Optimisation of outdoor shading devices with thermal comfort criteria: The case of the Venetian Port of Chania

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Abstract. While the optimisation of building shading devices is a frequently researched topic, few studies focus on optimising the form and location of devices that shade outdoor spaces. Consequently, there is no agreed consensus on the workflow that should govern the design of outdoor shading installations with respect to microclimate and human thermal comfort. The present study addresses this research gap by developing a flexible workflow that informs the architectural design process with parametric thermal comfort simulations. The proposed workflow acknowledges that although an environmentally optimal design may exist, the designer is often forced to select a sub-optimal solution that can satisfy non-comparable design objectives including practical on-site constraints and political pressure from stakeholders with often conflicting interests. Considering that outdoor shading devices are often found at the fringe of public and private spaces, the influence of the aforementioned non-environmental objectives on the design process becomes significant. For these reasons, the proposed workflow utilises state-of-the-art techniques such as ComfortCover in order to map the ‘usefulness’ of shade over a specified area and to explore alternative forms of shading devices. Thus, shading optimisation becomes a matter of weighting alternatives and choosing appropriate solutions from the examined parametric space, rather than a fully automated process. This ‘designer-first’ approach evolved through extensive pilot-testing at the Old Venetian Port of Chania, Greece as part of a series of urban regeneration interventions coordinated by the Municipal Port Fund of Chania. This design process resulted in a typology of shading devices that offer optimal annual thermal comfort conditions while satisfying the rest of the design objectives as well.

1. Introduction
There is now an extended body of scientific literature [1–5] that documents the significance of providing shade to both buildings and outdoor spaces in hot climates. Shading is one of the most effective measures to mitigate heat stress of humans, animals and vegetation during daytime [6]. In the urban environment, shading shields surfaces, such as the urban floor, seating areas, building façades and roofs from incoming solar radiation and effectively keeps their temperatures low [2,7]. Modern cities are prone to overheating due to combined effect of global warming and the Urban Heat Island (UHI) [8]. Shading constitutes one of the most important design strategies to enhance the resilience of public urban life against climate change considering that heatwaves are responsible for the most weather-related fatalities in European cities over the past decade [9].
Shading in nature is generated by terrain features and vegetation and in settlements shade is also cast by buildings and shading devices. While there are several examples of vernacular settlements in dry-hot climates where a compact building layout maximizes shade [10,11], modern cities cannot rely on the shade cast by buildings alone to cool themselves. This is because modern city centers, being vastly different in scale, geometry and materials from vernacular settlements are susceptible to the UHI phenomenon. Although the typical urban canyon intercepts solar radiation, it also traps it in its mass and releases it after sunset in the form of longwave radiation which causes urban overheating [12]. For this reason, an efficient urban shading strategy should utilize both vegetation and shading devices where appropriate to maximize summer thermal comfort. Despite the importance of urban trees as regulators of the urban environment [2,5,13], there are cases where the use of shading devices is both more practical and advantageous. Such cases include public spaces that are too narrow to accommodate trees, outdoor food and drink locations which should be kept clean and sites with extensive soil degradation and sealing by artificial surfaces such as ports.

While the majority of the scientific literature that examines shading devices is dedicated to a significant degree to building shading [14,15], few studies focus on outdoor shading devices. For example, Yezio and Shaviv [16] developed a software tool to calculate shading efficiency of buildings, vegetation and installations in a period where environmental analysis tools for architectural design were extremely rare. The advent of more sophisticated microclimate simulation tools eventually enabled more complex environmental studies. For example, Ali-Toudert and Mayer [17] used Envimet 3.1 to conduct a parametric study of the influence of galleries, overhangs and vegetation on asymmetrical urban canyons for hot-dry climates. Hwang et al. [18] calculated minimum shading levels required for different types of streets that can be used to guide the strategic planting of trees and the construction of shading devices in Taiwan. A similar study was conducted by Andreou [11] for the vernacular settlement of Tinos in Greece, who proposed climate-responsive design guidelines for public spaces in the modern parts of the settlement. The literature review reveals that although there are a number of studies that examine shading devices in the climatic design context, little attention has been given to the shading design process itself and how it can be informed with thermal comfort data.

