Urban Planning
2025 • Volume 10 • Article 10708
https://doi.org/10.17645/up.10708

ARTICLE

Open Access Journal

Microclimate Assessment and Outdoor Human Comfort Enhancement of a Historic Village in Sardinia, Italy

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Submitted: 10 May 2025 **Accepted:** 11 August 2025 **Published:** 5 November 2025

Issue: This article is part of the issue "Aligning Heritage Conservation and Climate Mitigation Through Adaptive Reuse" edited by Liam James Heaphy (University of Galway) and Philip Crowe (University College Dublin), fully open access at https://doi.org/10.17645/up.i461

Abstract

In Sardinia (Italy), more than 80% of municipalities have fewer than 5,000 inhabitants and are affected by progressive depopulation. The abandonment of traditional production systems has disrupted the synergy between the built environment and its geographic, topographic, and climatic context, accelerating the decline of these villages. Despite this, many of these settlements retain a recognisable historical urban fabric and traditional architectural features. Among them, the village of Osidda was selected as a case study. Although its urban structure remains intact, recent interventions, including the addition of new buildings, materials, and paving, have compromised its original character. These changes, combined with climate change, have increased outdoor thermal discomfort, contributing to depopulation. To address this, the research employs the urban microclimate design methodology, which integrates architectural and microclimatic analysis and design. A stratigraphic urban study and mapping of traditional buildings were conducted using QGIS, forming the basis for simulations with the ENVI-met software (first aim). A typical critical summer day was simulated, and outdoor thermal comfort was assessed using the Predicted Mean Vote index, with elderly females as the reference case (second aim). On this basis, mitigation strategies (sun sails and pergolas, with and without water sprays) were tested through dedicated simulations (third aim). Results highlight the significant role of solar radiation and confirm the effectiveness of shading interventions. The study proposes an integrated methodology to enhance outdoor thermal comfort and to support heritage conservation strategies, fostering sustainable urban reactivation and social cohesion in historical villages.

Keywords

heritage conservation; outdoor thermal comfort; small historical villages; urban landscape

1. Introduction

Sardinia's territorial structure is historically characterised by a polycentric network of small villages, closely connected to their rural surroundings. Since the mid-20th century, the decline of traditional production systems has triggered a widespread process of depopulation, with a progressive shift of inhabitants towards coastal areas and larger urban centres. Today, more than 80% of Sardinian municipalities have fewer than 5,000 residents, and many face critical demographic, economic, and environmental challenges (Puggioni & Bottazzi, 2013).

However, these historic settlements have often preserved their traditional urban fabric and architectural heritage, shaped by centuries of adaptation to local geographic, topographic, and climatic conditions. This inherited knowledge from the past offers valuable lessons for sustainable living in the face of today's energy and climate crises: Buildings and open spaces were once designed to provide comfort with minimal resources, relying solely on passive strategies and the intelligent use of local materials. However, the widespread use of industrial materials (e.g., concrete) has contributed to urban overheating (Olgyay, 2013), and the increase in building density has hindered natural ventilation (Oke, 1988). Moreover, the growing reliance on mechanical heating, ventilation, and air conditioning (HVAC) systems further intensifies these effects. The consequences of these changes are evident not only in the worsening of outdoor thermal comfort and living conditions but also in the progressive deterioration of landscape quality. This deterioration manifests in the erosion of traditional urban and architectural features, the loss of vernacular building practices, and the replacement of local materials with inappropriate contemporary ones. These transformations have progressively disrupted the delicate balance that once existed between the urban environment and the surrounding natural context and resources.

Moreover, climate projections reinforce the urgency of addressing these challenges. In a scenario where no mitigation interventions are adopted, average temperature projections for the region in the period 2071–2100, when compared to the period 1971–2000, show a marked seasonality, with temperature increases ranging from a minimum of 4 °C in the fall to a maximum of 7.5 °C in the summer (Bucchignani et al., 2016). The European Environment Agency (2012) highlights that Southern Europe is already experiencing more frequent hot days (maximum temperature > 35 °C) and tropical nights (minimum air temperature > 20 °C), and the trend is projected to intensify. Future scenarios indicate an increase in the number of combined tropical nights and hot days, along with a clear northward expansion of the affected areas (Fischer & Schär, 2010). Furthermore, both the intensity and duration of heatwaves are expected to increase (Barriopedro et al., 2011; Sterl et al., 2008).

Given this, improving thermal outdoor comfort becomes an essential strategy not only for public health but also for enhancing the attractiveness of historic villages. This article examines how enhancing environmental quality in key areas of social life can meet contemporary needs for thermal comfort, resilience, and sustainability.

To this end, the research adopts a recursive and multidisciplinary design process, the urban microclimate design (UMD) methodology (see Chiri et al., 2020). This is an integrated approach combining two complementary perspectives: the architectural one, aimed at analysing the characteristics of urban spaces and built heritage, identifying both cultural values and critical issues; and the microclimatic one, focused on understanding local microclimate dynamics and the interaction between built form and outdoor comfort. In this study, these different perspectives are integrated not only in the analytical phase but also in the development and selection of mitigation strategies.

In the UMD methodology, various design and planning strategies are employed to optimise thermal comfort, air quality, and energy efficiency at both the building and the urban scales, contributing to the creation of comfortable, efficient, sustainable, and resilient environments. Excluding those strategies specifically aimed at enhancing pollutant dispersion and energy performance, and following the classification proposed by Lai et al. (2019), UMD mitigation strategies for improving outdoor thermal comfort can be grouped into four main categories:

- Geometrical strategies, which rely on the shape, layout, and orientation of buildings or shading structures;
- Greening strategies, which exploit the thermoregulatory and shading properties of vegetation;
- Evaporative cooling strategies, which use the cooling potential of water through evaporation;
- Surface strategies, which optimise the thermal and reflective properties of ground and building materials.

Geometrical strategies primarily act by modifying ventilation and the sky view factor (which represents the amount of sky visible from a given point). In the planning phase, strategies using the urban canyon aspect ratio (e.g., Oke, 1988), the building aspect ratio (e.g., Garau et al., 2019), the street orientation (e.g., Ng, 2010), the building shape (e.g., roof shape, Ferrari et al., 2017; or courtyard shape, Ferrari & Tendas, 2024), the building height change (e.g., Nardecchia et al., 2018), the balconies (e.g., Jon et al., 2023), among others, can be effective. However, they can rarely be employed in the historic built environment, where only strategies like shading (e.g., Cortiços et al., 2024), windbreak structures (e.g., Peng et al., 2022), or wind-catchers (e.g., Zhang et al., 2024) are feasible.

Greening strategies act both passively, by modifying ventilation and shading, and actively, by reducing the surrounding air temperature through transpiration (Oke, 2002). Green roofs or pavements (e.g., Cuce et al., 2025), green walls (e.g., Zuckerman et al., 2025), pergolas (e.g., Watanabe et al., 2014), or planting trees or edges, can be used both within planning phases and as an addition to existing settlements. Even if they have a measured positive effect on people's wellness perception (e.g., Qin et al., 2013), the increase in humidity and the maintenance costs must be taken into account.

Evaporative cooling strategies take advantage of the temperature drop due to the heat subtraction when water evaporates (Manteghi et al., 2015). Typical interventions can be the introduction of artificial water bodies (e.g., Xue et al., 2015) or sprays (Ulpiani, 2019). These strategies can be effective in dry climates, where increased humidity can have positive effects.

Surface strategies typically make use of high albedo materials (often referred to as cool materials) and surfaces to reflect the direct solar radiation and reduce the heat absorption (e.g., Kumar Donthu et al., 2024). Even if cool materials are effective on single buildings (e.g., Santamouris, 2014), many studies have highlighted that they cause a decrease in the outdoor comfort due to the reflected radiation (e.g., Taleghani & Berardi, 2018; Yang et al., 2016).

Lai et al. (2019) have highlighted that the geometrical strategies are the most effective in reducing outdoor human thermal stress, followed by the greening and evaporative cooling strategies, while the surface strategies tend to worsen outdoor thermal conditions. A combination of strategies can be more effective than the use of a single one (e.g., Zhao et al., 2024).

As stated by Woolley (2003), comfortable urban outdoor spaces can highly improve the vitality of public spaces, bringing various benefits to the people in both physiological and social terms. Consequently, one of the main focuses when dealing with urban outdoor spaces should be outdoor comfort. Following Nicol and Humphreys (2002), outdoor thermal comfort can be defined as "a psychological state that expresses satisfaction with the thermal environment through subjective evaluation." However, summarising it in a single quantity is complicated, as both objective variables (such as wind speed, humidity, temperature, solar irradiation) and subjective ones (such as age, gender, activities, heat sensitivity, clothing) contribute to its definition (Yin et al., 2022). Coccolo et al. (2016) have highlighted this difficulty in their review of outdoor human comfort indices, classified into three main categories: the thermal indices, the empirical indices, and the indices based on linear equations. Among the thermal indices, the Predicted Mean Vote (PMV) is based on the energy balance of an individual. It is expressed as a vote representing the mean satisfaction (and the related thermal stress) sensed by a group of people, with zero being the vote for optimal comfort condition, positive values indicating thermal discomfort related to heat stress and negative values linked to cold stress. The PMV is standardised by ISO 7730 (International Organization for Standardization, 2005) and, unlike other indices, can be evaluated directly using measured or simulated quantities (Park et al., 2024). These quantities can be measured in situ using instruments at single points, but obtaining maps of them in the entire area of interest can be resource-consuming. For this reason, the use of software to simulate the urban microclimate is often essential.

