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Research paper

PERFORMANCE-BASED DESIGN OF MODULAR SHADING CONFIGURATIONS FOR OUTDOOR THERMAL COMFORT

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Abstract

Urban public spaces with limited natural shading can experience high thermal stress during hot summer periods. Modular shading systems can provide an adaptable solution. This study investigates how different spatial configurations of identical modular shading elements influence outdoor thermal comfort (OTC). A parametric workflow was applied to Katolička porta square in Novi Sad, Serbia. Three configurations (linear, centralized and scattered) were generated and OTC was calculated and evaluated using the Universal Thermal Climate Index (UTCI) for the hottest summer day. The objective was to minimize the average UTCI value within the shaded areas while maintaining the defined spatial constraints. The favourable configurations mitigated the average UTCI by 5.47% for the linear, 12.74% for the centralized and 4.49% for the scattered configuration. The centralized configuration achieved the greatest mitigation (4.203°C). The results show that the spatial arrangement of identical shading elements can influence their thermal performance. The proposed workflow provides a flexible approach for testing and optimizing shading configurations in different urban spaces.

Key words: *performance-based design, parametric design, outdoor thermal comfort, UTCI, modular shading system*

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1. INTRODUCTION

Increasing air temperatures and frequent heat events have intensified the need for climate-responsive design. High solar exposure in paved public spaces can increase heat stress and negatively affect outdoor thermal comfort (OTC) [1,2,3]. Shading is an effective mitigation strategy [4,5,6,7], while vegetation also provides cooling [8,9,10] but may be constrained by space, existing infrastructure and long growth periods. Architectural shading elements provide greater control over geometry and placement, while their form, orientation and dimensions can affect OTC [11,12,13,14]. Previous studies of vegetation also show that the number and spatial arrangement of shading elements influence OTC [15,16,17]. Urban geometry and shading conditions further affect OTC [18,19,20,21]. Thus, shading performance depends not only on the amount of shade but also on its spatial configuration. Parametric and evolutionary methods have been used to evaluate and optimize environmental performance in shading and urban design [22,23,24].

Despite the recognized importance of shading characteristics and spatial configuration for outdoor thermal conditions, a research gap remains in understanding how the spatial configuration of identical modular shading elements affects OTC. This provides a basis for investigating spatial configuration as an independent design parameter within a performance-based parametric workflow.

The research goal of this study is to evaluate how different spatial configurations – linear, centralized and scattered – of identical modular shading element influence OTC in a public square and to identify favourable layouts using a parametric workflow. The configurations are evaluated under hot summer conditions using UTCI performance evaluation and evolutionary optimization.

The study is guided by the following research questions:

RQ1: How do different spatial configurations of identical modular shading elements affect UTCI under hot summer conditions?

RQ2: Which of the tested configuration provides the greatest UTCI mitigation within the defined climatic and spatial conditions?

RQ3: Can a parametric evolutionary workflow support the identification of thermally favourable shading layouts?

2. METHOD FOR EVALUATING MODULAR SHADING CONFIGURATIONS

The proposed method was developed in order to evaluate how different spatial configurations of modular shading elements affect OTC. The workflow combines following steps:

- 3D modeling in Rhino 3D software, CAD program for 3D modeling.
- Parametric modeling in Grasshopper, visual programming tool in Rhino 3D.
- UTCI calculation in Ladybug, Grasshopper add-on for simulation analysis.
- Finding favourable configuration in Galapagos, an evolutionary algorithm.

2.1. 3D modelling

A simplified 3D model of the built environment was created to represent objects affecting the thermal conditions of the study area, including buildings and trees. Spatial information was obtained from OpenStreetMap (OSM) and Google Maps and further developed in Rhino 3D. Buildings were modelled according to their footprints and approximate height, while existing trees were represented as simplified 3D elements. This simplification reduces model complexity and computational load while retaining the main spatial features relevant to the analysis. The resulting 3D model provides the geometric basis for the generation of parametric modular shading configurations and their OTC analysis.

2.2. Parametric modeling and spatial configurations of shading modules

The modular shading system was created parametrically in Grasshopper, allowing the geometry and position of the modules to be controlled. The system consists of an equal number of identical circular shading modules, with the same dimensions and height, keeping the total shading area comparable across configurations.

