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Improving Climate Adaptation of Urban Spaces in Historical Contexts Through Shading Structures - A case study of integration of research and student work in Italy

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Abstract. The liveability of urban spaces is increasingly endangered by worsening climatic conditions. This is particularly alarming in hot and warm-temperate regions and in historical contexts due to the scarcity of vegetation, massive surfaces with low reflectivity materials and limited shading structures. To enhance climate adaptation in protected environments, one of the most effective strategies is to limit the impact of direct solar radiation through shading. The proposed paper documents a parametric design workflow that includes simulations and climatic morphogenesis using algorithmic software, prototyping with CNC machines based on digital fabrication technologies. This workflow is researched and experimented within a university course aimed at designing temporary and lightweight structures to enhance the thermal comfort of visitors in a historical cloister in Parma, Italy.

Keywords: Climate Change, Algorithmic Design, Digital Fabrication, Temporary Architecture, Courtyard

1 Introduction

Cultural Heritage (CH) is particularly vulnerable to extreme events related to Climate Changes (CC) (EEA, 2017) (Oke, Mills, Christen, & Voogt, 2017), extremes in temperature, strong storms, and heavy precipitation. Along with these changes, heat waves and droughts have become more frequent and severe in recent years. In addition to these changes also heat waves and drought have appeared with greater frequency and severity in recent decades.

In this context, the potential of open and transitional spaces referred intended as those spaces between outdoor and indoor environments, acting as buffer zones and physical links used in various urban civilizations), as part of CH in mitigating the impact of heatwaves, Urban Heat Island (UHI) effects, and other consequences of climate change is often overlooked (Erell, Pearlmutter, & Williamson, 2011).

In the ancient urban fabric courtyard is a widespread open space (Gherri, Maiullari, Finizza, Maretto, & Naboni, 2021). Few typological variations of the courtyard exist, so the development of a methodology of analysis and design to improve climatic adaptation can be applied to other spaces with similar characteristics.

Climatic studies of open spaces (Gherri, Maiullari, Finizza, Maretto, & Naboni, 2021) and courtyards (Diz-Mellado, et al., 2021) (Forouzandeh, 2018) (de la Flor, 2021) in historic urban texture suggest that climate change may lead to increased air temperature and relative humidity, significantly reducing users' thermal comfort. However, the use of temporary lightweight shading structures could improve the liveability of open spaces in historic centres and enhance their adaptability to climate change.

This research investigates a temporary architectural structure to enhance outdoor thermal comfort for visitors, considering ongoing climate change while revitalizing open spaces, especially courtyards and historic centres, to make them more appealing. The case study examines the Cloister of San Sepolcro, a courtyard in the Italian city of Parma. The research involves students from the University of Parma.

2 Aim

The study focuses on different shading strategies to achieving outdoor thermal comfort conditions in open spaces within historical cities. It aims to develop a workflow for climate change adaptation via design and development stages for temporary structures, to apply to existing courtyard building typologies. The research integrates simulation-based performance analysis and digital fabrication prototyping to enhance the design and development of temporary architecture within these urban spaces.

3 Methodology

The methodology is divided into the following stages:

1. Historical site selection and description
2. Outdoor comfort metrics
3. Ante-operam comfort analysis
4. Thermal comfort issues and mitigation strategies
5. Parametric and performance-based morphogenesis for tailored shading structures
6. Digital fabrication strategies

3.1 Historical site selection

The research deals with a specific open space in historic centres: the courtyard. The courtyard is a building element that can be found in many historical cities especially in hot and dry regions. It serves as an enclosed area surrounded by a building or wall and open to the sky.

To perform this study a key selected courtyard in the city of Parma (IT) is considered. Parma is a city of about 200.000 inhabitants, in the northern part of Italy and has experienced a considerable increase in the average values of the maximum summer temperatures and an increase in the duration of heat waves days (Rota, Gravante, & Zazzi, 2019). Parma, like many cities in the Mediterranean context, is a city characterised by dense and compact urban tissue, with a large variety of courtyards and semi enclosed spaces.