The UMD methodology is typically applied to large, modern cities, while in the present study it is adapted and applied to the specific spatial, cultural, and regulatory constraints of small historical settlements, addressing a recognised gap in the urban thermal outdoor microclimate research field (Battisti, 2017; Cirasa, 2011; Spanedda, 2007).

Osidda, a small historical rural village in northern Sardinia (Italy), was selected as the case study (Figure 1). The village stands on the western margin of the Bitti-Buddusò granite plateau, in a broadly flat landscape, amidst oak forests and bordered by the rivers Tirso and Molò. Its territory has been inhabited since prehistory, with significant archaeological remains (Di Cecilia, 1999). The original medieval settlement of Osidda (Zirottu, 2005), characterised by grey granite low-rise houses with limited use of courtyard spaces, gradually developed along the main streets over time. In the 19th century, the existing built heritage was enriched by the new architectural typology of the palazzo, incorporating a unique decorative terrace, the *altana* (Bianco & Cuboni, 2009; Fiorino & Grillo, 2023). More recently, concrete structures and modern buildings have been added to the historical layers. Although Osidda experienced a process of depopulation since the mid-20th century, from 1900 to 1960 it maintained a stable population of between 500 and 600 inhabitants, when it functioned as a significant urban centre. By 2025, the number of residents had declined to just 217 (Italian National Institute of Statistics, 2025).

Osidda was chosen as the subject of this study for several reasons. Its spatial characteristics are representative of typical hill villages in Sardinia, particularly in the north-eastern area. Its simple urban form and building types facilitate analysis and modelling. Although under a depopulation process, the small but active remaining community signals a potential for effective reactivation actions and heritage conservation strategies. Finally, Osidda falls within climatic zone D, one of the two most prevalent climatic classifications in Sardinia (Repubblica Italiana, 1993), which makes the proposed methodology transferable to many other areas in the island.

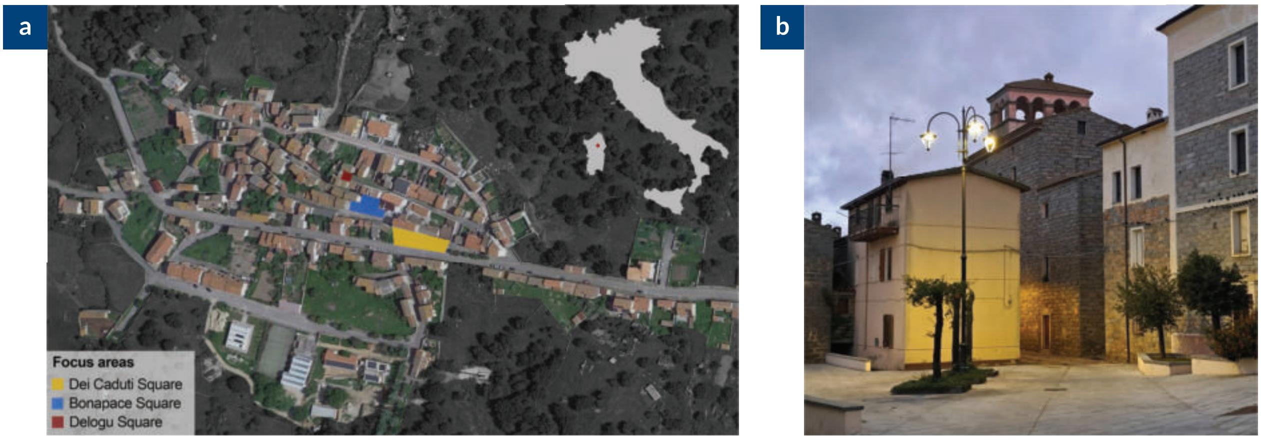


Figure 1. The case study (the village of Osidda): (a) geographical framework; (b) photo of the historical centre (Bonapace Square). Sources: (a) graphic elaboration by authors from Google Earth; (b) authors.

This article has three specific aims. The first aim involves conducting an in-depth analysis and mapping of traditional urban and architectural features. This is achieved through a combination of archival and bibliographic research, direct analysis of the settlement's characteristics, and the urban stratigraphic method. This phase aims to identify the historical and cultural significance of the traditional fabric, guiding the subsequent phases, as it identifies the key areas to focus on.

The second aim focuses on microclimatic behaviour and thermal outdoor comfort conditions in the built environment, conducted through computational fluid dynamics and microclimate simulations on a typical critical summer's day. As a consequence of the identified issues in the microclimatic analysis, a set of mitigation interventions is proposed for the focus areas identified in the first phase. These solutions are selected through the integrated approach previously mentioned.

The third aim is the assessment of the effectiveness of the chosen mitigating interventions, through quantitative comparisons among the key variables determining the thermal outdoor comfort, providing valuable feedback on the potential mitigation interventions to foster sustainable urban reactivation and heritage conservation strategies.

The article is structured as follows. Section 2 presents the methodologies and tools used to analyse the historical urban fabric, as well as those adopted for investigating the urban microclimate and outdoor thermal comfort. Section 3 focuses on the results, in particular: Section 3.1 is devoted to the outcomes of the urban and stratigraphic analysis (first aim); Section 3.2 describes the digital model for the simulations and presents the analysis of the microclimate and human comfort in the current state (second aim); in Section 3.3, the outcomes from Sections 3.1 and 3.2 are used to select appropriate mitigation interventions critically; Section 3.4 is devoted to the assessment of microclimate and comfort conditions after the implementation of the mitigation interventions (third aim). Finally, Section 4 is dedicated to conclusions and recommendations.

2. Methodology and Tools

As previously stated, in this work, the UMD methodology, developed by Chiri et al. (2020) in the context of an intervention to be built, has been adapted to the specific context of the revitalisation of an already existing historical village. This methodology can be summarised as a six-step process:

1. The current urban environment is analysed from an architectural and urban point of view, identifying both cultural values and critical issues.
2. A digital model of the built environment, featuring its meteorological characteristics, is developed.
3. The microclimatic behaviour of the current urban environment is assessed via numerical simulations to spot the related issues.
4. Mitigation interventions are selected through an interdisciplinary reflection, taking into account the constraints linked to the particular location and the historical value of the built environment.
5. Mitigation interventions are inserted into the digital model of the built environment, and their mitigative effectiveness is tested through new simulations.
6. If the results are satisfactory, the interventions transition from the preliminary design phase to the implementation phase. Otherwise, steps 4 and 5 are repeated, adapting the interventions until satisfactory results are obtained.

As this integrated methodology adopts a recursive and multidisciplinary design process combining the architectural and microclimatic perspectives, the tools used are useful from both points of view. In the following, the tools used to carry out the previously explained six-step process are presented.

The analysis of the historic village of Osidda from an architectural perspective began with the subdivision of the settlement into building units (BUs), structures sharing homogeneous typological features and functional autonomy (Fiorani, 2019). This preliminary articulation of the built fabric, based on the units previously identified in the Detailed Plan of the Historic Core (Comune di Osidda, 2015), enabled the launch of a systematic photographic campaign and direct analysis of the settlement's characteristics. The data gathering process focused on:

- The description of the historic urban space and architecture in terms of typology, volumetrics, construction techniques, materials, and use, along with observations on its current state of conservation and degree of transformation;
- The relationship between built and unbuilt spaces, considered in light of local geographic, topographic, climatic, social, and cultural conditions, as well as the functional, productive, and economic needs of the past;
- The interaction between natural and manufactured elements within the inhabited space, with particular attention to vegetation;
- The evolution of the urban space over time in response to emerging needs.

These collected data were then enriched with information from indirect sources, including:

- Historical cadastral maps from 1848, 1939, 1960, and 2014, which, through overlapping, enabled the classification of BUs into chronological phases and served as the basis for the stratigraphical analysis;
- Written reports from the 18th and 19th centuries, which provide population estimates for Osidda across the centuries and offer qualitative insights into the local climate and productive activities of the past (such as the *Fiscal Report* by de Zabarayn, 1701);
- The detailed plans for the historic centre (Comune di Osidda, 2002, 2015) are urban planning documents that include valuable information for the analysis of the historical urban fabric, such as the delimitation of the historic centre and the identification and classification of BUs;
- The Sustainable Energy Action Plan (Comune di Osidda, 2013), an urban planning document providing an overview of the municipality's energy consumption, emissions, and implemented energy retrofitting actions;
- The Sardinia Region's geoportal (https://www.sardegnageoportale.it), used to verify data through current and historical orthophotos and oblique aerial images, and to select the digital terrain model;
- Two monographs on Osidda, authored by local scholars, which focus on its history and territory (Di Cecilia, 1999; Zirottu, 2005);
- The Municipal Civil Protection Plan (Comune di Osidda, 2012) and the Regional Environmental Forestry Plan (Sardinia Autonomous Region, 2007, Attachment n.2) as the basis for the tree census within the settlement and its surrounding area;
- Historical photographs, offering visual documentation of the village between the 1930s and 1970s, which help reconstruct the past configuration of the urban fabric and its evolution;
- The knowledge of local communities, fundamental in small villages in Sardinia, where data from indirect sources is often limited, was gathered through informal conversations with residents, which, although not structured interviews, provided essential insights into the historical use of spaces, daily habits, and local environmental perceptions.

