Modelling and Testing Extendable Shading Devices to Mitigate Thermal Discomfort in a Hot Arid Climate

A case study for the Hajj in Makkah, Saudi Arabia

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ABSTRACT: Due to the annual pilgrimage of Hajj, the city of Makkah attracts around 2.5 million people from diverse backgrounds around the world. Many of these pilgrims may not have experienced conditions like the hot arid summer climate of Makkah. The pilgrims spend long hours exposed to high air temperatures and intense solar radiation levels while travelling between the Holy Sites of Makkah. The thermal discomfort they face can become extreme, leading to heat exhaustion or heatstroke that is severe enough to cause death. This research investigated a digitally-modelled expandable shading system that sort to mitigate this thermal stress at a microclimate level. The simulations used local data weather and quantified comfort conditions in terms of the Universal Thermal Comfort Index (UTCI) and operative temperature. The results showed a significant improvement in the thermal comfort when the expandable shades were applied, with the average yearly operative temperatures reducing by around 16%. For the most arduous and populated pilgrimage day of Hajj, the results indicated a 35% temperature difference between shaded non-shaded areas at the peak times and, for the same day, the solar radiation analysis yielded a reduction of around 90% between the shaded and the non-shaded areas.
KEYWORDS: Makkah, Hajj, Thermal Comfort, Expandable Shades, Outdoor

1. INTRODUCTION

The Saudi Arabian city of Makkah hosts the annual Islamic pilgrimage event of the Hajj. Around 2.5 million pilgrims assemble in Makkah over a 1-week period. Pilgrims visit four holy sites, walking significant distances (as much as 50 km) and spending, in total, 20 to 30 hours outside. Hajj can take place during the Saudi summer when Makkah’s air temperatures may exceed 43°C [1].

Illness at Hajj associated with heat stress is a major concern [2] that will only increase with predicted future climate change in the region [3]. Adapting the pilgrim routes to provide adequate thermal comfort conditions is crucial as a wide range of people - young and old, healthy, and poorly, from countries all around the world – go to Makkah [4].

This study investigated how the microclimate experienced by pilgrims walking between the holy sites might be improved. A parametric analysis of different urban solar shading options was undertaken digitally using a range of simulation software to identify the best combinations of shade shape, size and height. Significant improvements in local air temperatures under the shading systems were achieved, which could then be related to improved thermal comfort conditions.

2. LITERATURE REVIEW

One of the main goals of designing and planning urban spaces is to make them comfortable and attractive to the people who use them [5]. The main factor that determines whether an urban space is comfortable is the microclimate. A major case study related to this research is the shading of the Prophet’s Mosque in Madinah, Saudi Arabia [6].

The work of Otto and Rasch helped in mitigating the discomfort of the prayers within the semi-urban context of two courtyards within the Mosque by the use of kinetic shading devices (Fig. 1) [6].

Figure 1: The Inner courtyard of the Mosque of Madinah showing its shading system [6].