The case study under examination, the Cloister of San Sepolcro, is useful as a model for a wide range of other courtyards because of its dimensions and characteristics. In fact, it presents a structure that is closed on all four sides, and therefore falls into the most common category of courtyards. The portico is present on three out of the four sides of the courtyard. The courtyard ground is made of turf.

The dimensions and proportions of the building's height and base make it susceptible to the elements, making it a suitable candidate for climatic analysis. Its location within a dense urban fabric resembles the many historic courtyards found in cities with a rich architectural history.

Therefore, the case study responds to a specific method, which makes the study applicable to a wide range of urban contexts and courtyards' typology.

3.2 Geometric assessment

The courtyard of San Sepolcro is part of an ancient monastery, and it is surrounded by 4 sided porticoes and a covered walk around which the local religious community live. The courtyard's galleries are formed by an arcade of columns and the courtyard includes a well and a garden. The courtyards (the ancient monastic cloister) offers a secluded and quite space.

From a geometrical assessment of San Sepolcro, we can observe that the four-sided porticos ensure abundant shaded area along the entire perimeters of the central uncovered space and offer a great shaded potential, in contrasting the rising temperature controlling the direct solar radiation. Height H (m) and Width W (M) of courtyard space have been measured at the cornice of the inner open space. H is calculated as the most elevated point; W is calculated as the average value between the two sides of the quadrangular open area. In San Sepolcro H is 20 metres and W is 32 metres, so H/W= 0,69.

The H/W ratio is frequently associated to the Sky View Factor (SVF), which describes the sky obstruction caused by the courtyard and rises with the H.

H/W ratio is proved to be a useful parameter in evaluating the courtyard thermal performance (Martinelli & A., 2017).

Figure 1: a) Aerial view of San Sepolcro; b) the inner courtyard; c) general plan.

3.3 Outdoor comfort metrics

The UTCI (Bröde, Jendritzky, Fiala, & Havenith, 2010) predicts the perceived temperature for individuals in outdoor spaces, considering various climatic conditions and time periods. It relies on climatic and microclimatic factors such as air temperature, solar radiation, wind, humidity, as well as physiological and clothing models. There are 10 UTCI thermal stress categories that correspond to specific human physiological responses to the thermal environment: UTCI values in the range of 9 to 26 °C indicate thermal neutrality. For this study, the threshold of 26 °C UTCI is considered.

To calculate the UTCI accurately, a specific section of the parametric design workflow is developed, employing the Honeybee plugin of Ladybug Tools. This workflow integrated weather data, including solar radiation, dry bulb temperature, and relative humidity. For the analysis of outdoor enclosed spaces with minimal air movement, a consistent wind velocity of 0.5 m/s is used, as recommended. The Mean Radiant Temperature (MRT) of the surroundings and building surfaces is assumed to be equal to the air temperature, simplifying computations to avoid lengthy surface temperature simulations and view factor calculations.

In this study, the OTCA (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2013) method is also utilized to assess the comfort level of the analysed areas and evaluate the potential of different shading structure variations in providing comfort based on hourly UTCI assessments. The OTCA method quantifies the percentage of time during which a location meets specific thermal comfort criteria, with 50% considered as the threshold for considering the location comfortable. Therefore, the parametric workflow calculated the percentage of time the UTCI is below or above 26 °C at each point on the analysis grid.

The overall thermal comfort of the outdoor space is then assessed using the Spatial OTCA (sOTCA) index (Nazarian, Acero, & Norford, 2019), which considers the entire area to be comfortable if at least 50% of it met the 50% OTCA time criteria. Using the sOTCA metric and its threshold, the study assesses the thermal performance of diverse temporary shading structure variations in providing shade.

3.4 Ante-operam climatic analysis

Previous research on the cloister of San Sepolcro (Touloupaki, Gherri, & Naboni, 2023) (Naboni, et al., 2023), have shown how the introverted conformation of this courtyard building offers both climatic issues and thermal benefits.