This paper present a ‘designer-first’ approach to informing the design of outdoor shading devices using thermal comfort and microclimatic data. It focuses on the case study of the Old Venetian Port of Chania located in northern Crete, Greece ($\phi = 35.52^\circ, \lambda = 24.02^\circ$, WGS84). Modern Chania is a coastal mid-sized city with a population of around 100,000. The city has a rich history as it has been a centre of human activities since Minoan times and has been ruled by Byzantines, Venetians, Ottomans and Egyptians to finally become part of what is today Modern Greece. The Byzantine and Venetian fortifications, the vernacular buildings of the intra-muros city and the Old Port constitute important parts of the city’s architectural heritage. The Old Port forms a large part of the city’s promenade and is a major tourist attraction and leisure destination with several small shops, taverns, cafeterias, restaurants and bars housed in preserved buildings. The port includes a number of key landmarks, such as the Egyptian lighthouse, the Ottoman Sea Mosque and the Venetian Grand Arsenal that now houses the Centre for Mediterranean Architecture.

Over the past years the Municipality of Chania has made efforts to preserve and regenerate the Old Port. One major issue that the Municipality has struggled with is the spillage of private food-related activities into public space. On one hand taverns, café-bars and restaurants contribute to the vibrancy of the Old Port and provide a source of revenue for locals. On the other, these activities tend to creep outside the limits set by the Municipality and informally occupy public space. This condition is not unique to the Chania but is a problem of Greek public space in general and is aggravated by both the competition of private interests and the collective political pressure of the shop owners on local authorities to keep a blind eye [19,20]. As a result, the historic character of the Old Port has been undermined over the past decades by a visual cacophony of signs and custom-made shading devices, including tents, umbrellas and permanent metallic and wooden installations of varying materials, colors and construction quality.
Improving this condition has been a priority of the Old Port regeneration strategy developed by the Municipal Port Fund of Chania. The foundations for the regeneration strategy were established through the ‘Layout Design of the Chania Venetian Port and Syntrivani Square’ (2000-2004) led by Kalogirou, and Romanos [21]. The study found that the total public space area occupied by food-related activities was almost three times greater than the area originally allocated to the shop owners by the Port Authorities. The study proposed the clear delineation of two distinct types of public space zones that would be conceded for private food-related activities. The first would allow permanent shading devices to be installed, while the second would only permit the deployment of temporary shading devices such as umbrellas. Additionally, the study set out general design principles for the shading devices (visual uniformity, good environmental performance, structural integrity and appropriateness to the historic setting) and proposed a minimalistic design for fixed installations. Political pressure eventually halted this effort 2013 when the Port Authorities conducted an architectural design competition to rejuvenate the project by adopting clearer design goals that satisfied concerns raised among stakeholders. In particular, archaeologists stressed the need to design shades that are historically appropriate and initially opposed the use of modern materials and minimalistic design, while the shop owners perceived the endeavor as a potential threat as it would restrict the informal exploitation of public space. The design competition also highlighted the need for environmentally responsive design that would prioritize annual thermal comfort. Eventually, this decade-long political process resulted in the second design phase which started in 2016 and its results are presented in this paper. The second design phase was conducted as a funded research project entitled ‘Development of alternative public outdoor shading design suggestions for shops in the land area of the Venetian Port of Chania and specifications for the construction of shades and other shop equipment of shops by zones’ and conducted at the School of Architecture of Aristotle University of Thessaloniki by Kalogirou, Vasileiadis and Vartholomaios [22].

2. The climate of Chania and implications on shading design

Climatic data for this study are obtained for the 1991-2010 period using METEONORM [23], which combines meteorological data collected from the airport of Chania with a validated empirical solar radiation model to generate hourly climatic data for a Typical Meteorological Year (TMY). The impact of solar radiation on thermal comfort perception can then be assessed using the Universal Thermal Comfort Index (UTCI) [24]. UTCI is chosen for its appropriateness for outdoor studies and its easily interpreted ‘feels like’ temperature scale.

Chania has a warm Mediterranean climate with hot-dry summers and mild winters. It belongs to the CsA Köppen-Geiger climate zone [25], which includes the largest parts of Greece. A more detailed climatic zoning by the Greek Building Energy Code (KEnAK) includes Chania in the warmest climate zone among the total four [26]. The climate of Chania is moderated by the Aegean Sea and the mountain range of ‘Lefká Ori’ that lies south of town (Figure 1). The transitional periods of spring and fall are thermally comfortable for large time periods of the day.

