management.

4.2.2. Case Study B: Enhanced Cooling Through Strategic Combinations

For Case Study B, the variation of strategies and months is displayed in Figure 10. Case Study B exhibited a similar UTCI pattern to Case Study A, with a steady rise towards the summer months, peaking in July, and gradually declining. This pattern further confirmed the seasonal vulnerability of urban areas to heat stress, particularly during mid-year. The baseline UTCI once again highlighted the critical periods where interventions would be most needed to enhance thermal comfort.

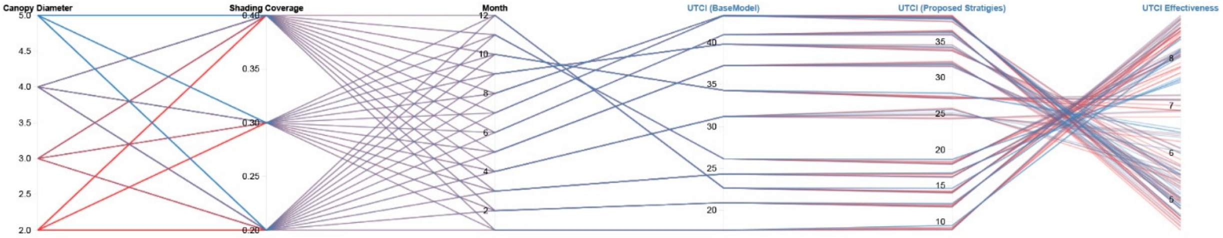


Figure 10. Variation of strategies by month for Case Study B.

In February (see Figure 11), the base model starts at 17.64 °C, which is reduced to 9.17 °C after applying the strategies, demonstrating a decrease of 8.47 °C. The effectiveness here is notable, with the UTCI dropping further to 8.47 °C, showing significant improvement. In July, the base model's maximum UTCI reaches 43.20 °C, but with the proposed strategies, it reduces to 38.39 °C, a decrease of 4.81 °C. The effectiveness of the strategies becomes less pronounced in hotter months, though the reduction still improves thermal comfort.

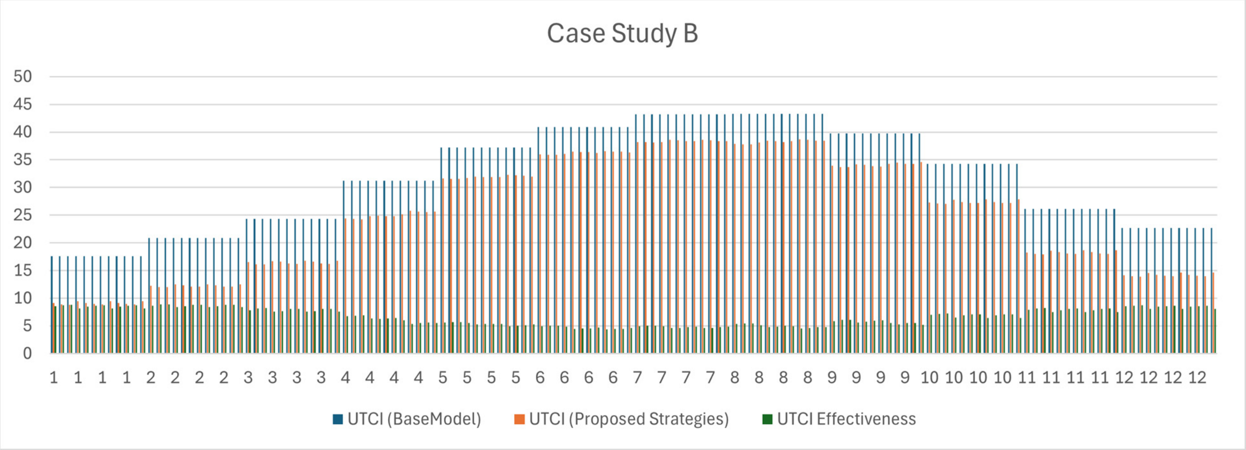


Figure 11. UTCI effectiveness.

The introduction of shading devices in Case Study B, particularly those with a 0.2 opening, substantially reduced UTCI values across all months. The effectiveness of these shading devices was most pronounced during the hottest parts of the year, particularly in June, July, and August. Smaller openings limited the amount of solar radiation reaching the ground, reducing the ambient temperature and improving thermal comfort. Larger openings (0.6), while still effective, did not achieve the same UTCI reduction; they allowed more sunlight to penetrate the shaded areas.

When trees with varying canopy diameters were introduced alongside shading, the cooling effect was significantly amplified. Trees with larger canopies (4 and 5 m) were particularly effective in further reducing the UTCI, with the most significant impact observed during the summer months. The combination of shading and large canopy trees provided a dual benefit: shading reduced direct sunlight, while the trees helped cool the surrounding air through evapotranspiration. This combination was especially successful during peak heat times, as the UTCI was much lower than the baseline, highlighting the need to use multiple techniques concurrently to achieve maximum thermal comfort.

The efficacy of these integrated tactics was apparent over the summer and yet provided advantages year-round. During the milder months, despite a lower baseline UTCI, shade and tree canopies helped sustain pleasant temperatures, mitigating the effects of excessive heat and cold on the urban environment. The consistent performance throughout many seasons underscores the adaptability of these tactics in regulating urban thermal comfort throughout the year.