San Sepolcro microclimatic assessment demonstrates the cloister's ability to offer a large nighttime radiative loss, mainly due to the high emissivity, that compensates for the higher amount of energy absorbed in the daytime in urban surroundings. The increase in temperature in the courtyard and under the covered-vaulted is connected to the type of materials used. In San Sepolcro the inner open area is covered by a lawn, that assures a good evapotranspiration, that just partially reduces the thermal stress inside the courtyard.

Solar gains are then stored by the materials used in the cloister (due to their heat capacity, and thermal conductivity) and the enclosed architectural configuration increases the heat flux stored in these areas.

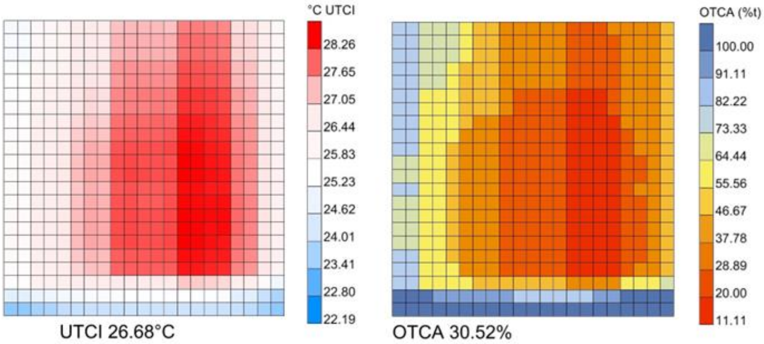

Figure 1 Ante operam UTCI and sOTCA climatic analysis performed trough Ladybug tools

The assessments are performed using an analysis grid of 2.00 m x 2.00 m in size, with the centre point of the cells at 1.50 m from the ground to consider user' body height. The assessed hours (occupied time) consider July 7th from 10 a.m. to 6 p.m., the busiest hours. The selected day describes one of the hottest days during the year, thus it represents a worst-case scenario. The

UTCI and sOTCA are calculated for every hour of the analysis period. According to the UTCI and sOTCA indexes summer period is thermally critical in many ways. The courtyard area has an average UTCI value of 26.68°C UTCI and an sOTCA value is 30.52% (figure 2).

3.5 Thermal comfort issues and mitigation strategies

Comparing the micro-climate analysis of previous research, with the results of the UTCI and sOTCA values, we report that the most critical climatic issues are high solar radiation, high temperatures and lack of horizontal ventilation in the summer period.

The proposed mitigation strategy relays on different shading structures to provide a large shade on the courtyard floor, without creating any obstructing the vertical airflow. The feasibility of such a shading structure is linked to the technical feasibility of the product, which will be created via digital fabrication techniques, and paired to the microclimatic performance.

A synthesis between the micro-climatic requirements and the actual capabilities of materials, processing machines (CNC machines) and assembly logistics is the guide for the development of the construction systems of the shading structures. Two temporary architectural structures are experimented with student contribution.

3.6 Parametric and performance-based morphogenesis for tailored shading structures

The morphogenesis of the shading structure is realized in the parametric design environment in two steps. In the first step, a parametric model is realized to generate and allow variations of form, size, and location of the temporary shading structure. In the second step, the parametric model is linked to the outdoor thermal comfort analyses to investigate the different performances in providing shade in the courtyard, thanks to different forms and positions of the shading structure.

In the study, two different types of forms are used for the structure: one composed of extruded elements (project A); the other using planar elements (project B). For both types a free-form surface is generated interpolating cross-section curves through the Loft method. The parametric model allowed to change position of the splines control points thus, to generate several variations of the structure base surface. Additionally, once generated, the parametric model allowed to change the size (scale), rotate and move the final shading structure.

For the extruded elements structure, points were generated on the base surface (the amount and distribution of which is controlled by parameters) which were used to subdivide the surface through the 3D Voronoi tessellation method. The edges of the polygonal surfaces were then joined to form three-dimensional polylines and extruded in the direction of a point on the ground representing the position of a visitor of the courtyard positioned below the structure in search of its shading effect (figure).

For the planar elements structure, the base surface is subdivided first in smaller quadrangular free-form surfaces (the amount and size of which is controlled by parameters), and then in planar triangles, two for each surface. The edge of each triangular surfaces is scaled toward the central point of the surface, and a hole is cut in the triangular planar surface (figure).