Summer is the least thermally comfortable period, with mean maximum air temperature exceeding 35.0°C during August (Figure 1). Thankfully, there is a moderate and constant northwestern sea breeze (Etisiai) that reduces heat stress during this period. Sporadically the southern wind (Livas) may introduce hot air masses and African dust to the area (Figure 1). Skies are almost always clear between April and October. As the warm period is prolonged, shading becomes essential from May till September. Solar radiation contributes significantly to thermal discomfort from 8:00 till 16:00 (Figure 1). Heat stress for an exposed person is maximized at around 15:00, where the highest air temperatures are combined with intense incoming solar radiation (Figure 1). Heat stress conditions prevail from noon till sunset even in locations under shade (Figure 1). After the sun sets, air temperature drops significantly and can reach a minimum of 19.0°C - 21.0°C before sunrise (Figure 1). The low nocturnal temperatures provide an opportunity for efficient radiative cooling of urban surfaces and natural ventilation. Mean relative humidity during summer is around 52% (Figure 1). Rainfall in Crete during summer is rare.

Winter is generally mild, as the mean air temperature during daytime ranges from 11.2°C to 13.6°C (Figure 1). January is the coldest month, where mean minimum and absolute minimum air temperatures
can reach 6°C and 2.2°C respectively (Figure 1). Increased cloud cover results in a more uniform distribution of incoming sky radiation and as a result southern, southeastern and southwestern vertical surfaces receive almost equal amounts of radiant heat. The prevailing northwestern winds may sometimes exceed 10m/s.

Figure 1: Top left: The location of Chania (red dot) in relation to the local landscape, the prevailing winds and the apparent sun trajectories during summer and winter solstices. Top right: The impact of solar radiation on thermal comfort perception on a seated and a standing person during the 15th of August. Bottom left: Mean hourly air temperature and total horizontal radiation per month. The grey band shows the range of adaptive thermal comfort according to ASHRAE 55/2010. Bottom right: UTCI for a person fully exposed to the sky versus a person under shade.

The urban climate of Chania is generally warmer than the local rural. Both the historic intra-muros city and the surrounding modern urban tissue are compact. A meteorological study during the May-October 2007 period observed a mean UHI intensity of approximately 2.6°C, which could reach an absolute maximum of 8°C towards the end of August [27]. Although this intensity is considerable, the study showed that the UHI effect greatly diminishes at the Old Port of Chania, due to the heat-moderating effect of the open sea. Since the presence of the UHI effect at the Old Port is reduced, it is not further examined in this study.

The findings from this initial climatic study can be used to formulate the following basic shading design guidelines for Chania:

i) A horizontal solid surface can efficiently intercept solar radiation during noon, when its intensity is maximized. During sunrise and sunset solar radiation intensity is significantly
lower and shading is not required as its influence on thermal comfort is minimal. During afternoon the high air temperatures coincide with a lower apparent sun position in the sky. In that case solar radiation can be effectively intercepted by sloped and protruding or vertical solid surfaces.

ii) Brighter colors should generally be preferred as they reflect solar radiation more efficiently. As the shading devices face towards the sea, the risk of generating unwanted solar glare inside nearby buildings is small.

iii) Shading devices should be able to withstand the presence of strong winds. This can be achieved through the appropriate use of materials and construction methods (e.g. avoid light cloth or extremely lightweight constructions) and by adopting a permeable design that minimizes air pressure difference below and over the shading devices.

iv) Shading devices should adapt to seasonal weather changes and thermal comfort needs. They should be easy to set-up, operate and maintain. The devices should allow the winter sun to penetrate through the use of a basic retractable mechanism.

3. Optimisation the location and general shape of shading devices

The next step is to optimize the spatial distribution and the general shape of shading devices so that the annual thermal comfort perception is maximized at the designated zones. This can be achieved by using the ComfortCover method proposed by Mackey, Roudsari and Samaras [28]. This method can be used to describe which parts of a shading surface have an overall positive, negative or neutral effect on annual thermal comfort for a given area to be shaded. It draws inspiration from previous shading optimization techniques for buildings such as the ‘cut-off dates’ method proposed by Olgyay and Olgyay [29] and the cell-based Shaderade method proposed by Sargent, Niemans and Reinhart [30].

The method estimates the relative desirability of shade by projecting hourly solar vectors from grid points over the area to be shaded which in turn intersect a shading surface that is subdivided into grid cells. The difference between the perceived hourly temperature and a thermal neutrality point is then calculated for each solar vector. This temperature can refer to UTCI but other metrics can be used as well. The thermal neutrality point is the median of the temperature range that is perceived as comfortable by most people. For example, the UTCI ‘universally’ acceptable temperature range is 9°C – 26°C and the median is 17.5°C. The calculation of this temperature difference can be used to estimate the total number of degree-days for which shade contribution to thermal comfort is harmful (mostly during winter) or positive (mostly during summer). The resulting degree-days are a measure of the positive or negative contribution of shade to thermal comfort for the entirety of the examined period and for each cell of the subdivided shading surface.