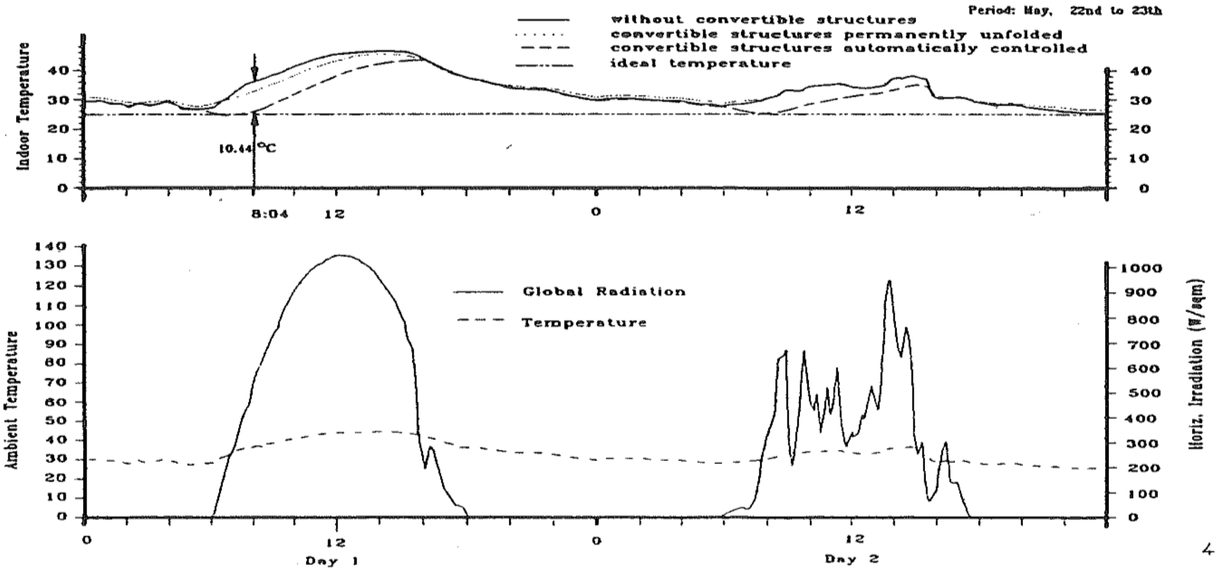

Figure 2: A microclimate regulation study for the courtyard in the Prophet's Mosque in Madinah [7].

The shading of the Prophet's Mosque took the form of retractable white canopies that could be either kept closed, remain unfolded and opened throughout the day or opened intermittently in response to environmental conditions via the use of automatic controls. The results from the study by Rasch [7], as seen in Fig. 2, shows how the canopies could reduce shade air temperatures by 10.4°C in the morning by around 08:00 compared to the ambient value.

Sijiny [8] examined pedestrian flows between the Hajj's holy sites and considered various lightweight shading alternatives to protect the pilgrims. It was noted that the shaded route will increase the number of pedestrians and decrease vehicle usage. As well as the severe climatic conditions, the density of the people gathering for Hajj can increase microclimatic temperatures within the crowd. A modelling study by Chen et al [9] simulated the conditions of the Hajj disaster on 24th September 2015, where crowds collided at the intersection of two roads. The study estimated that the temperature in the middle of the crowd might have almost reached 50°C.

The potential risk to life for pilgrims to Hajj highlights the importance of trying to improve their microclimate as they move between the holy sites to reduce thermal stress. In this study, the effectiveness of large expandable shading systems along the pilgrim routes that open and retract in a manner similar to a parasol is considered. A recent review of other mitigating strategies to improve the thermal environment and thermal comfort of urban outdoor spaces has been given by Lai et al [10], who found that shading from trees was one of the most effective mitigating strategies.

3. THE ROUTE OF HAJJ

When people arrive at Makkah, they start performing a series of religious tasks, while wearing the garment of Hajj (two white pieces of clothes that are wrapped around the upper body and the lower body for men with no other layers). Most people keep this garment on until the end of Hajj, which starts after the declaration of Hajj [6].

On the morning of the eighth day of the Islamic lunar month of Thul-Hijjah, on which the actual Hajj (pilgrimage) starts, the pilgrims begin to go to Mina. On the next morning, often before sunrise to avoid the later heat of the sun, people in Mina usually start travelling the 14 kilometres to Arafat toward Namirah Mosque. The percentage of the pilgrims who choose to walk this route exceeds 30% of the total travellers [7]. After the sunset of the nineth day, people go back to Muzdalifah where around 85% of pilgrims stay the night. On the tenth day, people who spent the night in Muzdalifah, go to the three individual places of Al-jamarat, where they perform a religious rite of stoning the devil's pillars. After that, the pilgrims go back to Mina to rest. During the eleventh and twelfth-days people start going back to Makkah from Mina.