4.2.3. Case Study C: Consistency in Cooling Across Seasons

In Case Study C, the baseline UTCI followed the same seasonal fluctuations observed in the previous studies, with a noticeable peak in July. Figure 12 displays the variation of strategies and months. Analysis of this case study provided further insights into the effectiveness of the proposed interventions, particularly in how they performed across different months.

In February (see Figure 13), the base model UTCI stands at 17.75 °C, and the proposed strategies lower it to 9.06 °C, achieving an effectiveness of 8.69 °C. The winter months see the most significant improvements in thermal stress due to these interventions. However, in August, the base model UTCI is 43.38 °C, which reduces to 39.00 °C after implementing the strategies, achieving an effectiveness of 4.38 °C. While still providing relief, the improvement is less impactful compared to colder months.

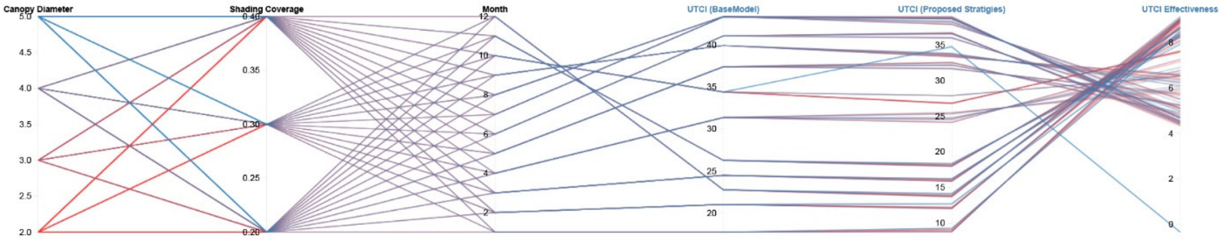


Figure 12. Variation of strategies by month for Case Study C.

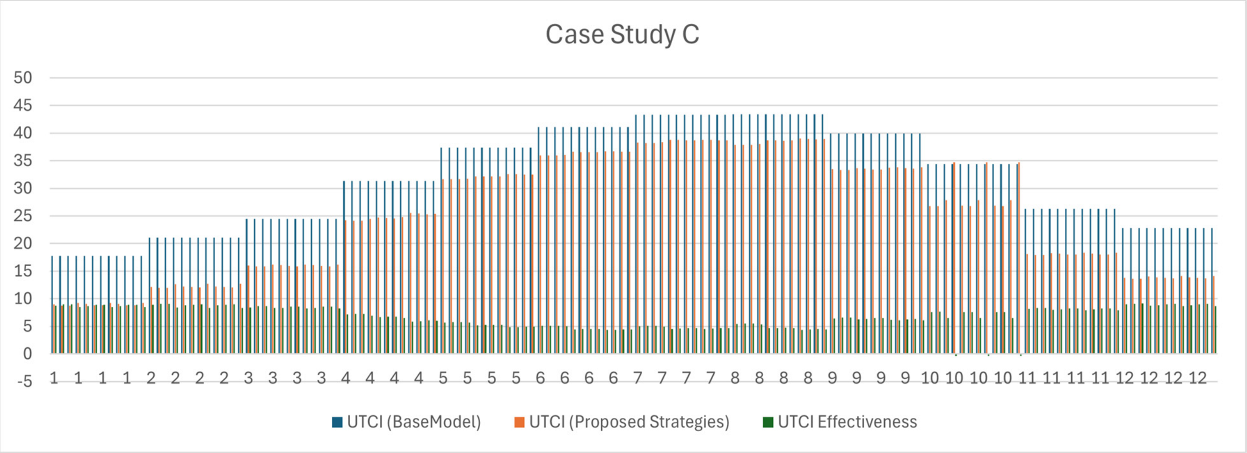


Figure 13. UTCI effectiveness.

Shading devices with smaller openings (0.2) proved to be the most effective in reducing UTCI, particularly during the summer months when thermal discomfort was highest. The smaller openings yielded the most substantial decrease in direct solar radiation, resulting in reduced ambient temperatures and enhanced thermal comfort. Larger apertures (0.4 and 0.6) similarly reduced the UTCI but were less efficacious than the smaller openings. This performance disparity highlights the need for the judicious selection of shade solutions according to the particular temperature conditions of the urban area.

The implementation of trees with expansive canopies, specifically those measuring 5 m, produced the most pronounced cooling impact. The trees offered substantial shade, which, together with the shading devices, established a multi-faceted strategy for alleviating heat stress. The cooling impact was most apparent during the summer months, as the integration of these techniques led to a substantial decrease in UTCI relative to the baseline. The efficacy of these treatments extended beyond summer; they also conferred advantages throughout the transitional seasons of spring and fall, ensuring a pleasant thermal environment year-round.

The sustained efficacy of these solutions over many seasons underscores their significance in urban thermal management. Mitigating UTCI in the peak summer months and sustaining acceptable conditions in the colder months foster a more stable and serene urban environment throughout the year. This constancy is especially crucial in climate change, where rising temperatures and more frequent heat waves are anticipated to intensify urban heat stress.

4.2.4. Case Study D: Addressing Extreme Thermal Conditions

Case Study D presented the highest baseline UTCI among all the case studies, indicating a more challenging thermal environment. The UTCI followed the typical pattern of increasing temperatures progressing to a peak in July followed by a gradual decrease. This case study provided a critical test of the effectiveness of the proposed strategies in managing extreme thermal conditions. Figure 14 displays the variation of strategies and monthly combinations.