Given the quantity and heterogeneity of the data, and the need to manage them across multiple spatial and temporal scales, a structured digital database was essential. Geographic information systems (GISs) are one of the most widely used tools for territorial information management. They support, among other purposes, the handling of complex data related to cultural heritage and can be effectively employed throughout the various phases of a strategic design process (Deidda et al., 2010; Fiorino et al., 2009). QGIS was chosen for its ability to organise thematic data and to link descriptive attributes to specific elements of the urban fabric and the surrounding natural environment. Each one of the BUs was digitised as a georeferenced polygon and assigned a unique identification code. Then, the corresponding data collected was linked to it. These attributes were then used to generate thematic maps, providing a visual representation of the observed phenomena. This mapping not only supports the recognition of patterns but also stimulates the identification of both cultural values and critical issues associated with the studied heritage.

The use of QGIS also enabled the assignment of volumetric coordinates to each polygon, generating a three-dimensional model of the settlement that accurately reflects its spatial configuration. This 3D representation supported the development of a stratigraphic urban analysis aimed at tracing the settlement's evolution over time and identifying modern volumetric additions. This analysisreveals stratigraphic relationships among units, allowing for the establishment of relative and, when possible, absolute chronologies. While this analysis is widely applied at the architectural scale (e.g., Brogiolo, 1988), the use of this approach at the urban scale remains limited (Fiorino, 2010). Even if previous applications typically treated façades as individual units, in this case, in addition to works to the façades, transformations can involve rear additions that fill internal courtyards or urban voids. For this reason, the approach was innovatively applied to the chosen urban context by considering each stratigraphic unit as a three-dimensional portion of a building, defined by coherent construction techniques, materials, and formal features that correspond to a specific historical phase.

The structured digital database allowed for the identification of numerous thematic layers in terms of built environment and public space: altitude profile of the terrain and the species and height of vegetation (entire area of interest); building typology and chronology, uses, number of storeys, masonry technique, roof type, eaves detail, window and door frames, ironworks, balconies and finishes, presence of distinctive architectural elements, degrees of transformation, and overall conservation status (built heritage); paving materials, retaining walls, steps, elevation changes, sidewalks, and ramps (public space).

The data gathered through the analysis previously described have been used to build the digital model for the simulations with the microclimate software ENVI-met (Bruse & Fleer, 1998). As previously mentioned in the Introduction, the use of microclimate software is often essential to obtain the spatial distribution of thermal outdoor comfort-related variables, from which predicted mean vote (PMV) maps can subsequently be calculated. ENVI-met is one of the most frequently used software for simulating the urban outdoor microclimate in complex urban and natural domains (Fabbri & Costanzo, 2020), taking into account the main involved variables, including the daily variations of the sun position according to the chosen geographical location. For these reasons, even with the typical limitations of numerical software, ENVI-met has been widely used as a useful tool capable of returning feedback on urban interventions (e.g., Dinić Branković et al., 2025; Fu et al., 2025; Zheng et al., 2025).

Moreover, accurate meteorological input data are essential to ensure physically consistent ENVI-met simulations (e.g., Ferrari et al., 2024). In the present work, meteorological data have been extracted from the ERA5 hourly dataset from 1940 to the present (Hersbach et al., 2023). This dataset by the European Centre for Medium-Range Weather Forecasts combines modelled and observed meteorological data into a globally complete and consistent dataset, including key parameters for the simulations such as air temperature, dew point temperature, wind speed and direction, and solar radiation. It is important to note that the use of the ERA5 dataset is supported by recent validation studies in the Sardinian region based on in situ measurements by Sirigu and Montaldo (2022) and by Montaldo and Corona (2024). These meteorological data were subsequently analysed to identify a representative day to be simulated. The extracted data have been used to define the simulated “typical critical day” (see Section 3.2 for details on the selection criteria).

3. Results and Discussion

3.1. Urban Fabric and Stratigraphic Analysis

From the QGIS database, it was possible to export visual thematic maps on the analysed topics. By comparing them, it was possible to identify cultural values and critical issues of the urban fabric. Figure 2 shows the thematic map illustrating the degree of transformation of the original building fabric. The degree of transformation measures the extent of modifications each BU has undergone over the centuries, and it can be interpreted as a level of authenticity. The scale ranges from 0, indicating complete loss of authenticity (i.e., the building has been destroyed), to 5, representing full preservation, where the BU has not undergone any relevant transformation and retains its original form.

Figure 2. Visual map of the degree of transformation of the original building fabric.

By comparing this parameter with the thematic map of the conservation state (see Figure 1S, where "S" defines a figure in the Supplementary File) and the stratigraphic analysis of the built fabric (described further on; see Supplementary File, Figures 2S, 3S, and 3), it becomes evident that the buildings which are both the oldest and least altered are often in the worst condition. On the other hand, older buildings that have been significantly modified, whether for structural or functional reasons, are generally in better shape. This highlights a correlation between usability and preservation: Buildings that have been adapted over time, even through inconsistent or unplanned changes, tend to be better maintained due to their continued use and care. However, more than one-third of the traditional masonry buildings, which represent half of the total building stock, are in an advanced state of decay. The level of degradation has become so critical that public access to some parts of the historic core has been restricted for safety reasons. Nevertheless, targeted conservation efforts have played a key role in preserving several traditional structures, currently in a very good state of conservation. The most extensive among these were the LEADER I and II European initiatives of the 1990s, which, in the case of Osidda, aimed to develop a "distributed" hotel by repurposing 13 traditional buildings. Thanks to this initiative, one of the most historically preserved areas is Delogu Square (Figure 1), surrounded by historical buildings once owned by the influential Delogu family. Today, while some of these buildings have been carefully preserved, others remain in a state of ruin. Nevertheless, their condition does not jeopardise the square's historical character, which continues to express a strong sense of identity.

The LEADER European initiatives enriched the already existing offer of services. Several public services are available within the village, most of which are located in the historic core. They are primarily concentrated around Bonapace Square and Dei Caduti Square, two interconnected, wide open spaces (Figure 1). This area hosts essential services such as the town hall, the post office, a café, and the ethnographic museum. Several accommodation facilities are located near Bonapace Square and are a part of the aforementioned distributed hotel. Except for a few contemporary additions (such as the town hall, built in reinforced concrete; the prefabricated wooden structure of the café; and the modern granite paving of Bonapace Square), these spaces retain a connection with the historical nucleus. This is particularly due to the fact that most of the services are accommodated within traditional buildings.

The urban analysis led to the selection of three focus areas that serve as case studies in the subsequent phases of the research. The first is Delogu Square, a historically significant square whose identity is well preserved (as visible from Figure 2, the area is mostly characterised by 3, 4, and 5 values of the index, which refer to the most intact and authentic buildings), yet whose full potential remains unrealised due to the presence of disused and derelict buildings. Moreover, its perception as an abandoned and neglected place jeopardises its role as a social attractor. Although Bonapace Square and Dei Caduti Square, the second and third focus areas, contain most of the services offered within the village, they are not used as a gathering place in everyday life. For this reason, they can be considered potential centres for the future social life of the village.

These spaces have already been part of a conservation and enhancement strategy called INCANTO (Cherchi & Fiorino, 2023). This initiative, consistent with recent guidelines for the regeneration of small villages promoted by the Italian Government (Repubblica Italiana, 2017, 2021), adopts a "design for all" or "universal design" approach (see, for example, Ormerod & Newton, 2005), aiming to promote inclusivity and accessibility for all, fostering sustainable urban reactivation, advancing heritage conservation strategies, and supporting social cohesion.

Figure 3 presents the three-dimensional chronological reconstruction of the urban stratigraphy in the surroundings of the focus areas. The stratigraphic analysis conducted in these areas allowed for the reconstruction of the settlement's evolution over time. The urban fabric was divided into stratigraphic units, which were grouped into three main chronological phases: the first includes buildings constructed before 1939, the second comprises additions made between 1939 and 1960, and the third includes structures built after 1960. The years 1939 and 1960 were selected as reference points due to the availability of cadastral maps from those years, which provide reliable and geometrically accurate information on urban morphology. By contrast, the 1848 cadastral map was excluded from the analysis because it lacks geometric precision, making superimposition with later maps unreliable. The year 1939 was also chosen as a meaningful reference as by that time the settlement had reached a mature urban form, structurally comparable to the one still visible today.

The first chronological phase was further subdivided based on close examination of specific buildings. In particular, features such as masonry discontinuities, the use of different construction techniques, and varying degrees of material degradation across different parts of the same structure suggest that some buildings were not built in a single phase, but rather in two or more successive stages, all occurring before 1939.