The distances walked by pilgrims during the five days of Hajj can be significant – perhaps 30 to 50 km in total. In particular, people endure a great deal of walking and tiring activities during the 14 km journey between Mina and Arafat (Fig. 3) [11]. For that reason, this route was the proposed location for the shading system investigated in this study. The advantage of allocating objects in this location is that it will protect the vast majority of pilgrims from heat stress. This is particularly important as many of the pilgrims come from places around the world where they are physiologically adapted to their own cooler climates and so are likely to find Makkah's hot and arid climate very discomforting [12].

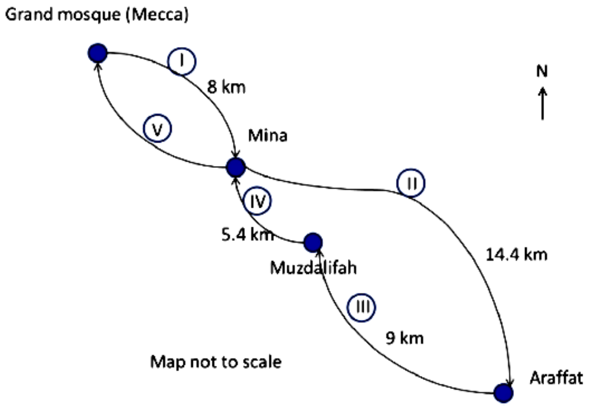

Figure 3: Routes and distances of Hajj pilgrimage [11].

4. METHODOLOGY

4.1 Climate analysis

The climatic analysis of this study focused on the holy sites in Makkah, especially during the Hajj 2019 period of 9th – 14th August. Two software were used for the study: Climate Consultant 6.0 and LadyBug Grasshopper [13]. The weather file for Arafat was chosen for the analysis as it was the closest site for this research. These data analyses were acquired using historical weather data and were logged in Grasshopper and LadyBug's components to illustrate different data for the 2019 Hajj, such as dry bulb temperature, relative humidity, global horizontal solar radiation and wind speed (Fig. 4). The weather analysis for August shows that for most times between 6:00AM and 6:00PM the conditions are thermally uncomfortable.

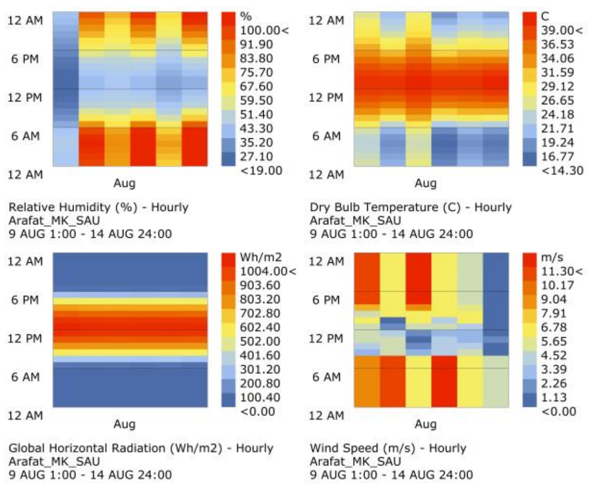

Figure 4: Arafat, Makkah - August hourly output of the dry bulb temperature (top right), relative humidity (top left), global horizontal radiation (bottom left) and global wind speed (bottom right).

The Arafat weather file that was obtained from the LadyBug website (ladybug.tools/epwmap2019) was in a standard EnergyPlus EPW weather file format. The data readings gave a clear picture of the climatic behaviour for the years provided, and it was clear that the Arafat climate was hot and arid climate. After analysing the Arafat climate data, four hourly worst-case scenarios (in terms of thermal comfort) were identified, when the dry bulb temperatures and the relative humidity were at their highest and lowest values (Fig.5).