A 3D urban model of the port of Chania is developed in Rhinoceros 3D using a CAD plan provided by the Municipal Port Fund of Chania. The plan includes building height and roof type data and provides the designated zones where shading by permanent and non-permanent installations (i.e. umbrellas) is permitted. Zone depth varies between 2.5m and 10.0m for zones to be shaded by permanent installations and between 2.5m and 5.0m for umbrella-only zones. The next step is to classify these areas by orientation in order to develop a typology of shading device geometries for specific orientations. In total there are 18 designated zones for fixed shading installations, of which six are northern, five are western, three are eastern, one is southern and one is northeastern.

Horizontal shading surfaces are then drawn above these zones at a height of 3.0m, which is the median of the permitted shade height range (2.0m-4.0m). These surfaces are drawn significantly larger than their matching zones so that the analysis can show which parts of these surfaces provide the greatest shading benefit, effectively optimizing the general layout of shading devices. The study employs UTCI for a seated person as a shading optimization metric, while the thermal neutrality point is set to 21°C, following the findings from a UTCI temperature range reclassification study by Pantavou et al. [31] for the Mediterranean context. The analysis grid for the shading surfaces is set to 0.5x0.5m² which is sufficient at this point of early design and the 3D building geometries are used as shading context. The calculations are run separately for each zone using Ladybug Analysis Tools for Rhinoceros 3D [32].
The results of the analysis (Figure 2) can then be used to determine the location and the general geometry of the fixed shading devices that generate optimal conditions of annual thermal comfort. Due to the northern orientation of the port and the mild winter climate, the negative impact of unwanted shade on winter thermal comfort is limited. Therefore, their design can focus on the summer period where shade is most needed. The results show that shading devices with a southern orientation should protrude slightly towards the South. This arrangement is not required where an additional zone of umbrellas is designated. In zones with northern orientations, buildings already cast a short albeit persistent shadow. In these cases, the analysis shows that shading devices can stand freely at a small distance from the buildings instead of attaching to them. This is advantageous considering that the impact of shading installations on preserved buildings is minimized. Minimal shade protrusion or none at all is required for northern zones. Zones with western, eastern, northwestern and northeastern orientations demand additional shading which can be achieved by significantly extending the protrusion of shading devices. The alternative is to use a combination of vertical and horizontal shades or to increase the slope of shading surfaces.

Figure 2: Results of the ComfortCover calculations for the Old Port of Chania in degree-days. The darker the blue color, the more efficient the contribution of shading surfaces on annual thermal comfort in the designated seating zones below.

4. Fine-tuning the form of shading devices with a parametric thermal comfort analysis
As the introductory section has shown, shading design objectives are not limited to environmental performance but also include aesthetics, place identity, ease of construction and costs, operation and maintenance, appropriate use of materials, structural integrity and stakeholder demands. Architectural and urban design are fundamentally multi-objective synthetic processes that involves both qualitative and quantitative parameters that might not always be directly comparable. The design of outdoor shading devices for the Old Port is no exception. For this reason, the present study proposes a two-step ‘designer-first’ form optimisation approach. This approach starts with the designer initially developing a general shading device typological solution that satisfies to a reasonable degree all design objectives. At this stage the design process is guided by both intuition and the environmental data presented in the previous two sections. During the second step, this typology is fine-tuned through a parametric thermal comfort analysis that is described in more detail further below in this section. The parametric analysis allows the
exploration of design alternatives that stem from an initial design concept and results in the development of a standardized typology of architectural forms that offer optimal thermal comfort conditions.

In the case of the Old Port, the first step of the design process points towards a typology of shading devices made from a sturdy metallic structure that supports a retractable pergola-tent mechanism (Figure 3). This typology offers several advantages. The metallic frame and the use of bright-coloured sail cloth make a visual reference to ship masts and sails, highlighting the marine character of the area (Figure 3). The minimalist design achieves uniformity without creating visual monotony, since shading devices change their geometry according to local orientation and shading needs. The metallic skeleton provides the necessary structural integrity against strong winds and earthquakes and minimises the loss of visual openness towards sea and sky. The pergola-tent mechanism is easy to operate and maintain and provides a choice between sun and shade at different times of the day and at different seasons. It is also highly resistant to winds, as the sail cloth is firmly supported by the pergola (Figure 3). The shading device typology is complemented with additional lightweight structures, including separators made from wood and tempered glass, umbrellas and small fixed tents of similar aesthetics. This shading device typology allows for easy and low-cost construction and adaptation to different geometrical contexts within the port. Maintenance is relatively easy as more complex mechanisms are avoided. The design is both appropriate to the historic setting and interventions to the preserved building façades are kept to a minimum and only when necessary.