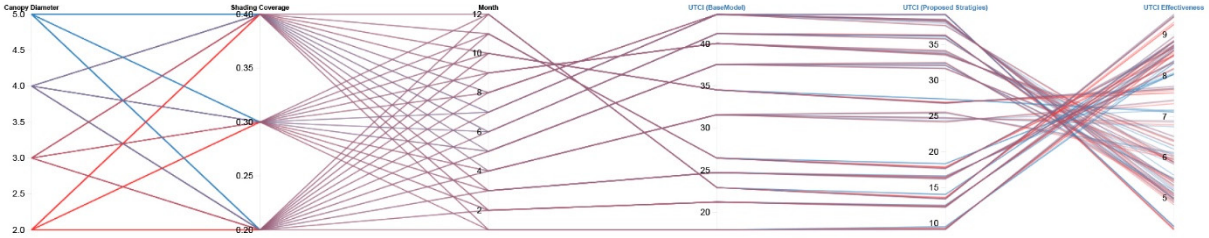


Figure 14. Variation of strategies by month for Case Study D.

For February (see Figure 15), the base model registers a UTCI of 17.88 °C. After implementing strategies, the UTCI drops to 9.36 °C, reducing thermal stress by 8.52 °C. The effectiveness here is similar to the other case studies, with cold months benefitting the most. In July, the base model's maximum UTCI reaches 43.49 °C, and the proposed strategies bring it down to 39.27 °C. This is a decrease of 4.22 °C, demonstrating less effectiveness in reducing thermal stress during hot months.

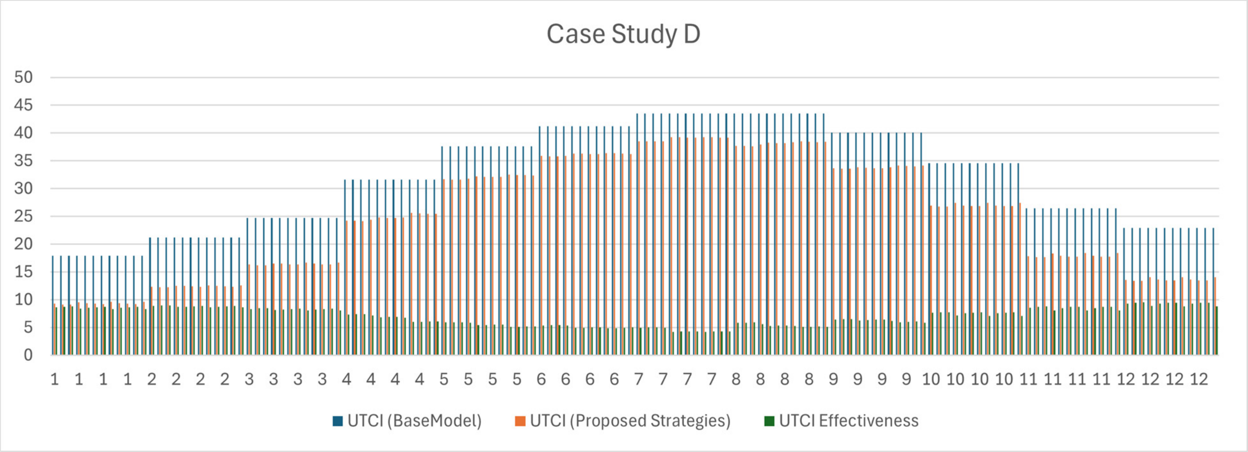


Figure 15. UTCI effectiveness.

Once again, implementing shading devices with smaller openings (0.2) was the most effective way to reduce the UTCI, particularly during the summer months. Smaller openings provided the greatest reduction in solar radiation, crucial in lowering the ambient temperature in an environment with an already high baseline UTCI. Larger openings (0.6) provided some cooling benefits but were less effective than smaller openings, particularly during the peak heat periods.

The introduction of large canopy trees (4 and 5 m) combined with shading resulted in the most significant reduction in UTCI, particularly during the hottest months. These trees provided extensive shading and contributed to cooling the surrounding air through evapotranspiration, which is particularly important in an environment with high baseline temperatures. The combined impact of shade and extensive canopies was most evident in summer, when the UTCI was much lower than the baseline, underscoring the need to use several methods to mitigate severe temperature conditions.

This case study highlighted the need for a comprehensive strategy of urban thermal management, especially in regions subjected to intense heat. The integration of shade and substantial canopy trees offered an effective strategy for mitigating heat stress, especially at the height of summer. The efficacy of these techniques in reducing UTCI throughout several seasons underscores their significance in fostering a more robust and pleasant urban milieu, especially under rising temperatures and more frequent heat waves.

4.2.5. Across All Case Studies

Significant patterns appeared across all four case studies, offering crucial insights for urban planners and designers. The efficacy of shade devices, especially those with smaller apertures (0.2), in mitigating UTCI was regularly noted, with the most significant effect reported during the summer months when thermal discomfort peaks. The diminutive apertures restricted sun radiation, thereby lowering ambient temperatures and enhancing thermal comfort throughout various months. This constancy in performance underscores the need to meticulously choose shade solutions tailored to the distinct heat requirements of the urban area.

The implementation of trees with expanded canopy diameters (4 and 5 m) significantly enhanced the cooling impact, particularly during the peak heat of the year. The expansive canopies offered significant shade and facilitated the cooling of the ambient air by evapotranspiration, establishing a multi-tiered strategy for mitigating heat stress. The amalgamation of both strategies—reduced shade apertures and expansive tree canopies—demonstrated the most efficacy in alleviating heat stress and improving thermal comfort, especially during the peak summer period.