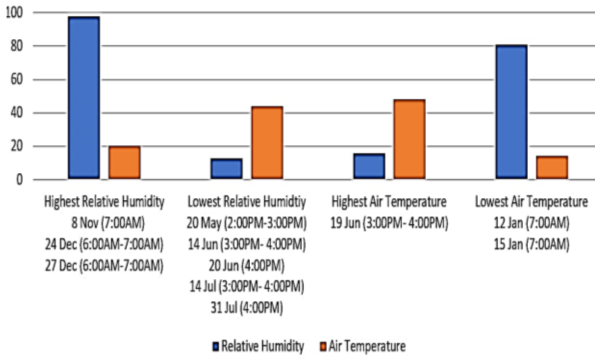

Figure 5: Worst-case scenarios of air temperature and relative humidity from the Arafat weather file.

4.2 The Universal Thermal Comfort Index (UTCI)

In order to study the impact of the proposed shading system on microclimate comfort, it was necessary to identify an outdoor thermal comfort index. Although many such indices have been developed over the last twenty years, most of them only consider the role of a single climatic parameter, such as solar radiation or wind speed, on comfort.

The Universal Thermal Climate Index (UTCI) has the benefit of combining four climatic variables (air temperature, radiant temperature, humidity, and wind speed) and calculating a temperature that 'feels like' being exposed to those combined weather conditions [14]. Another advantage of the Universal Thermal Climate Index for this study, when compared to other indices, such as the Physiologically Equivalent Temperature (PET), is its capability to adjust the assumed outdoor clothing level of people, whereas the PET uses a standard clothing level [15]. The advantage here is knowing that the Makkah context embraces different cultures with different clothing expectations besides the clothing of Hajj, where men are expected to wear two white garments during the days of the pilgrimage. This suggests that the UTCI is more appropriate to illustrate the thermal physiological stress than the PET. It is also a more recently developed thermal model [15].

Table 1 shows the range of UTCI 'feels like' temperature values and the equivalent thermal stress categories.

Table 1: The UTCI 'feels like' temperatures in °C and the equivalent thermal stress.

UTCI range in ℃	Stress category
above +46	extreme heat stress
+38 to +46	very high heat stres
+32 to +38	high heat stress
+26 to +32	moderate heat stress
+9 to +26	no thermal stress
0 to +9	slight cold stress
-13 to 0	moderate cold stress
-27 to -13	high cold stress
-40 to -27	very high cold stress
Below -40	extreme cold stress

4.3 Modelling procedure for the shading devices

The modelling and simulation of the proposed shading systems were undertaken using Rhinoceros 3D software with Grasshopper to calculate values of UTCI, operative temperatures and incident solar radiation levels. The simulations were based on an example performed by Mackey using LadyBug Tools [16]. The climatic data were obtained from the LadyBug Tools LLC website for EPW maps [17] where the climatic data of Arafat - the nearest location of the tested area - was connected to the algorithmic process of the simulation. For modelling purposes, a square-shaped shading canopy model was found to be the most practical. The canopy was 15m high and 30 x 30m in plan, giving an extendable area of up to 900m^2 (Fig. 6). These dimensions were suggested based on the size of the pedestrian paths between Mina and Arafat, Makkah. The canopies were formed as a 9-unit (3x3) cluster to shade the chosen location around Arafat. The materials were assumed to be solid with zero transmittance properties as it was found that, in terms of shade benefits, the shades' materials had minimal impact when made of a low thermal mass fabric [18].

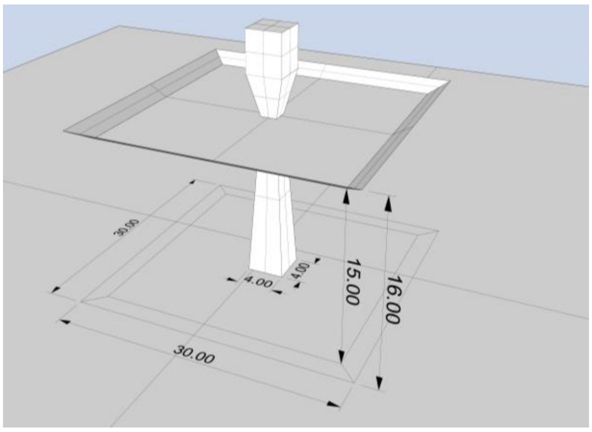

Figure 6: Details of the modelled canopy shading device.