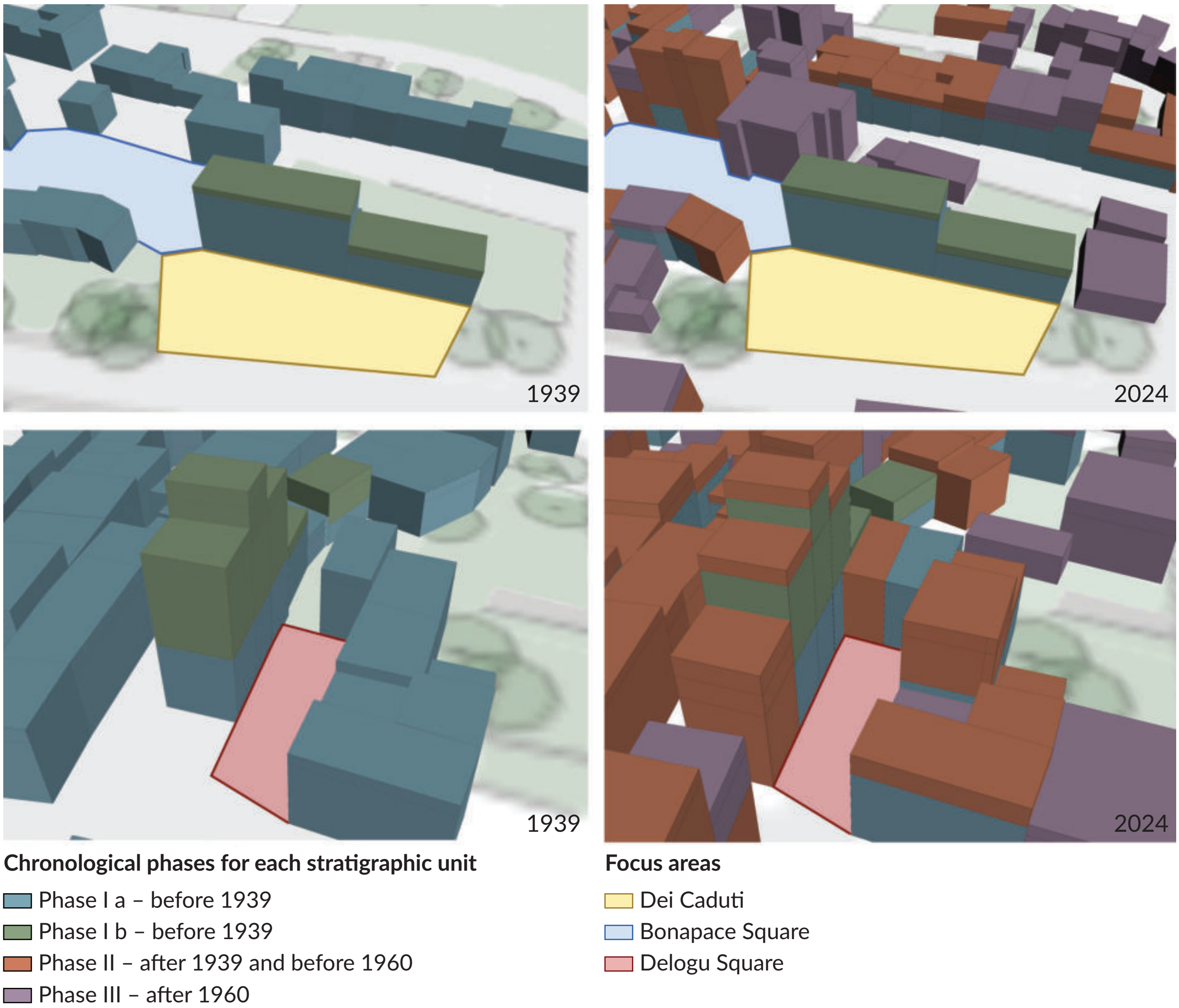


Figure 3. The three chronological phases of the stratigraphic units, from the most ancient to the most recent. The figures on the left represent the aspect of the built heritage in 1939 (comprising phases I a and I b); the figures on the right represent the present situation.

The second phase was identified through the comparison between the 1939 and 1960 cadastral maps and includes additions still based on traditional techniques, such as granite masonry or roofing systems typical of the local building culture. In contrast, the third phase consists of more recent constructions, characterised by the use of industrial materials and contemporary construction methods.

In Figure 3, the left column illustrates the state of the built environment in 1939, while the right column shows the present situation, allowing for a visual comparison between the traditional settlement and its present-day urban morphology. Although new constructions have occupied former courtyards and open spaces, and some existing buildings have been vertically extended or modified in typology (e.g., transformed from pitched to flat roofs), the original layout of the settlement has remained largely intact.

All focus areas were already present in the 1939 cadastral map. Although Dei Caduti Square was not explicitly named until the 1960 map, its boundaries are recognisable in the 1939 documentation. This continuity suggests that all the squares have preserved both their spatial configuration and their role as public gathering spaces over time. The activity conducted in this stage corresponds to the first step of the methodology described in Section 2.

3.2. Analysis of the Microclimate and Outdoor Thermal Comfort in the Present Situation

Following step two of the methodology, the data gathered through the analysis described in Section 2 have been used to build the ENVI-met digital model for the simulations.

This model measures 515 m in length, 196 m in width, and 92 m in height, which frames the historical core of the village. A cubic grid cell with a side length of 1 m was selected as the basic unit for mesh generation. A telescoping factor of 20% was applied to have only 64 cells instead of 92 cells in the vertical direction, for a total of 6,460,160 cells. The model includes the digital terrain model (Figure 4a) and was rotated 20° counter-clockwise to better align with the area of interest. After preliminary simulations, 29 additional cells were added to each lateral boundary to ensure numerical convergence.

The QGIS plugin "Geodata to ENVI-met" was used to export into ENVI-met the building heights and construction materials for each building, both for the roof and vertical walls, and the material properties of vehicular and pedestrian infrastructures, soils, and vegetation.

Regarding the meteorological input data, the choice of the particular day to be simulated was based on the analysis of ERA5 data from 1940 to the present (Hersbach et al., 2023; see Section 2). In the present study, a "critical day" is defined as any day that combines tropical nights and hot days. The analysis of the critical day trend in Osidda shows a significant upward trend, from only one critical day in 1940 to 14 in 2024. The daily temperature and humidity evolution on these 14 critical days (Figures 4b and 4c) highlights a substantial variability. It is relevant to note that these 14 days are concentrated in 33 days, meaning that, during this period, almost half of the days are critical ones.

Among the identified days, July 12, 2024 (in black in Figures 4b and 4c) was selected as the "typical critical day," as it best represents the daily trend of air temperature and relative humidity. This day is also characterised by the typical summer wind conditions in Osidda (light winds blowing from the western sector). Consequently, the day of July 12, 2024, was chosen for the simulations: The start time was 5:00, one hour before sunrise in Osidda on that day, and the simulation comprised 24 hours, ending the following day at 5:00.

A constant wind speed of 1.15 m/s and a wind direction of 271.50 °N at an altitude of 10 m, as well as the air temperature and relative humidity of July 12, 2024 were set as boundary conditions at the inflow border of the model (Figure 4).