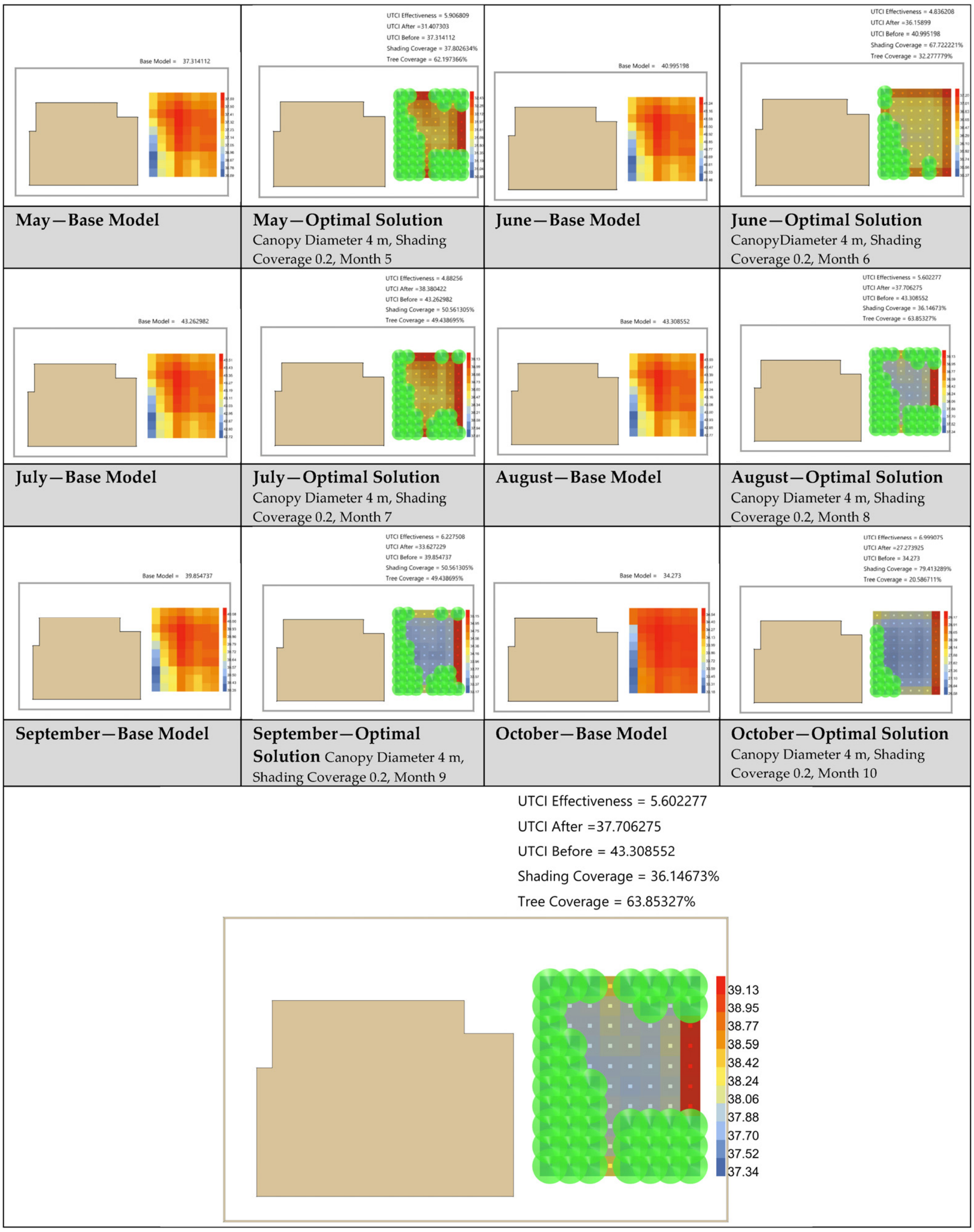
The continuous efficacy of these solutions across several seasons underscores their significance in urban thermal management. Mitigating UTCI in the hot summer months and sustaining pleasant circumstances in the colder months foster a more consistent and comfortable urban environment throughout the year. This stability is crucial in the context of worsening climate change, where rising temperatures and more frequent heat waves are anticipated to intensify urban heat stress.

5. Discussion

The universal thermal climate index (UTCI) shows changes by month across different case studies for both the base model and proposed strategies. However, for Case Study A, the UTCI in the base model consistently increases from January to July and then decreases, peaking in the summer months. The proposed strategies effectively reduce the UTCI across all months, with the greatest effectiveness in the hottest months (June to August) as shown in Figure 16.

Case Study B is shown in Figure 17. Similar to Case Study A, the UTCI peaks in the summer months and the proposed strategies are most effective during these months. However, the overall UTCI in Case Study B is slightly lower than in Case Study A. In Case Study C, the pattern is again similar, with the UTCI peaking in the middle of the year. The proposed strategies show a significant reduction in UTCI during the peak months, demonstrating their effectiveness in mitigating extreme heat (Figure 18). Case Study D shows the highest baseline UTCI, with a similar peak in the summer months. The proposed strategies are effective throughout the year, with notable effectiveness in the hotter months (Figure 19), though the overall UTCI remains higher compared to the other case studies. Overall, the findings on the effectiveness of the proposed strategies in altering the UTCI across the four case studies can be expanded by focusing on several key areas, as noted below.