The amount of the extrusion of the three-dimensional polylines and of the scale of the edge of the triangular surfaces, thus of the size of the hole, for the two distinct types of structures, were determined according to thermal comfort parameters assessed in the ante-operam climatic analysis. The point of the analysis grid closer to each point on the base surface for the extruded element’s structure, and to the central point of the triangular surfaces for the planar elements structure, is determined and the UTCI value in the existing conditions is read. Consequently, the algorithm regulates the amount of the extrusion and scale of the elements as a function of the UTCI equivalent temperature.

The performance-based design allowed to generate shading structures with elements with larger extrusions and smaller holes where the thermal discomfort in the courtyard is higher. In conclusion, each shading structure variation achieved by manually adjusting the model's parameters is tested and assessed based on the thermal comfort thresholds, previously defined.

Among the variations fulfilling the sOTCA requirements, one is selected for each structure type on the basis of the quantity of material used (the smaller the better) and of structural and architectonic considerations.

3.7 Digital Fabrication Strategies

Digital fabrication is selected as the construction technology for the temporary shading structures. The compositional complexity derived from the parametric design method from a constructional point of view has two significant characteristics: it has a discrete compositional complexity and can generate many formal variants. The prototyping phase, in this case of the parametric design process, itself takes place with parametric methods and tools. Parametric prototyping combined with the CAD/CAM process of digital fabrication makes the realisation of design complexity accessible and easily repeatable.

The choice of construction material and CNC transformation machine influences the design itself. The laser cutting transformation technique is functional on an architectural scale. This technique imposes a modular construction system, in fact both projects tested are modular. The suitable material for a scale model is cardboard. For the full-size staircase, there are various material possibilities, cardboard, wood, aluminium, or aluminium sandwich with other synthetic materials.

The relationship between the material and its transformation process defines the anchoring system between the modules. In the case of the scaled-down laser-cut model, the connection between the modules is made by means of easily bendable tabs due to the properties of cardboard.

4 Results

Results show that outdoor thermal comfort can be guaranteed in the cloister with improvements in the range 196-295%, and 221-290% using different locations and form parameters of two selected shading structures with different morphology. Additionally, the students succeeded in designing a self-supporting structure with minimal use of material. The innovative aspect of the method lies in the integration of architectural, fabrication, and environmental considerations with performance-driven design which enhance students' learning experience.

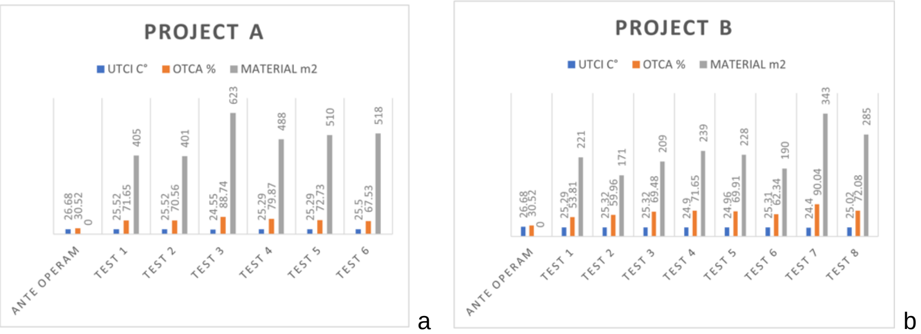

Figure 5 Data comparison of Project A and Project B phenotypes. The parameters analysed are UTCI, sOTCA and quantity of materials.

4.1 Post-operam climatic analysis

The definition of a dozen compositional variants (phenotypes) of the same parametric design (genotype) of the temporary architecture allows for a comparison of the designs. Each phenotype of the generative design genotype is defined in relation to the variation of the generated surface area, the number of modules, the extrusion of the modules (for structure A only), the width of the openings of each module (for structure B only), and the position and orientation within the courtyard area.