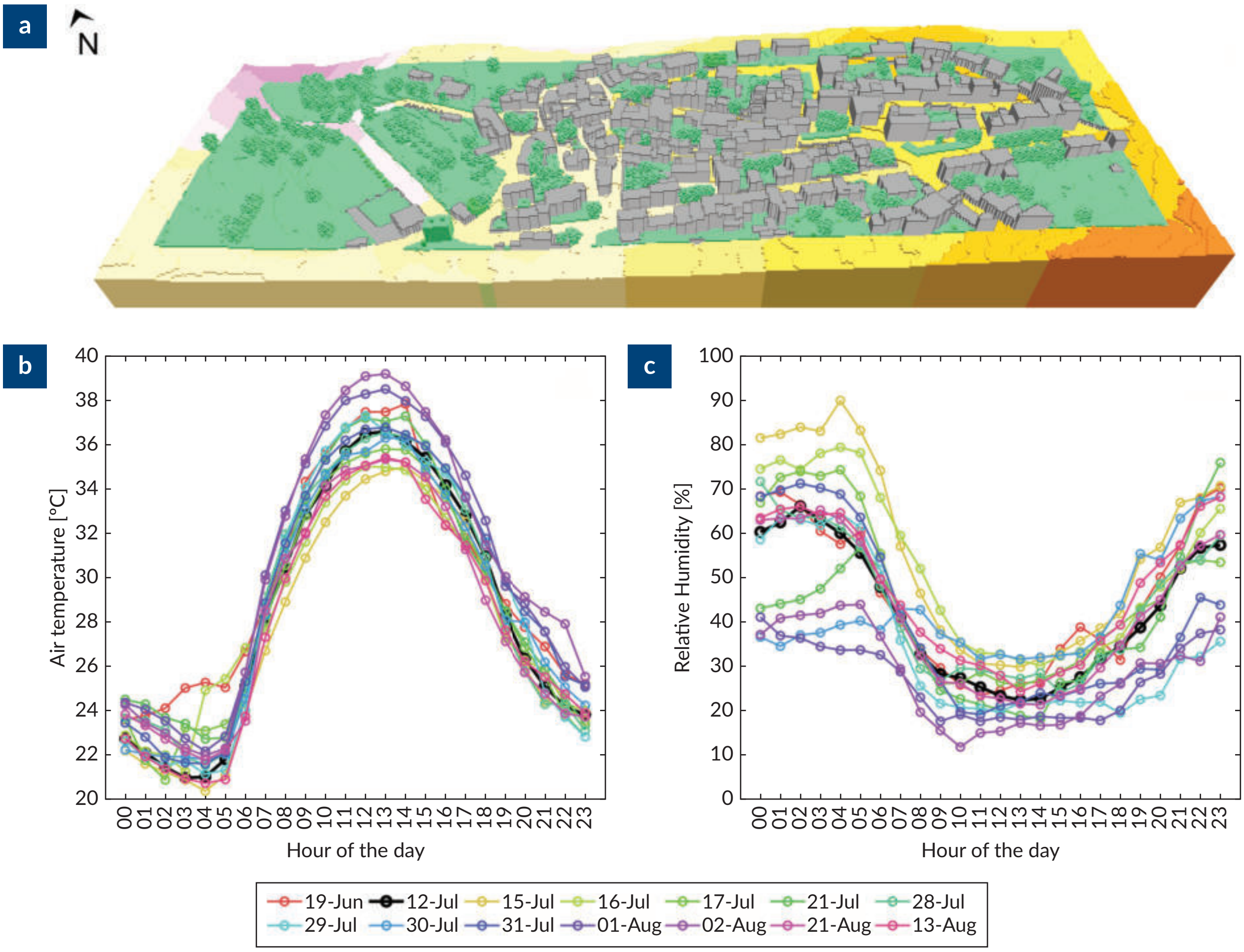


Figure 4. Model and input data: (a) three-dimensional model of Osidda (buildings are shown in grey and vegetation in green; the level of the underlying terrain topography starts from dark pink, for the lowest elevation, and then ranges, as the level increases, to light pink, light yellow, and orange, indicating the highest elevation); (b) air temperature (°C) and (c) relative humidity (%) during the critical days in Osidda in 2024 (in black the values for the simulated typical critical day).

The simulation results were post-processed using “Biomet,” a tool integrated within ENVI-met that calculates human thermal comfort indices based on the model’s atmospheric outputs. As previously stated, the PMV index was used.

The PMV calculation was tested for four categories, representing the most relevant age classes among the inhabitants of Osidda: (a) elderly female (80 years old); (b) elderly male (80 years old); (c) adult female (52 years old, the average female population age); and (d) adult male (45 years old, the average male population age). All categories shared the same body position (standing), walking speed (1.21 m/s), and summer clothing parameters. The results showed that the first category (elderly females, 80 years old) experienced the highest level of thermal discomfort, and consequently, it was selected as the reference case.

In Figure 5, the maximum hourly PMV values during the analysed day are shown. The highest PMV value is found at 14:00, and consequently, it was chosen as the reference hour (the most critical) for the following discussion.

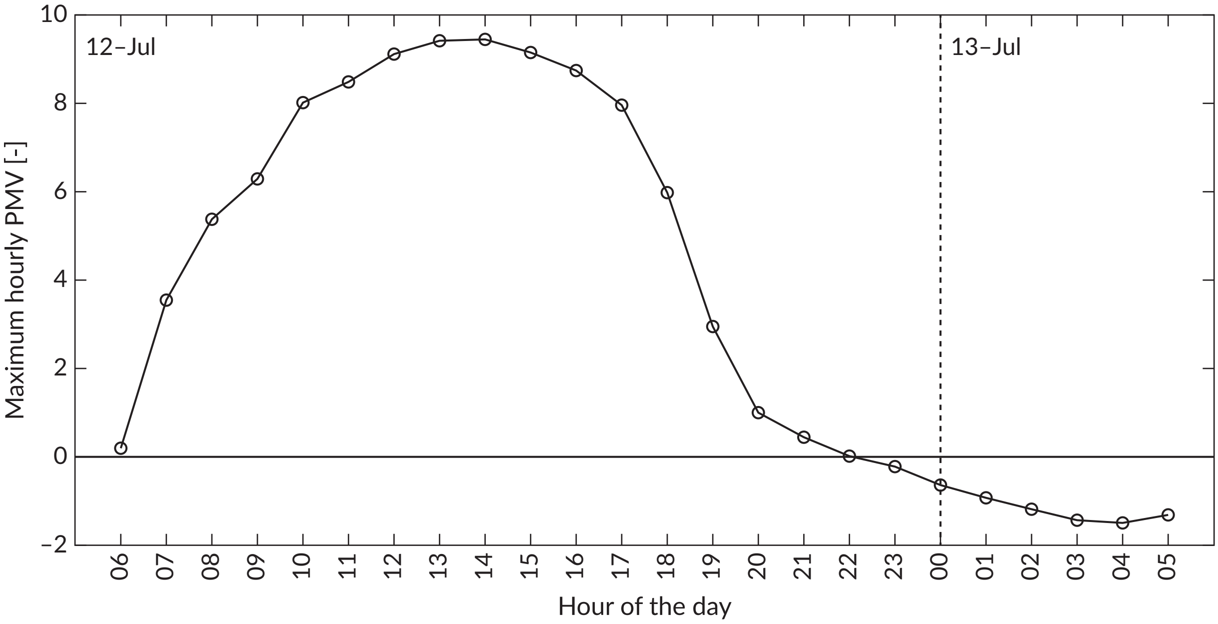
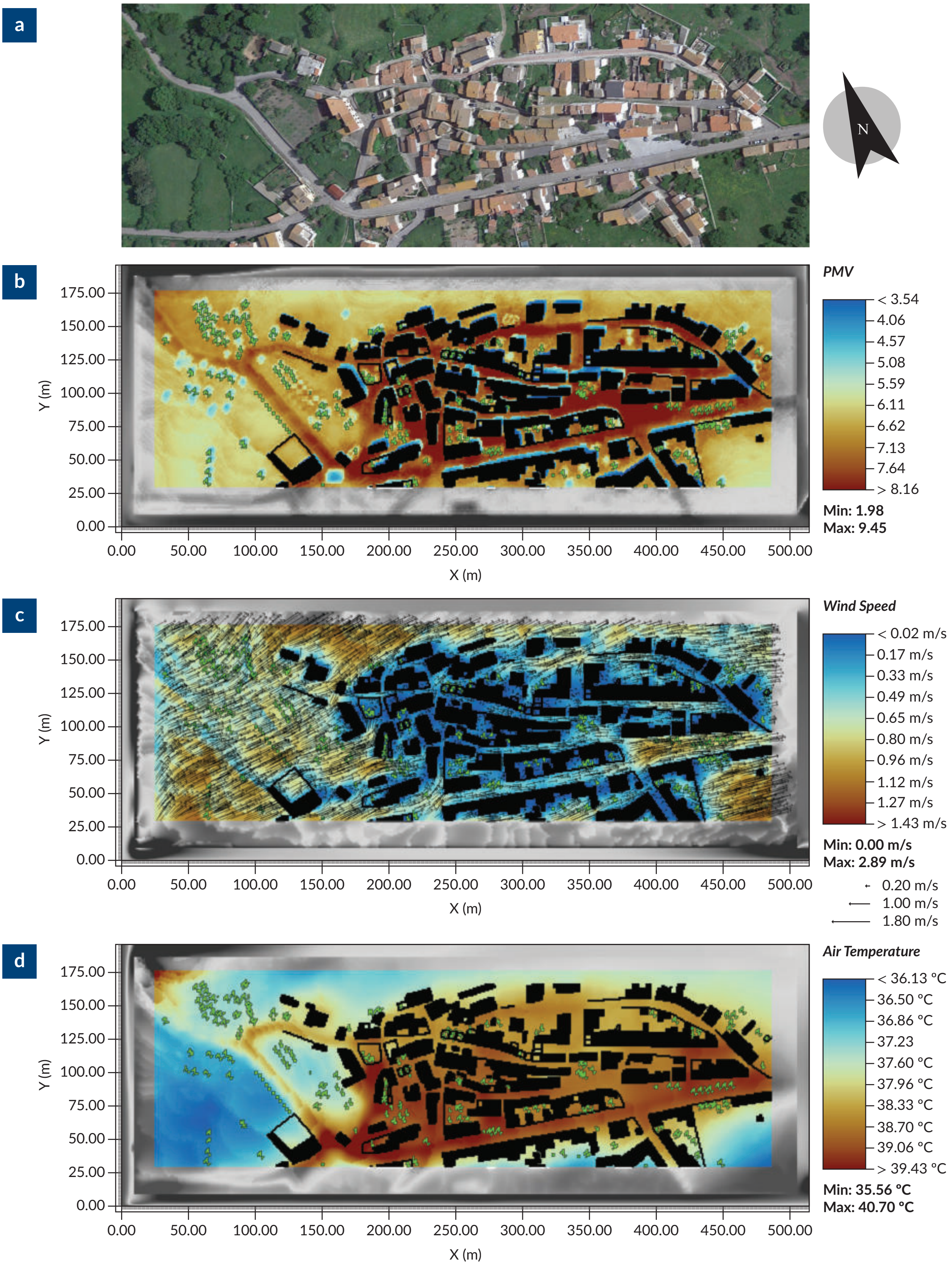


Figure 5. Maximum hourly PMV [-], at 1.5 m above ground, during the simulated day. Note: [-] means that the quantity is unitless.