5. RESULTS

5.1 The UTCI temperatures

The performance of the proposed device was quantified in terms of the UTCI values created under the canopy measured over a grid of 5m at a height of 1m above the ground for the 10th August 2019 (max/min DBT of 37^o/31^{o}C, RH 48-62%, wind speed 1.9 to 5.5 m/s). Fig. 7 shows the average UTCI values with the canopy retracted and extended. Average UTCI dropped from 36.5°C (strong heat stress) to 31.5°C (moderate heat stress).

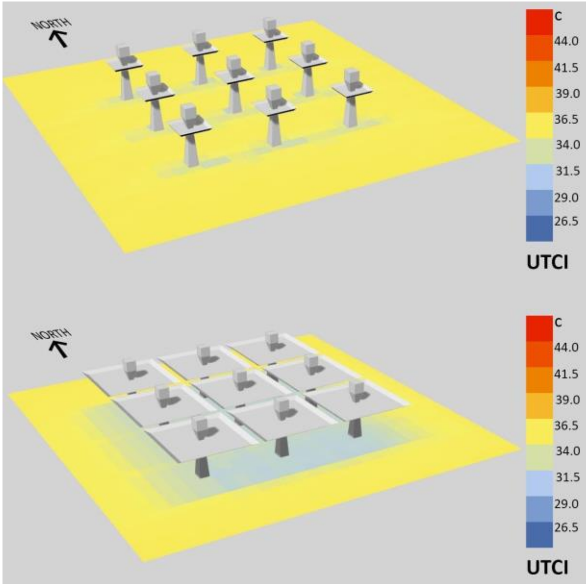

Figure 7: Average UTCI for 9-cluster shading of the site on 10th August (retracted [above] and extended [below]).

Hourly operative temperatures for the 10th August for extended and retracted canopy scenarios were also examined (Fig. 8). Temperature differences between shaded and sunlit areas start to appear at 07:00, where the sunlit area was around 38.6°C while the shaded area was around 34.5°C. The biggest difference in operative temperatures between the shaded and non-shaded areas was around 16°C at 09:00 and 17:00. The last time to record a difference was 18:00, when the non-shaded area was around 46.8°C while the shaded area was around 38.6°C (Fig. 9). After that time, the sun had set, and no further differences were found.

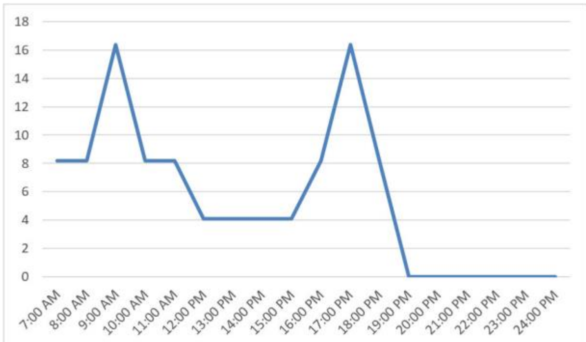

Figure 8: Hourly operative temperatures differences (°C) between the shaded and non-shaded areas, 10th August.