For each phenotypic case, a climate comfort simulation is carried out according to the UTCI and sOTCA indices (figure 4 - 5), and a measurement of the amount of material used is made. This approach helps students to understand the relationship between the form and climatic behaviour of the structure and monitors the quantity of material (figure 3). The selection of the most suitable solution results from the intersection of the numerical results.

Project A is developed in 6 phenotypes. Figure 4 shows the UTCI and sOTCA analyses of some of these variants. By comparing the data of the different variants (figure 3a), the students were able to evaluate the results and made a choice that prioritises the climatic result. In fact, the chosen solution, Test 3 (Figures 3a, 4) has the best results in terms of climatic comfort, UTCI 24.55 C° and sOTCA 88.74%, however the amount of material of 623m2 is the highest compared to the others.

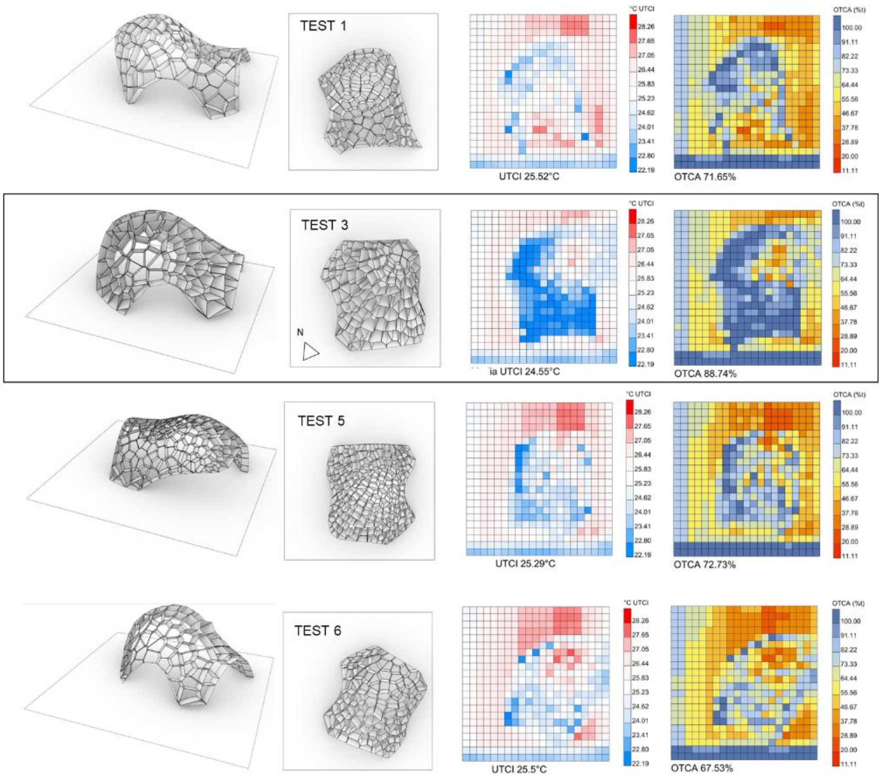

Figure 4 Project A phenotypes climatic analysis. UTCI and sOTCA metrics.