In Figure 6, the analysis of the PMV and its main drivers, at 1.5 m from the ground (i.e., at pedestrian level), in the present situation is shown. In particular, in the first panel (Figure 6a), an orthophotography of the analysed area is reported. The borders of Figures 6b to 6g are in grey, being the cells added to ensure the convergence of the simulations. In Figure 6, the values of each quantity are represented in colours according to the colorbar on the right, the buildings in black, and the vegetation in green.

The PMV in the present situation is illustrated in Figure 6b. In general, as all the values are positive and significantly higher than zero, the perception of people frequenting outdoor spaces during the afternoon is one of discomfort due to the extremely hot conditions, resulting in a high degree of physiological stress caused by the heat. The highest values are recorded inside the built area, while moving away from it, the PMV values are lower, with the sole exception of the provincial access road to Osidda, visible on the left and built in asphalt. Within the built environment, the lowest values are recorded in shaded areas, due to the position of the sun at 14:00. On the other hand, the daily variation of PMV (Figure 5) shows an acceptable condition from 20:00 until 5:00 (with values in the range from −2 to +2). However, from sunrise until sunset, the PMV values always exceed +3, highlighting that the previously mentioned thermal stress condition is always present during the hours of sunshine. Thus, during daylight hours, the built environment worsens outdoor thermal comfort. In contrast, at night, it contributes to improving thermal perception throughout the village. These results suggest that the compact urban form and construction materials of Osidda provide effective protection from nighttime heat loss. This behaviour is consistent with a traditional design logic oriented toward mitigating cold conditions, which, in the past, were the prevailing climatic stressor in the Northern hilly areas of Sardinia.

In the following, the main drivers of comfort in the present situation will be analysed.


a
N
b
PMV
< 3.54
4.06
4.57
5.08
5.59
6.11
6.62
7.13
7.64
> 8.16
Min: 1.98
Max: 9.45
Y (m)
0.00
25.00
50.00
75.00
100.00
125.00
150.00
175.00
X (m)
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
c
Wind Speed
< 0.02 m/s
0.17 m/s
0.33 m/s
0.49 m/s
0.65 m/s
0.80 m/s
0.96 m/s
1.12 m/s
1.27 m/s
> 1.43 m/s
Min: 0.00 m/s
Max: 2.89 m/s
0.20 m/s
1.00 m/s
1.80 m/s
d
Air Temperature
< 36.13 °C
36.50 °C
36.86 °C
37.23
37.60 °C
37.96 °C
38.33 °C
38.70 °C
39.06 °C
> 39.43 °C
Min: 35.56 °C
Max: 40.70 °C

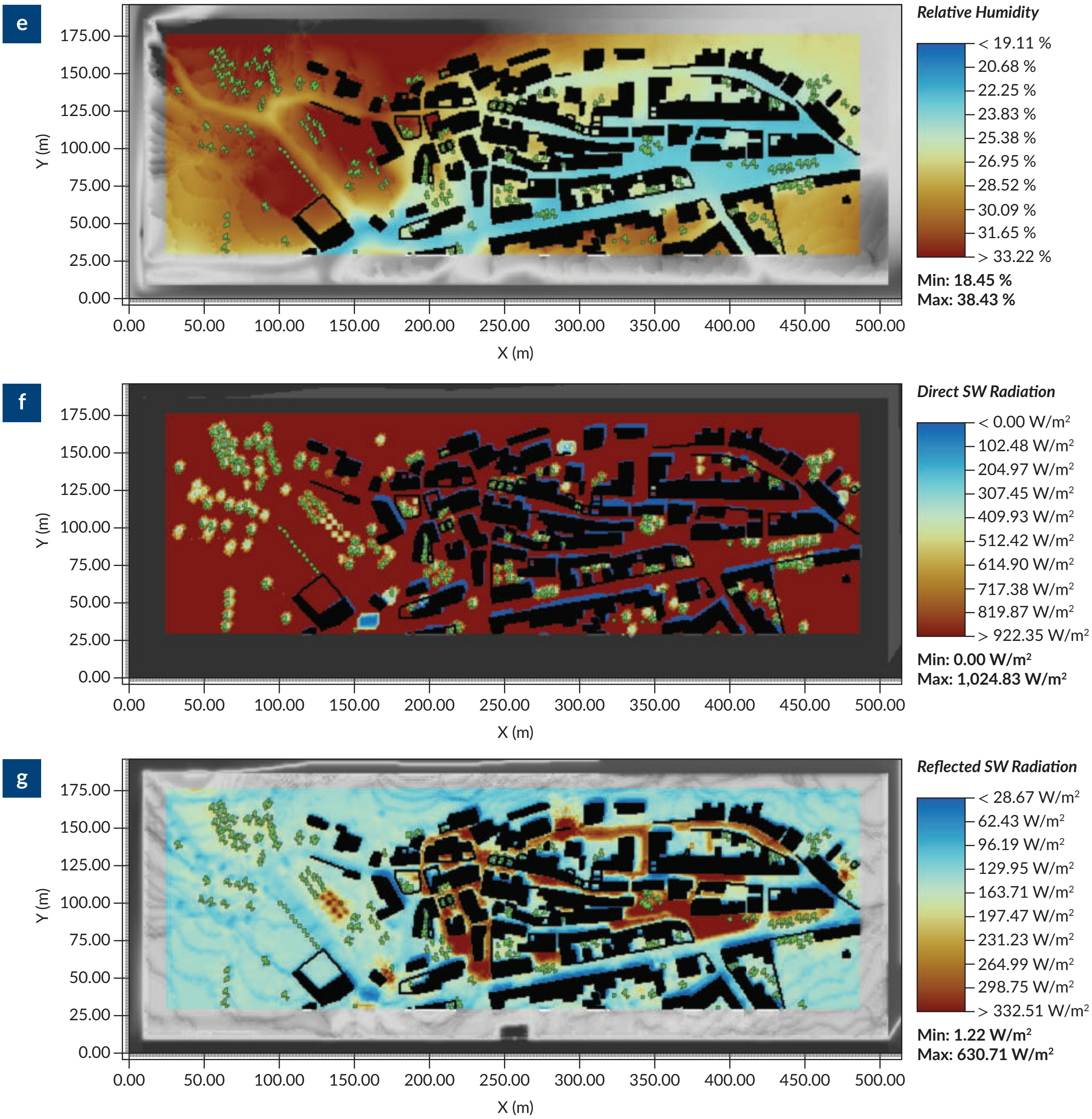


Figure 6. Microclimate analysis of the present situation at 14:00 of July 12, 2024: (a) orthophoto of the analysed area; (b) PMV [-]; (c) wind speed (m/s) and direction; (d) air temperature (°C); (e) relative humidity (%); (f) direct solar radiation (W/m^2); (g) reflected solar radiation (W/m^2). Notes: All values at 1.5 m above the ground; SW = short wave; [-] means that the quantity is unitless. Sources: (a) Google Earth; (b)–(g) authors.

The absolute value and direction of the wind speed, which drive the ventilation of the built environment, are shown in Figure 6c: The colours (together with the length of the vectors) represent the absolute value of the speed, while the orientation of the vectors highlights the direction of the wind. The critical summer days in Osidda are characterised by poor ventilation: In this case, the highest wind speed values are everywhere less than 1.5 m/s and are strongly attenuated inside the built space, highlighting its sheltering function.

Figure 6d shows the air temperature in Osidda. Even though it is a small village, an evident urban heat island phenomenon can be spotted, as the temperature inside the built environment tends to be between 2 °C and 4 °C higher than outside. To highlight that the outdoor thermal comfort is a complex phenomenon not only related to the air temperature, it is worth noting that the areas with the highest air temperature do not correspond to the areas of highest PMV (Figure 6b).

In Figure 6e, the relative humidity is presented; as previously shown, the summer critical days in Osidda feature low humidity levels during the day, with almost all the village tending to have values more than 10 percentage points lower than the surrounding area.

Figures 6f and 6g show, respectively, the direct and reflected solar radiation. Even if the values of the direct radiation are very high everywhere, as expected on a summer sunny day without clouds (except where buildings or trees provide shading), the spatial distribution of the reflected radiation is particularly interesting. The values of the reflected radiation are very high where the granite has been used to pave the squares and to cover the building façades, resulting in total radiation values (direct plus reflected) equal to or even higher than 1,360 W/m^2 (i.e., the energy transported by solar radiation to the ground at noon at the equator), with a consequent deterioration of the thermal outdoor comfort.

The analysis of the microclimate and outdoor thermal comfort in the present situation, which corresponds to the third step of the methodology described in Section 2, highlights that the most relevant factor influencing the PMV is the solar radiation.

3.3. Selection of the Mitigation Interventions

The results of the analysis of the historic urban fabric (Section 3.1) led to the selection of three focus areas: Delogu Square, Bonapace Square, and Dei Caduti Square, all of which are potential centres for the future social life of the village. According to step four of the methodology, to select the mitigation interventions in these squares, architectural and microclimatic factors, as well as the costs of installation and maintenance, were taken into account. Delogu Square, being entirely pedestrian, offered more design flexibility. In contrast, Bonapace Square and Dei Caduti Square had to remain accessible to vehicles.