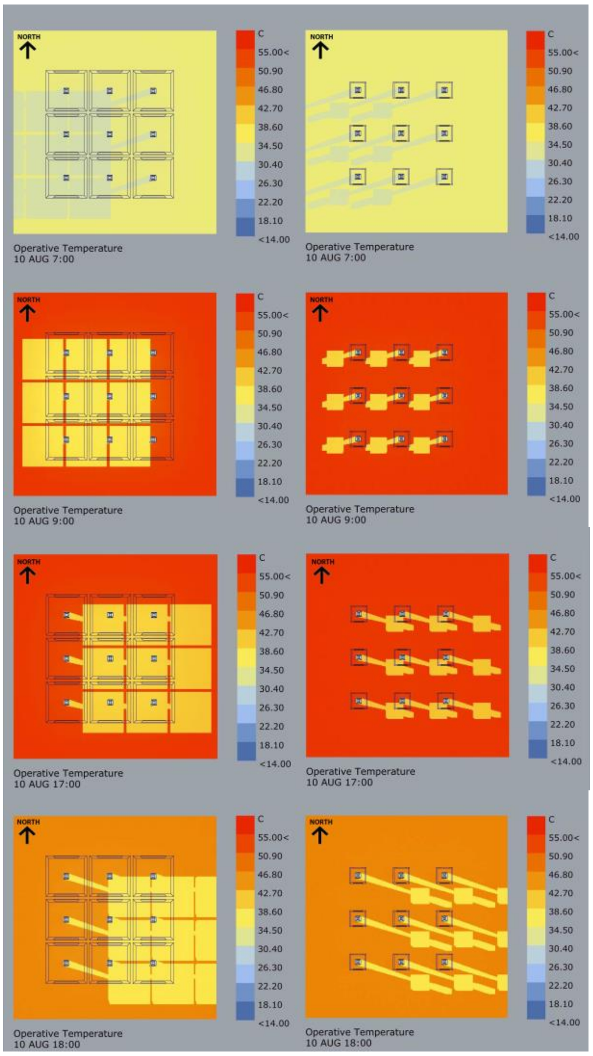

Figure 9: Operative temperatures at the site on 10th August at (top to bottom) 07:00; 09:00; 17:00 and 18:00 (shading extended [left] and shading retracted [right]).

5.2 The solar radiation analysis

The solar radiation analysis results showed large difference between shaded areas and the exposed sunlit areas. The analysed period was between the 9th – 13th August for the hours 09:00 – 15:00. The shades affected the radiation levels significantly. Solar radiation values outside the shaded area exceeded 24 kWh/m^2, while inside the shaded area they were between 9.41kWh/m^2 and 2.35kWh/m^2 toward the central area of the shades, rising to 16.47kWh/m^2 at the boundary of the shaded/unshaded areas (Fig. 10).

5.3 The shading benefits analysis

For a whole year, a visual scale of comfort (-3 to +3, where -3 indicates extremely cold and +3 extremely hot), was produced for shade and no shade areas, which showed the year-round benefits of shading the chosen urban area in Makkah (Fig. 11). It showed that there was an extreme discomfort for most of the year between the hours of 09:00 and 18:00. The simulation showed that for around 41% of the time during the year people felt heat stress outdoors, around 19% of the time people felt cold stress and around 27% of the time people felt comfortable outdoors. During the Hajj period, people felt heat stress for almost all the time outdoors. The shading system helped mitigating the thermal discomfort for the pedestrians walking beneath them during the year (Fig. 11 below).

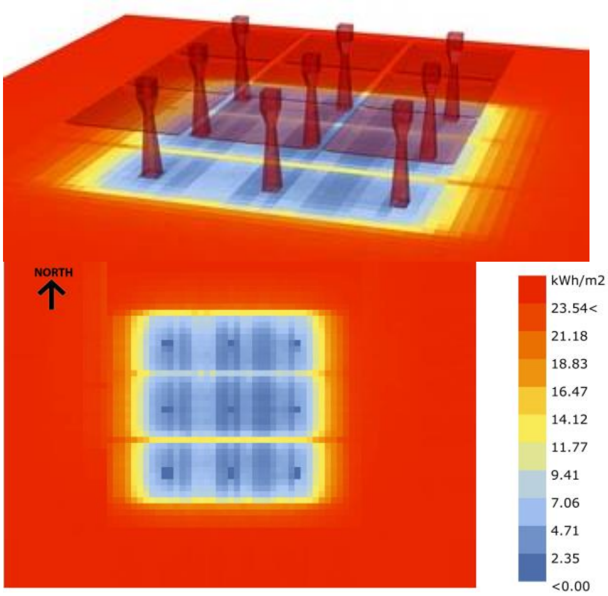

Figure 10: Solar radiation levels for the modelled canopy shading device, 9-13 August, between 09:00 and 15:00.