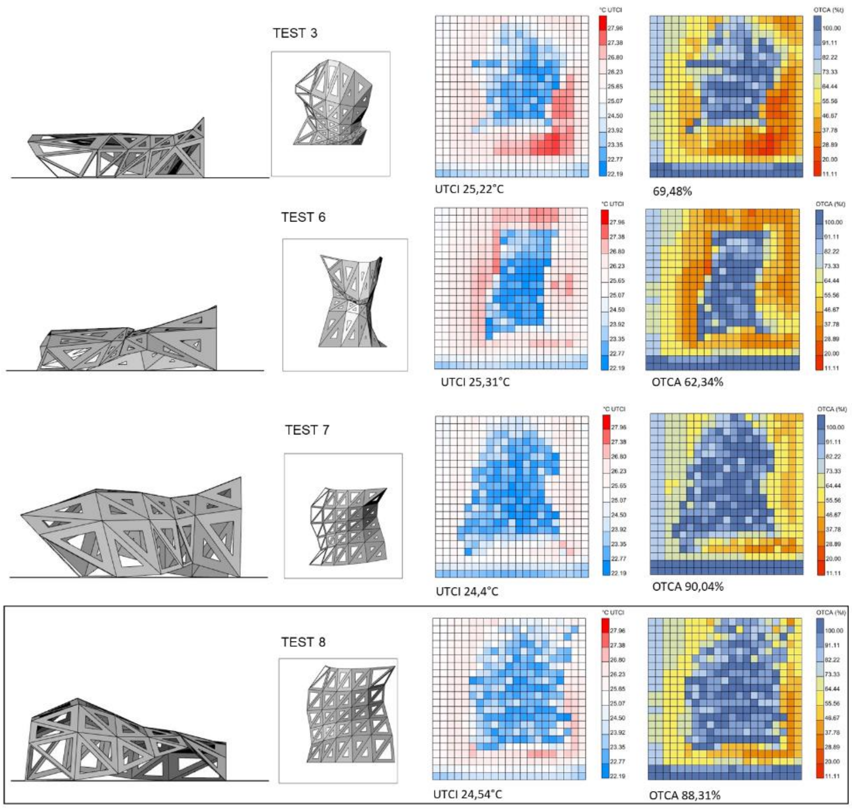

Figure 5 Project B phenotypes climatic analysis. UTCI and sOTCA metrics.

Project B is developed in 8 phenotypes. Figure 5 shows the UTCI and sOTCA analyses of some of these variants. The choice of the most suitable solution obtained by comparing the data of the different variants (Figures 3b) in this second case encourages a balance between climatic performance and minimum material quantity. The students actually choose the two climate solutions that perform the best (Tests 7 and 8), as well as the solution that requires the least amount of materials (Test 8), surrendering a tiny amount of climate comfort in favour of resource conservation.

Test 8 (Figures 3b, 5) offers 25.02 C° UTCI and 72.08 % sOTCA, slightly less performing than Test 7 data (24.4 C° UTCI and 90.04 % sOTCA), while the material required for Test 8 is 285 m^2, and 242 m^2 in Test 7.

4.2 Digital fabrication prototyping

The students produced two digitally fabricated 1:30 scale prototypes of the two designed temporary architectures. The construction material is 2mm thick cardboard. The CNC machine is the laser cutter. Parametric prototyping creates a nesting of the modules including tabs for the attachments. The CAD/CAM process is used to translate the graphic data into machine commands. Assembly is performed following the steps of bending, module assembly and part assembly. The two models are useful for studying the production process and verifying the entire design.

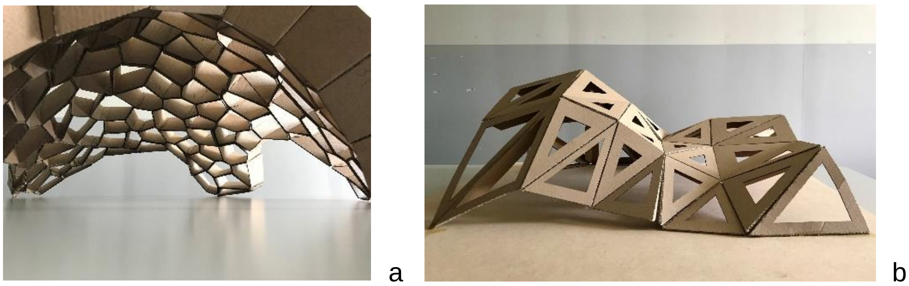

Figure 2 Project A prototype (a). Project B prototype (b)

5 Conclusion

A workflow that combines microclimatic study with algorithmic design on environmental morphogenesis and digital fabrication leads to the design development of temporary architecture with worthy thermal performance for CC adaptation. Although varying in size and H/W ratio, the courtyard typology presents peculiar characteristics, such as being closed laterally and open to the sky. Thus, the strategies adopted for our case study can also be adapted to other similar courtyards.

To perform the defined workflow, a multidisciplinary team is set up. This choice proved to be fruitful. The experimentation done in the class reveals that even students with no prior knowledge of climate analysis, algorithmic design, or digital manufacturing learnt and embraced profitably the entire workflow.

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