Cases A, B, C, and D reveal consistent seasonal patterns, with UTCI values peaking in the summer and decreasing in the winter months. All cases demonstrate the effectiveness of smaller aperture shading devices (0.2) and larger tree canopies (4–5 m) in reducing UTCI values, especially during the hottest months. Despite these similarities, notable differences emerge in baseline UTCI values, with Case D exhibiting the highest baseline UTCI due to more challenging site conditions, possibly linked to increased sun exposure or limited surrounding vegetation. In contrast, Case B showed slightly lower baseline values, potentially due to a denser surrounding context or favorable microclimatic conditions. These differences suggest that while the proposed shading and vegetation interventions are broadly applicable, site-specific characteristics significantly influence their effectiveness. This comparative approach underscores the need for adaptable design strategies that respond to each site’s unique thermal environment.



May—Base Model

May—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 5

June—Base Model

June—Optimal Solution CanopyDiameter 4 m, Shading Coverage 0.2, Month 6

July—Base Model

July—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 7

August—Base Model

August—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 8

September—Base Model

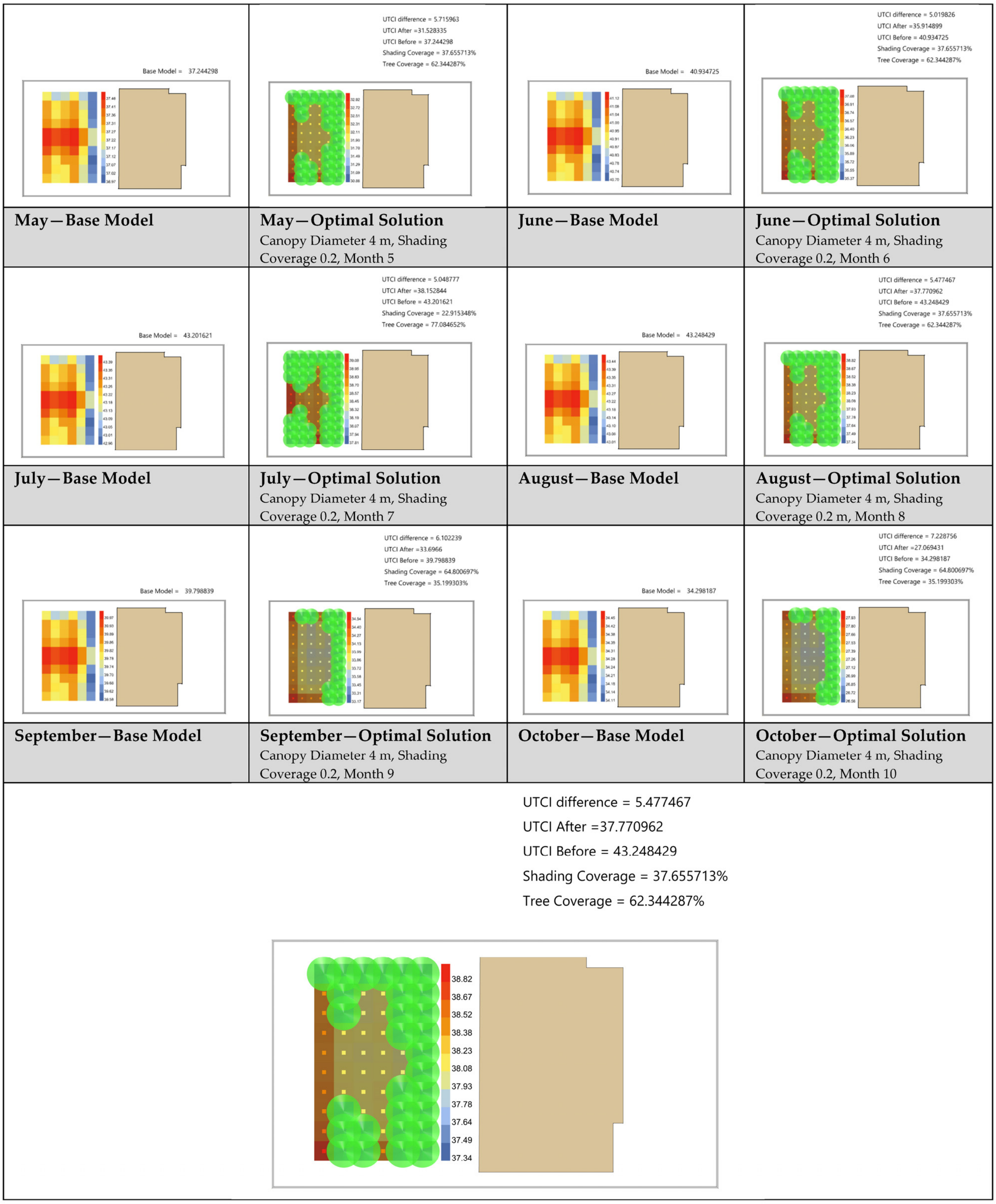
September—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 9

October—Base Model

October—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 10

Figure 16. Case Study A base model and optimal solutions from May to October.