Three spatial configurations were investigated: linear, centralized and scattered. In the linear configuration, modules are arranged at equal distances along a defined linear path. In the centralized configuration, they are grouped around a common central area, while in the scattered configuration, they are distributed across the available area. Module positions are controlled through parametric inputs. Grasshopper was also used to generate measurement points for the UTCI simulation within the shaded areas beneath the modules. This enables the same parametric workflow to generate and evaluate different spatial arrangements.

2.3. UTCI calculation

OTC was evaluated using the Universal Thermal Climate Index (UTCI) in Ladybug. The UTCI heat stress categories used for the interpretation of the results are presented in Figure 1.

UTCI (°C)	Stress category
> +46	Extreme heat stress (EHS)
+38 to +46	Very strong heat stress (VSHS)
+32 to +38	Strong heat stress (SHS)
+26 to +32	Moderate heat stress (MHS)
+9 to +26	No thermal stress (NTS)
0 to +9	Slight cold stress (SCS)
-13 to 0	Moderate cold stress (MCS)
-27 to -13	Strong cold stress (SCS)
-40 to -27	Very strong cold stress (VSCS)
< -40	Extreme cold stress (ECS)

Figure 1. UTCI heat stress categories [25]

The location and meteorological inputs, including dry-bulb temperature, relative humidity, wind speed, direct normal radiation and diffuse horizontal radiation, were obtained from the EPW file for the study location. The analysis period, measurements points location and standing posture were specified according to the study objectives.

The 3D context shading included the surrounding buildings, trees and generated shading modules. This geometry was provided as context shading input to the Ladybug Solar Adjusted Temperature component together with the solar radiation data. Ground reflectivity was also specified as an input to this component.

The shading panels were modelled as geometric obstruction to direct solar radiation only. The radiative material properties, including solar reflectance, absorptance and logwave emissivity, were not explicitly assigned. The Solar Adjusted Temperature component was used to calculate mean radiant temperature (MRT), which was then used with the relevant meteorological parameters, as an input to the Ladybug Outdoor Comfort Calculator for the UTCI calculation. MRT was therefore used as an intermediate variable in the UTCI calculation rather than as a separate thermal comfort indicator.

For each shading configuration, UTCI values were calculated at parametrically generated set of measurement points to evaluate the OTC within the shaded areas. The same number of points was used for all configurations. The calculated UTCI values were first averaged over the analysed hours for each measurement point and then across all measurement points to obtain a single average UTCI value for each configuration.

2.4. Finding favourable shading modules layout

An evolutionary algorithm was applied in order to find favourable positions of the shading modules. Galapagos is a single-objective algorithm and it uses genes and a fitness value to search for a solution. The fitness value represents the objective that the algorithm aims to optimize, while genes are the input parameters that can be changed during the optimization process.

In this study, the fitness value was the final average UTCI, which was minimized using the *Minimize* option, with the maximum of 50 stagnant generations. Module positions were defined as genes, with their function adapted to each spatial configuration: for the linear configuration, the gene selects one of the predefined parallel lines; for the centralized configuration, it controls the position of the module group along the central axis; and for the scattered configuration, it controls the seed generating the spatial distribution. The same approach is applied separately to each predefined spatial configuration.

3. APPLICATION OF THE METHOD

3.1. Study area

The proposed method was applied to a real-world scenario at Katolička Porta (Catholic Port) square, Novi Sad (Serbia), shown in Figure 2.

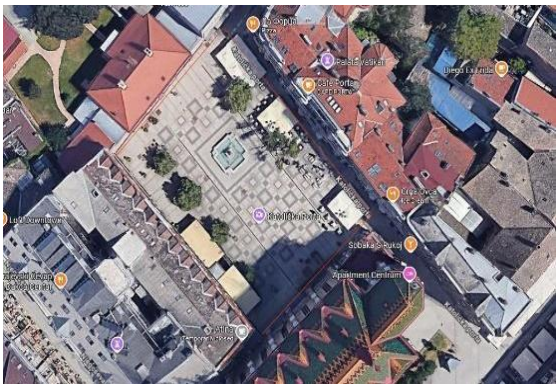


Figure 2. Katolička Porta square

The selected site is an open urban space used for pedestrian movement and outdoor stay, with limited natural shading and paved surfaces are exposed to summer solar radiation. It therefore provides a suitable case for testing different spatial configurations of modular shading elements.