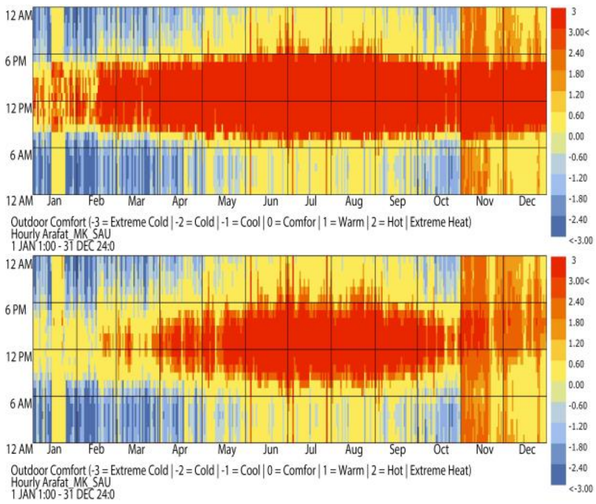

Figure 11: Annual outdoor comfort levels without (above) and with (below) the shading canopies.

A visual illustration with a scale of degree days/m^2 was made to show the best location to walk beneath the shade and was calculated for the whole year (Fig. 12). The degrees per day are representing the balance temperature difference between the external air temperature and the temperature at a point under the shade on an hourly basis for the analysed period per square metre. The smaller the temperature difference then the less good that spot.

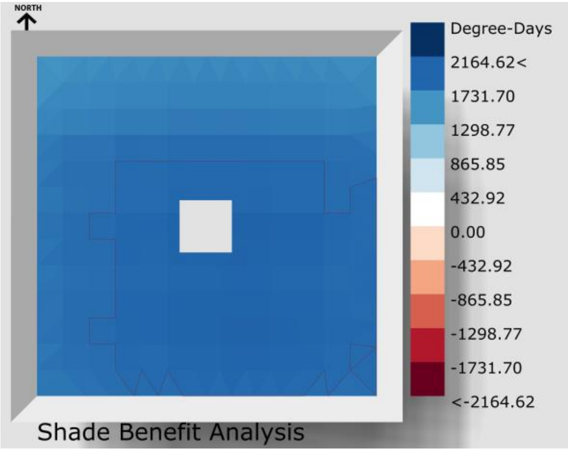

Figure 12: The shade benefit analysis, where the darker blue areas are the best locations to walk beneath the shading device.

Finally, an analysis calculated the number of hours of direct sunlight received at the site on 10th August from 9:00AM to 15:00PM when the shading devices were expanded and retracted. Fig. 13 shows how the very minimal shade provide by the support stands and the folded shading led to sunshine hours on the ground of between 9 and 10+ hours of direct sunlight. Conversely, with the shading fully extended, the direct sunlight hours were typically 1 to 2 hours.

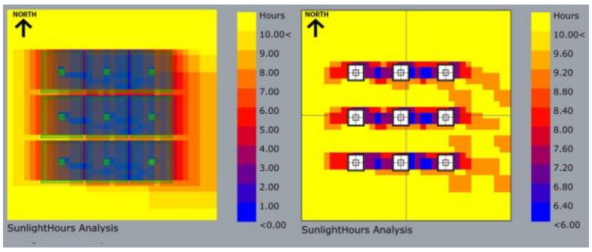

Figure 13: Sunshine hours for 10 August from 9:00AM to 3:00PM for the extended (left) and retracted (right) shading.

6. CONCLUSION

This study has examined the effect on outdoor pedestrian comfort of a cluster of prototype shading canopies. There was a significant improvement in the thermal comfort when the canopies were opened, for both daily and yearly periods. A significant increase in the thermal comfort was found when the canopies were applied. The benefits outreached the Hajj period to be suitable for the most year. Further work will investigate integrating other passive cooling measures into the canopies, such as evaporative cooling.

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