The microclimate analysis (Section 3.2) revealed that, in this study case, wind is not the primary contributor to thermal discomfort. Moreover, the historical value of the built environment did not allow for deep modifications. For these reasons, most wind-oriented geometrical strategies (excluding shading, as discussed in Section 1) were considered unsuitable. Instead, direct and reflected solar radiation emerged as the most relevant driver of the PMV. Therefore, the use of shading strategies was considered the most appropriate, having the effect of reducing both types of solar radiation. Additionally, as high humidity was not a problem (Figure 6e), greening and evaporative cooling strategies were also considered suitable.

Therefore, the final choices for the mitigation interventions included a geometrical shading through sun sails (removable during the night or winter) in Delogu Square (Figures 7 and 8), and greening shading through pergolas, coupled with evaporative cooling with sprays, in Bonapace Square (Figure 7) and Dei Caduti Square (Figure 7 and 8). Deciduous plants were chosen for the pergolas, to allow winter sunlight to pass through. This choice also allowed a quantitative comparison between the mitigation capabilities of different interventions.

Following step five of the methodology, each proposed intervention was implemented and parameterised in the ENVI-met digital model. The sun sails installed above the pedestrian area in Delogu Square were modelled as a suspended building element, with assigned values (i.e., absorption, transmission, reflection, emissivity, specific heat, thermal conductivity, density) derived from experimental data reported by Zhao et al. (2024). The element was designed to extend from the nearest lane to guide the visitor towards the square. At the same time, the shape followed the perimeter of the bordering buildings, with 1 m of distance from them to avoid interactions with the historical surfaces and to allow ventilation. The result was a light impermeable structure, composed of two adjacent parts positioned at different elevations to adapt to the variation of roof heights of the buildings constituting the limits of the square.

In Bonapace Square and Dei Caduti Square, shading was implemented through green-covered pergolas in two configurations: with and without water spray systems. Moreover, to assess the impact of vegetation density on microclimate, different leaf area density (LAD) values, i.e., the one-sided leaf surface area per unit volume of canopy (m^2/m^3), were assigned to the plants covering the pergolas. The two values used (0.15 m^2/m^3 and 0.5 m^2/m^3) represented, respectively, the foliage density expected shortly after installation and after several years of growth. This enabled an evaluation of whether it is preferable to invest from the outset in more expensive but mature vegetation, rather than in younger plants.

Both pergolas had a height of 3.5 m and simple geometrical configurations (Figure 7). The one in Bonapace Square was a 30 m-long, 4 m-wide rectangle with a covered area of 120 m^2, designed to cover an area already arranged as a sitting area. The one in Dei Caduti Square was L-shaped, with a long side of 30 m, a short side of 7 m, and a width of 4 m, with a covered area of around 150 m^2. Such a configuration was thought to serve

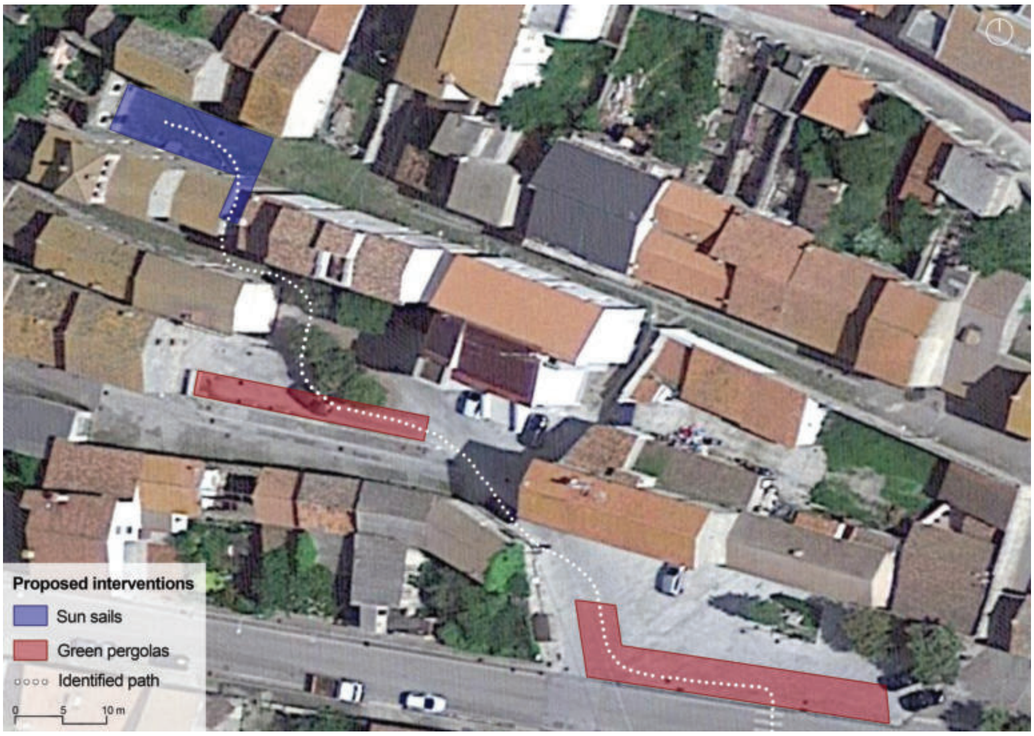


Figure 7. The positioning of the proposed interventions within the three focus areas and the identified path that they form (Dei Caduti Square, Bonapace Square, and Delogu Square). Source: graphic elaboration by authors from Google Earth.

as a separation between Garibaldi Avenue, a fast-moving road, and the square, enabling pedestrians to feel safer. Moreover, the L-shape was intendend to guide the visitors towards the historic core of the village.

The water spray system was modelled using point sources representing water nozzles, with each source positioned at 2.5 m above the ground level. This value was selected based on findings by Zhao et al. (2024), who identified 2.3 m as the optimal spray height for cooling pedestrians at 1.5 m, but it was slightly adjusted to 2.5 m to align with the model's vertical mesh resolution. The sources were arranged in linear rows, with a spacing of 1 m between adjacent sources and 2 m between the two rows. A total of 60 sources were installed beneath the pergola in Bonapace Square, while 79 were placed under the pergola in Dei Caduti Square. Each source operated at a flow rate of 2 g/s, consistent with the findings of Zhao et al. (2024), resulting in a total water demand of approximately 1 m^3/h. This raised practical concerns about resource consumption, particularly in a region like Sardinia, which frequently faces drought conditions. This consideration motivated the decision to run the simulations also without the evaporative cooling system, to weigh the comfort benefits against water consumption and to identify the most sustainable configuration (i.e., with or without evaporative cooling).

A dedicated simulation was conducted for each of the proposed configurations, all keeping the sun sails in Delogu Square, resulting in a total of four simulations, whose effectiveness in terms of comfort improvement will be discussed in the next section.

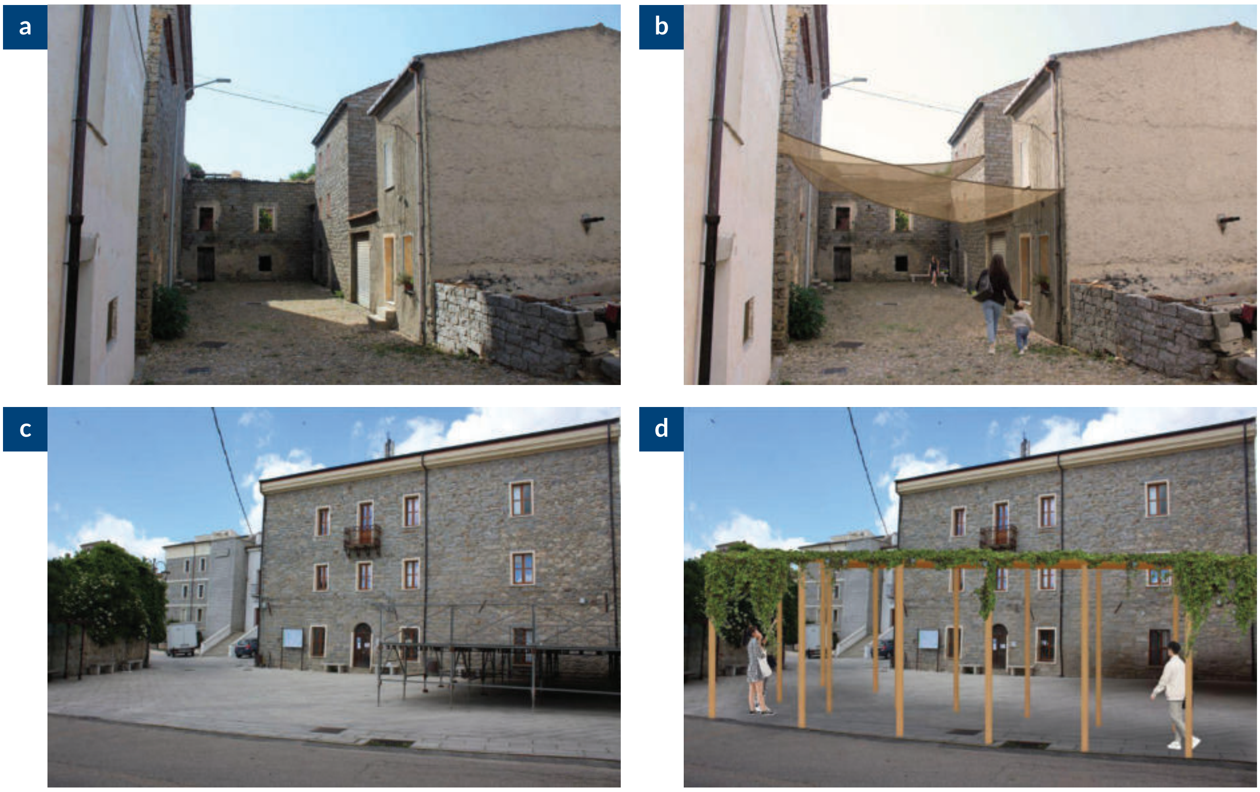


Figure 8. A visual representation of the mitigation inteventions: (a) Delogu Square before the intervention; (b) Delogu Square after the intervention; (c) Dei Caduti Square before the intervention; (d) Dei Caduti Square after the intervention.