3.2. Creating digital environment

A simplified digital environment was created for the analysis (Figure 3), including the surrounding buildings, the Catholic church and the existing trees. There is also a fountain located in the central part of the square. Its area was excluded from the available surface for panel placement. The resulting digital environment was used as the context for the parametric generation and calculation of the shading module layout.

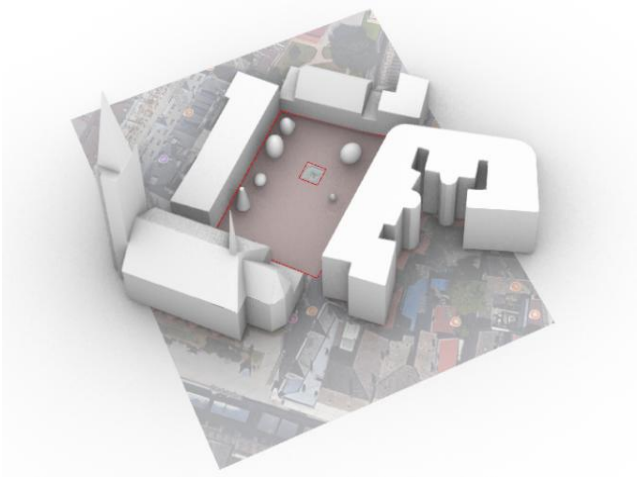


Figure 3. Digital environment of the study area

3.3. Parametric shading module configurations

Three spatial configurations of the shading modules were tested: linear, centralized and scattered (Figure 4).



Figure 4. Linear, centralized and scattered configuration

Each configuration consisted of seven identical circular shading panels, with a radius of 1.5m, positioned at a height of 4m. Their positions were controlled through parameters in Grasshopper and constrained to avoid intersections with existing trees, the fountain and the seating areas. The three configurations were analysed as separate scenarios for OTC analysis.

3.4. UTCI calculation setup

The UTCI analysis was performed for 7 July, representing the hottest summer day, over the period from 8-18 h. Meteorological data were obtained from the EPW file, while ground reflectivity was set to 0.350, representing a typical value for concrete surfaces. The surrounding buildings, trees and shading panels were included as context shading.

For each configuration, 35 measurement points were defined, with five evenly distributed points beneath each of the seven panels and positioned at pedestrian height (Figure 5). UTCI values were averaged across the analysed hours and measurement points.

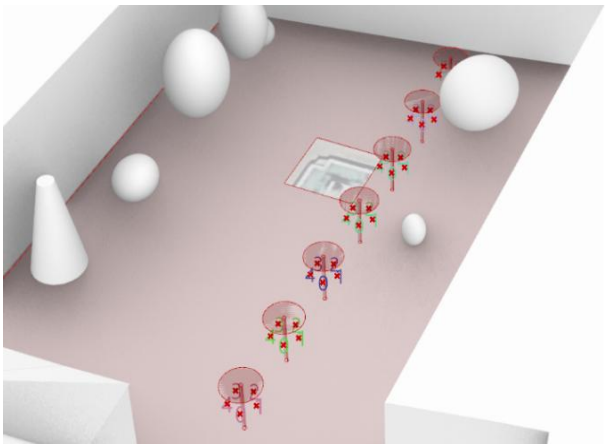


Figure 5. Example of measurements points distribution

For each minimized shading configuration, a corresponding unshaded reference condition was generated by removing only the shading panels, while retaining the same 35 measurement points and their coordinates. Thus, each shaded condition was compared with its corresponding unshaded condition at identical spatial locations. The measurement points differ between the shading configurations (linear, centralized and scattered), because the followed the respective minimized panel configuration, but remained unchanged within each shaded – unshaded comparison. This ensured that the observed

UTCI differences reflected the effect of the shading configuration rather than differences in measurement point locations.

The resulting average UTCI values were interpreted according to the UTCI thermal stress categories.

3.5. Finding favourable shading layout

Galapagos was used to identify favourable panel positions for each predefined configuration. Panel positions were defined as genes, while the average UTCI within the shaded areas was used as the fitness value. The objective was to minimize the average UTCI while maintaining the defined spatial constraints.

The resulting favourable configurations were then used for the final comparison of OTC with corresponding unshaded references.

4. RESULTS

The results show that all three shading configurations mitigated outdoor thermal stress, as indicated by the decrease in the average UTCI values compared with the corresponding unshaded condition (Table 1).