The trends observed across all case studies indicate a consistent rise in UTCI from the beginning of the year, peaking in the summer months, followed by a decline towards the end of the year. This pattern reflects the typical seasonal variation in temperature. The proposed strategies have their most significant effect during the winter months, with decreases of 7–9 °C in UTCI being especially remarkable. This significant improvement in thermal comfort during colder seasons may be ascribed to the capacity of the technique to reduce heat loss, increase insulation, or efficiently alter microclimates. Nonetheless, throughout the peak summer months, the decreases in UTCI, while still considerable, are milder (about 4–5 °C), suggesting that the techniques may face constraints in mitigating severe heat situations when variables like radiant heat gain and ambient temperature prevail in determining thermal comfort results. This aligns with previous research by Sun et al. [33], where adding 30% vegetation decreased ambient temperature by 3.8 °C, and Musa et al. [20], where added vegetation lowered UTCI by 4.2 °C. Moreover, the researchers that studied courtyards and mixed more solutions, such as Diz-Mellado et al. [35], managed to reduce by 11.7 °C, and Mirrahimi et al. [34] reduced by 5.2 °C.



May—Base Model

May—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 5

June—Base Model

June—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 6

July—Base Model

July—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 7

August—Base Model

August—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2 m, Month 8

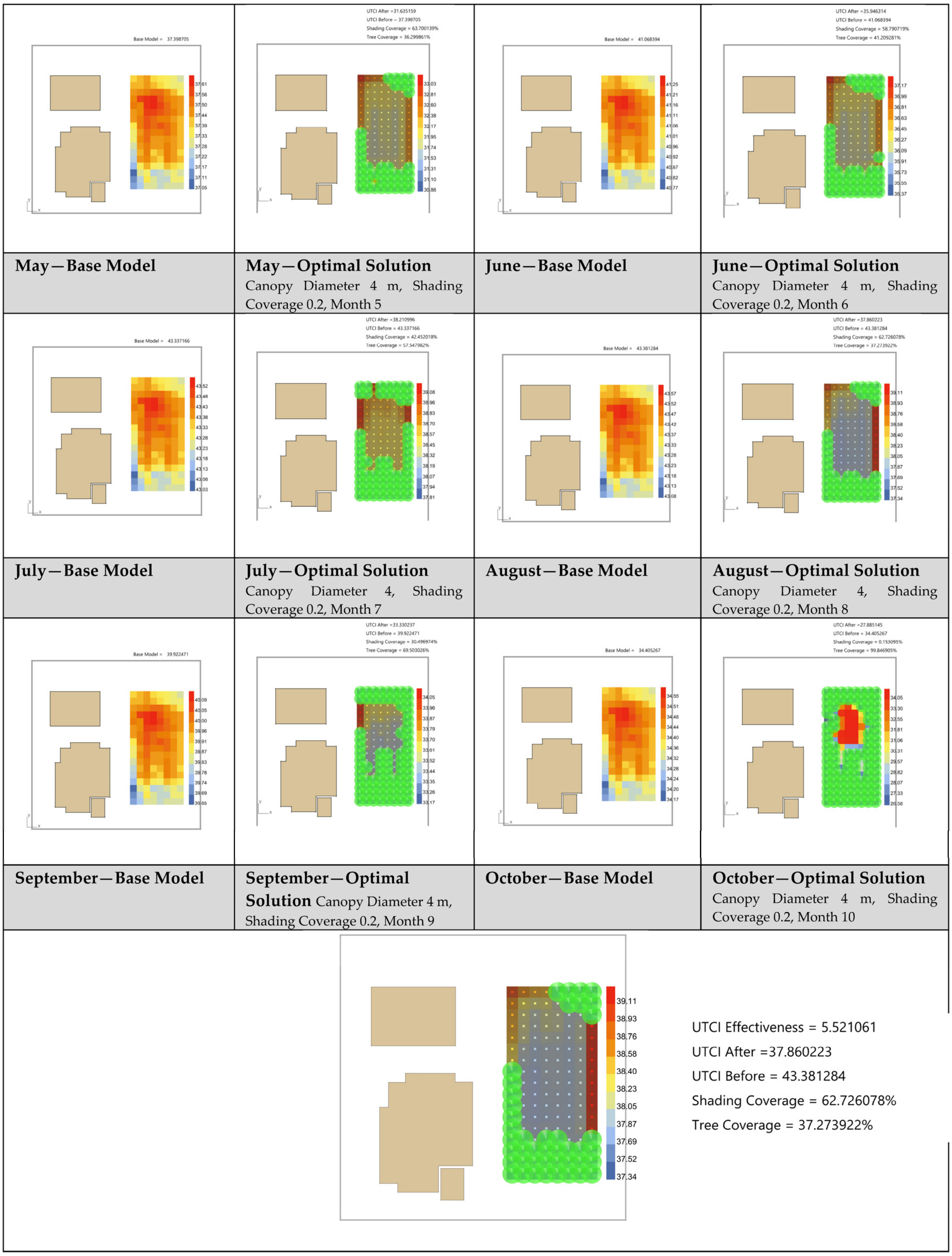
September—Base Model

September—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 9

October—Base Model

October—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 10

Figure 17. Case Study B base model and optimal solutions from July to October.