Figure 3: Photorealistic representations of the generic shading device form that was used to generate the typology of eight different shading device types for each zone orientation and depth.

Figure 4: The eight typological shading device types whose geometry was fine-tuned through the parametric thermal comfort analysis.
The second step fine-tunes the general shading device form developed during the first step of the design process (Figure 3). This fine-tuning is done through a parametric thermal comfort analysis from where eight shading device types are selected, one for each possible geometrical configuration (Figure 4). The parametric analysis seeks to answer the following question: ‘Given zone orientation and depth find the range of possible geometrical combinations of slope and depth of a planar shading surface that ensure good annual thermal comfort’. The range of acceptable solutions should respect certain geometrical limitations (shading device height between 2.0 and 4.0 m, maximum device protrusion = 2.5 m). The parametric analysis was conducted using Ladybug Tools and Grasshopper for Rhinoceros 3D. A simple 3D parametric model of the general shading device typology was set up in Grasshopper with minimum height, shading protrusion and zone orientation as variables, while maximum shading device height was held constant at 4.0 m (Figure 5). The analysis examined a total of 216 parametric combinations using the ComfortCover method. The major difference from the investigation of the previous section is that the degree-days calculated for each subdivision cell are totaled over the entire shading surface. The result of each parametric combination is then divided by the total degree-days calculated for a base case scenario of a fixed horizontal shading installation with a depth equal to that of the zone. This dimensionless ratio represents the relative shade benefit improvement of each parametric combination over the base case scenario. The results are shown in Figure 5.

Figure 5: The parametric 3D model (left) and the results of the parametric study (right) for each orientation. The darker the color the greater the improvement over the base case shading device configuration (horizontal shading surface with no protrusion). Red highlights the chosen combinations for each orientation.

The results of the parametric analysis (Figure 5) reveal the relative influence of orientation on shading device form. For example, southern zones are easily shaded by several parametric combinations that offer an improvement over the base case. For northern zones the biggest improvements are obtained by slightly increasing shading device protrusion. Eastern, northeastern and northwestern orientations generally require increased slope and protrusion, while for western orientations it is better to maximize them both. The selected parametric combinations outlined in red (Figure 5) were used to generate the eight distinct shading device types, one for each orientation (Figure 4). Although maximizing both shade protrusion and slope offers the greatest improvement over the base case in all orientations there
are some advantages to choosing different geometries. Smaller protrusions minimize material use and associated costs and do not visually dominate the urban landscape of the port. This is reflected by the general preference of a greater slope over a greater protrusion (Figure 5). Furthermore, the use of a slightly varying forms disrupts the visual monotony that would otherwise result from a single unchanging shading device geometry. In contrast to an algorithmic optimization approach, the parametric analysis provides the freedom to choose from design alternatives and also maps the influence of the examined parameters on thermal comfort improvement across the entire space of possible parametric combinations.

5. Discussion and Conclusions

Shade design for outdoor urban spaces is a little investigated subject, despite the significant influence of shade on human thermal comfort. The present study focuses on the case study of the Old Venetian Port of Chania in Crete and demonstrates a methodology for informing the process of designing fixed outdoor shading devices with thermal comfort data. The proposed methodology optimizes the environmental performance of shading devices by following a ‘designer-first’ approach that acknowledges the synthetic and complex nature of design. Although the main role of shading devices is to provide effective shade, their design is influenced by both quantifiable and non-quantifiable parameters which may not always be directly comparable. The main advantage of the presented ‘designer-first’ approach is the high adaptability to the fluidity and the associated uncertainties of the architectural design process. Instead of seeking an environmentally optimal solution algorithmically the presented method provides the necessary scientific evidence to support the decision making process at different stages. This is achieved by initially informing concept design with general climatic design guidelines and by suggesting an optimal shade layout using the ComfortCover method. The next step is to fine-tune the shading device typology that emerges from the intuitive design process and generate optimal forms for different geometrical contexts using a parametric thermal comfort study. Hence, the proposed method avoids the shortcomings of both a post-design environmental assessment approach that is usually constrained by its confirmatory nature and an algorithmic optimization approach which might lead to solutions that do not equally satisfy non-environmental objectives. The use of the ComfortCover method in the Grasshopper visual scripting environment contributed significantly to the speed and responsiveness of the proposed methodology. Although the methodology was tested in the limited context of the Old Port of Chania, the positive results indicate that it can be applied to future studies that involve outdoor shading design.

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