Table 1. comparison of OTC of unshaded and favourable shaded solutions

Shading configuration	Average UTCI – unshaded ($°C$)	Average UTCI – minimized ($°C$)	UTCI mitigation ($°C$)	Mitigation (%)	UTCI category - unshaded	UTCI category - minimized
Linear	32.880	31.080	1.800	5.47	Strong heat stress	Moderate heat stress
Centralized	33.000	28.797	4.203	12.74	Strong heat stress	Moderate heat stress
Scattered	32.422	30.966	1.456	4.49	Strong heat stress	Moderate heat stress

The unshaded values for the linear, centralized and scattered configurations were within the strong heat stress category, while all favourable shading configurations reached the moderate heat stress category.

The linear, centralized and scattered configurations achieved UTCI mitigation of 1.800 $°C$ (5.47 %), 4.203 $°C$ (12.74 %) and 1.456 $°C$ (4.49 %), respectively, with centralized configuration achieving the greatest mitigation. The favourable solution for each configuration is shown in Figure 6.

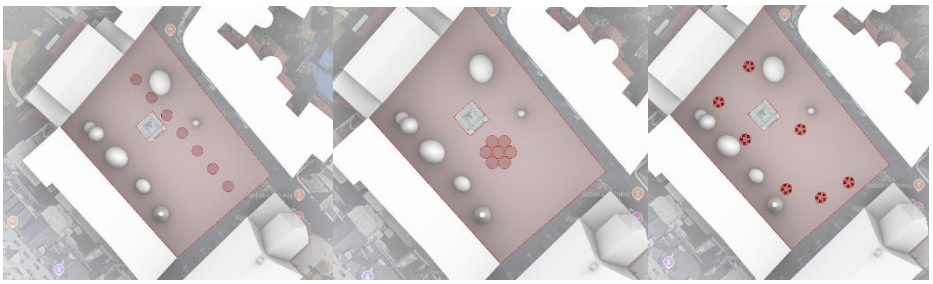


Figure 6. Favourable solutions for linear, centralized and scattered configuration

Although all three configurations resulted in a transition from strong to moderate heat stress, the magnitude of the mitigation differed. The centralized configuration provided the greatest UTCI mitigation, while the scattered configuration produced the smallest change. This indicates that the spatial arrangement affects the thermal performance of modular shading elements, even when their number, size and height remain constant. However, the shift to moderate heat stress in the linear and scattered configuration should be interpreted with caution. Their unshaded UTCI values were already close to the lower threshold of the strong heat stress category. Thus, relatively modest mitigation of 1.800°C and 1.456°C were sufficient to cross the category boundary. In contrast, the centralized configuration achieved a substantially larger mitigation of 4.203 °C, indicating a more pronounced thermal improvement rather than a mere boundary effect.

5. DISCUSSION

The results show that the parametric workflow can effectively evaluate thermal impact of different shading configurations. The centralized configuration achieved the greatest UTCI mitigation (12.74%), although the number, size and height of panels were identical among configurations. The more continuous and concentrated shaded area of centralized configuration resulted in greater UTCI mitigation compared with the more dispersed shadow patterns of the linear and scattered configurations. This indicates that spatial distribution of shading, not only the total shading area, influences OTC.

From a practical standpoint, this workflow is highly adaptable to other sites and shading geometries. Its parametric structure allows different module properties, spatial constraints and space layouts to be tested. The only requirements are the necessary weather data and spatial and geometric data of the study area.

6. CONCLUSION

This study explored how spatial configurations of identical modular shading elements affect OTC in a public square with limited natural shading. A parametric workflow was developed to generate and evaluate linear, centralized and scattered configuration under hot summer conditions. The results show that spatial arrangement influences OTC despite identical module number, size and height. The centralized configuration achieved the greatest UTCI mitigation, while the linear and scattered configurations achieved smaller mitigation. This confirms spatial configuration as an important design parameter for modular shading.

The proposed workflow supports the identification of thermally favourable layouts through parametric generation and environmental simulation. It can be adapted to different shading geometries and spatial constraints in other public squares, provided that appropriate weather data and sufficient spatial data are available.

This study is limited by the simplified representation of the environment and tree geometries that cast full shadow. In addition, the analysis was conducted for a single summer day. The shading panels were created as geometric obstruction to direct solar radiation. Consequently, the potential influence of material properties on OTC was not included in the analysis**.**

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