May—Base Model

May—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 5

June—Base Model

June—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 6

July—Base Model

July—Optimal Solution Canopy Diameter 4, Shading Coverage 0.2, Month 7

August—Base Model

August—Optimal Solution Canopy Diameter 4, Shading Coverage 0.2, Month 8

September—Base Model

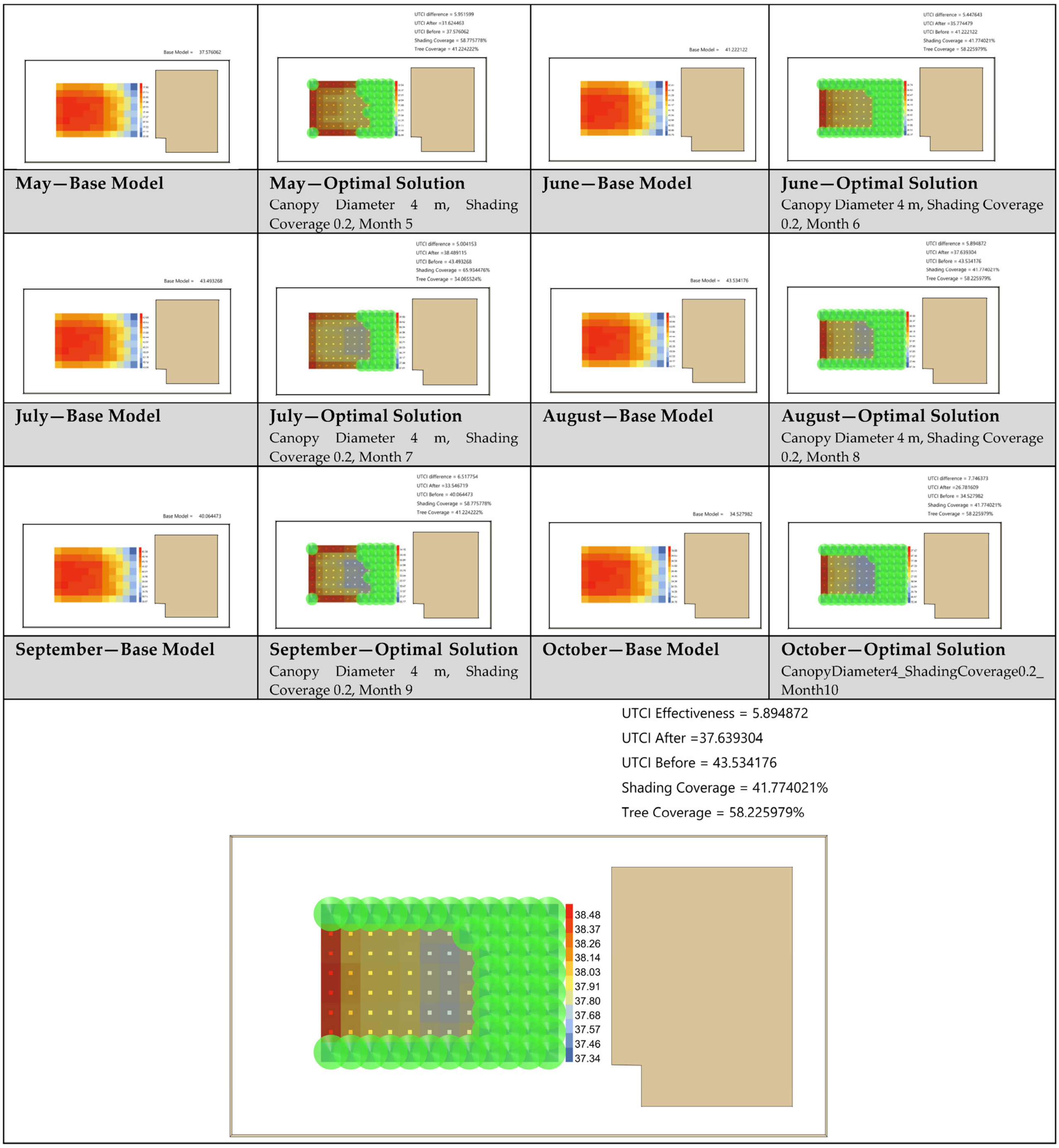
September—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 9

October—Base Model

October—Optimal Solution Canopy Diameter 4 m, Shading Coverage 0.2, Month 10

Figure 18. Case Study C base model and optimal solutions from July to October.

A comparative analysis of case studies uncovers notable discrepancies in both the foundational concept of UTCI and the efficacy of the suggested solutions. For example, Case Studies A, B, and C have similar UTCI patterns, characterized by a distinct peak during the summer months; however, the baseline UTCI in Case Study B is inferior to that of Case Study A, suggesting that the environmental context or prevailing characteristics (e.g., urban density, vegetation, or building materials) in Case Study B may be more conducive to thermal comfort. Case Study D is notable for exhibiting the greatest baseline UTCI throughout the year, especially in the summer months. Notwithstanding the efficacy of the recommended techniques, Case Study D exhibits a greater UTCI relative to the other case studies. This may suggest more severe baseline circumstances in this instance, perhaps associated with issues such as increased sun exposure, urban heat island effects, or inadequate shade.



May—Base Model

May—Optimal Solution
Canopy Diameter 4 m, Shading Coverage 0.2, Month 5

June—Base Model

June—Optimal Solution
Canopy Diameter 4 m, Shading Coverage 0.2, Month 6

July—Base Model

July—Optimal Solution
Canopy Diameter 4 m, Shading Coverage 0.2, Month 7

August—Base Model

August—Optimal Solution
Canopy Diameter 4 m, Shading Coverage 0.2, Month 8

September—Base Model

September—Optimal Solution
Canopy Diameter 4 m, Shading Coverage 0.2, Month 9

October—Base Model

October—Optimal Solution
CanopyDiameter4_ShadingCoverage0.2_Month10

UTCI Effectiveness = 5.894872
UTCI After =37.639304
UTCI Before = 43.534176
Shading Coverage = 41.774021%
Tree Coverage = 58.225979%

Figure 19. Case Study D base model and optimal solutions from July to October.

While the recommended solutions decrease the UTCI across all case studies, their differing efficacy underscores potential for improvement. The substantial decrease in

UTCI during winter months is encouraging; nevertheless, the relatively modest reductions noted in summer indicate a need for further strategies. Additional techniques, such as improving shade, augmenting plant covering, or using reflecting materials, might be included to further alleviate summer heat. Moreover, example Case Study D's persistent demonstration of the greatest UTCI indicates that location-specific modifications may be required, considering the distinct microclimatic and urban variables of each example.

The total decrease in UTCI achieved by the suggested techniques, especially during the warmer months, has significant implications for urban planning and sustainability. Enhanced thermal comfort, particularly in hot climes, may diminish energy requirements for cooling, mitigate heat-related health hazards, and improve the general habitability of urban environments. The findings suggest that these strategies can play a key role in mitigating the effects of climate change, particularly in regions prone to extreme heat. Additionally, the success of the strategies in colder months points to their potential for year-round thermal management, contributing to both heating and cooling efficiency in built environments.

However, the optimal solutions were chosen based on their ability to minimize UTCI values effectively during peak summer months, which is critical for enhancing outdoor thermal comfort in hot climates like Riyadh. The selection of shading devices with smaller apertures (0.2) was made because these structures provided the most substantial reduction in direct solar radiation, thereby lowering surface and air temperatures in the shaded areas. Smaller apertures limit solar exposure without entirely blocking daylight, creating a balance that maximizes comfort while maintaining visibility and spatial openness.

Additionally, the choice of larger tree canopies (4–5 m) was made due to their dual functionality: they not only provide shade, which directly reduces UTCI values, but also contribute to cooling the air through evapotranspiration. This cooling effect was especially valuable in open areas where air temperatures tend to rise rapidly during the day. Arranging these trees strategically around high-traffic zones, such as playgrounds or seating areas, enhanced their impact by maximizing the shaded area and ensuring the most comfortable conditions where students are likely to gather.

The arrangement of shading structures and vegetation was guided by an iterative optimization process using evolutionary computing (Galapagos). The algorithm tested various configurations to achieve the lowest UTCI values possible across different times of the day and seasons. This iterative process allowed for a tailored design in each case study, where trees and shading structures were placed in positions that blocked the highest levels of solar radiation during peak hours. For instance, in Case D, which had the highest baseline UTCI, larger clusters of shading devices were placed strategically to address the more intense sun exposure specific to that site. This adaptive approach ensured that the final arrangement of the optimal solutions would align with each site's unique thermal profile, resulting in an evidence-based, effective design solution tailored to Riyadh's climate.

Despite the positive results, there are limitations to the study that should be addressed. The moderate reduction in UTCI during peak summer months calls for further investigation into more extreme heat mitigation methods. Additionally, while the present case studies provide valuable insights, expanding the research to include a greater variety of urban settings with diverse climatic conditions would offer a more comprehensive understanding of the effectiveness of the strategies.

6. Conclusions

In all four case studies, the recommended techniques consistently lower UTCI values, especially in the colder months (e.g., February), with reductions ranging from 7 to 9 °C. The enhancements evident in the summer months (e.g., July and August) are modest, with temperature decreases of around 4 to 5 °C, indicating that while the techniques are efficacious, they provide less substantial respite during the height of summer heat. Furthermore, these findings underscore the efficacy of the recommended solutions in improving thermal comfort, particularly during colder seasons, with differing degrees of benefit in warmer months. This technique utilizes powerful computational tools to analyze and simulate the thermal comfort of outdoor areas while optimizing them for improved comfort using evolutionary algorithms. The inclusion of shading devices and vegetation, optimized using evolutionary computing, proves to be an effective strategy for mitigating outdoor thermal discomfort in school environments, leading to more comfortable and sustainable urban designs. In addition, there are several other key contributions: a simulation of outdoor thermal comfort using the UTCI, integration of evolutionary optimization to find optimal shading and vegetation solutions, and a year-round analysis of thermal performance with and without intervention strategies. Overall, this methodology bridges environmental analysis with computational design tools, demonstrating how parametric design processes can lead to more climate-responsive architectural interventions. However, future research could also explore the integration of dynamic strategies that adapt to seasonal changes, providing optimized thermal comfort throughout the year. Finally, a list of main conclusions of this research are listed as follows:

- The proposed strategies consistently lower UTCI values, particularly in the colder months, with reductions ranging from 7 to 9 °C, demonstrating effective improvements in thermal comfort.
- During peak summer months, the reduction in UTCI values is more modest (around 4 to 5 °C), indicating the limitations of the strategies in mitigating extreme heat.
- Shading devices with smaller apertures (0.2) are highly effective in reducing thermal discomfort, especially during the summer months when thermal stress is at its peak (15–25%).
- The combination of expansive tree canopies (3 to 5 m) and optimized shading provides the most significant reduction in thermal discomfort, emphasizing the need for multi-faceted strategies. That reduces thermal discomfort by approximately 30–40% during the peak summer months.
- The strategies demonstrate consistent performance across different seasons, contributing to more stable and comfortable outdoor environments year-round.
- The findings highlight the importance of integrating passive design strategies in educational settings to improve thermal comfort, serving as a model for similar hot, dry climates worldwide, while keeping in mind the local settings and site limitations.

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