3.4. Analysis of the Microclimate and Outdoor Thermal Comfort After the Mitigation Interventions

To evaluate the effectiveness of the selected mitigation strategies, as noted in step six of the methodology, Figure 9 (where the values of each quantity are represented in colours according to the colour bar on the right, the buildings in black, and the vegetation in green) shows the percentage difference in PMV between the current scenario and each proposed intervention. In particular:

- Figure 9a highlights the focus areas of the study.
- Figure 9b illustrates the effect of the sun sails in Delogu Square and pergolas with the low LAD in the other two squares.
- Figure 9c represents the same situation as Figure 9b, but with the high LAD.
- Figure 9d shows the sun sails and pergolas with the low LAD and water sprays.
- Figure 9e represents the sun sails and pergolas with the high LAD and water sprays.

Since the sun sails' features in Delogu Square remain constant, its outcomes are identical across all scenarios: a consistent PMV reduction of over 50%, reaching peaks of more than 60%. This confirms its high effectiveness in this context.

In Bonapace and Dei Caduti Squares, the basic pergola setup (low LAD, no sprays; Figure 9b) already achieves some thermal comfort improvements (with PMV reductions of up to 10.66% and 17.76%, respectively). Still, their effectiveness is lower than that of the sun sails. Increasing the LAD (Figure 9c) enhances performance, especially in Dei Caduti Square, where PMV reductions reach levels previously seen only at peak points.

Adding water sprays (Figure 9d) to the basic pergola setup improves both the magnitude and extent of PMV reduction, thanks to the diffusion of moisture in the surrounding air. These results confirm the benefits of combining shading and evaporative strategies, as supported, among others, by Zhao et al. (2024).

The results obtained with the pergolas with the high LAD and water sprays, which compose the most mitigative potential setup, are illustrated in Figure 9e. Compared to Figure 9d, there is a slight increase in the improved comfort area and, more notably, an expansion of the areas showing a PMV peak reduction (around 17.76%), particularly in the Bonapace Square area. Compared to Figure 9c, there is a broader mitigated area in both Bonapace Square and Dei Caduti Square, as well as a significant increase in the mitigation effectiveness in Bonapace Square.

In summary, geometrical shading using sun sails proved to be the most effective strategy in this specific urban context. Shading through vegetation was also beneficial and, as expected, more efficient when using plants with higher LADs. The addition of an evaporative cooling technique via the use of sprays leads to a higher PMV reduction in both cases. However, it raises sustainability concerns: A water consumption of approximately 1 m^3/h can be intolerable in Sardinia, due to drought problems. Consequently, the configuration with the higher LAD and without the sprays can be considered as the most suitable in this specific case.

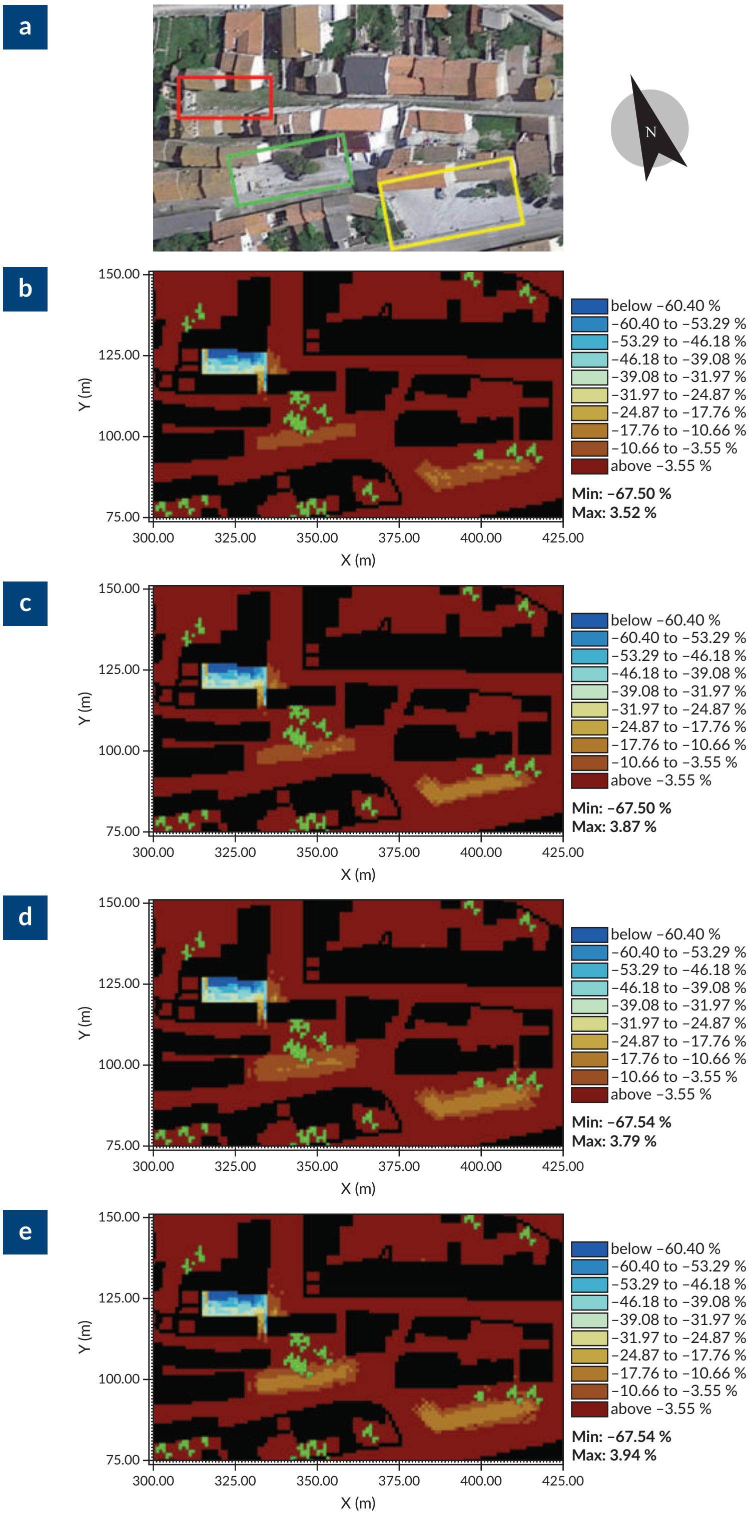


Figure 9. Microclimate analysis after the mitigation interventions at 14:00 on July 12, 2024: (a) orthophoto of the analysed areas; (b) relative difference between PMV in the present situation and after intervention of sun sails and pergolas (LAD = 0.15 m^2/m^3); (c) relative difference between PMV in the present situation and after intervention of sun sails and pergolas (LAD = 0.5 m^2/m^3); (d) relative difference between PMV in the present situation and after intervention of sun sails, pergolas (LAD = 0.15 m^2/m^3), and sprays; (e) relative difference between PMV in the present situation and after intervention of sun sails, pergolas (LAD = 0.5 m^2/m^3) and sprays. Note: All values at 1.5 m above the ground. Sources: (a) graphic elaboration by authors from Google Earth; (b)–(e) authors.

To support this conclusion, in Figure 10 (where the values of each quantity are represented in colours according to the colour bar on the right, the buildings in black, and the vegetation in green), this setup is compared with the current state, in terms of relative difference (in %) in the main PMV drivers, specifically: wind speed (Figure 10b), direct solar radiation (Figure 10c), and reflected solar radiation (Figure 10d). Wind speed (Figure 10b) is not significantly affected by the pergolas, due to their permeability. Although the sun sails have a stronger shielding effect, they still allow ventilation from above, thanks to the 1 m distance from the surrounding buildings (this explains the positive velocity peaks in Figure10b). Air temperature differences are minimal (see Figure 4Sb in the Supplementary File), with reductions up to −0.3% under pergolas and −1.1% under sun sails. Humidity changes are also modest (see Figure 4Sc in the Supplementary File), increasing up to +0.67% under pergolas and slightly above +2.5% under sun sails. The most impactful PMV driver is direct solar radiation (Figure 10c), characterised by reduction peaks of −36.7% under pergolas and −100% under sun sails, as well as reflected radiation (Figure 10d), with reductions of −35% under pergolas and −96.86% under sun sails.

To conclude, in this case study, as expected, when the mitigation strategies were selected, the dominant driver in the PMV improvement was the solar radiation reduction.

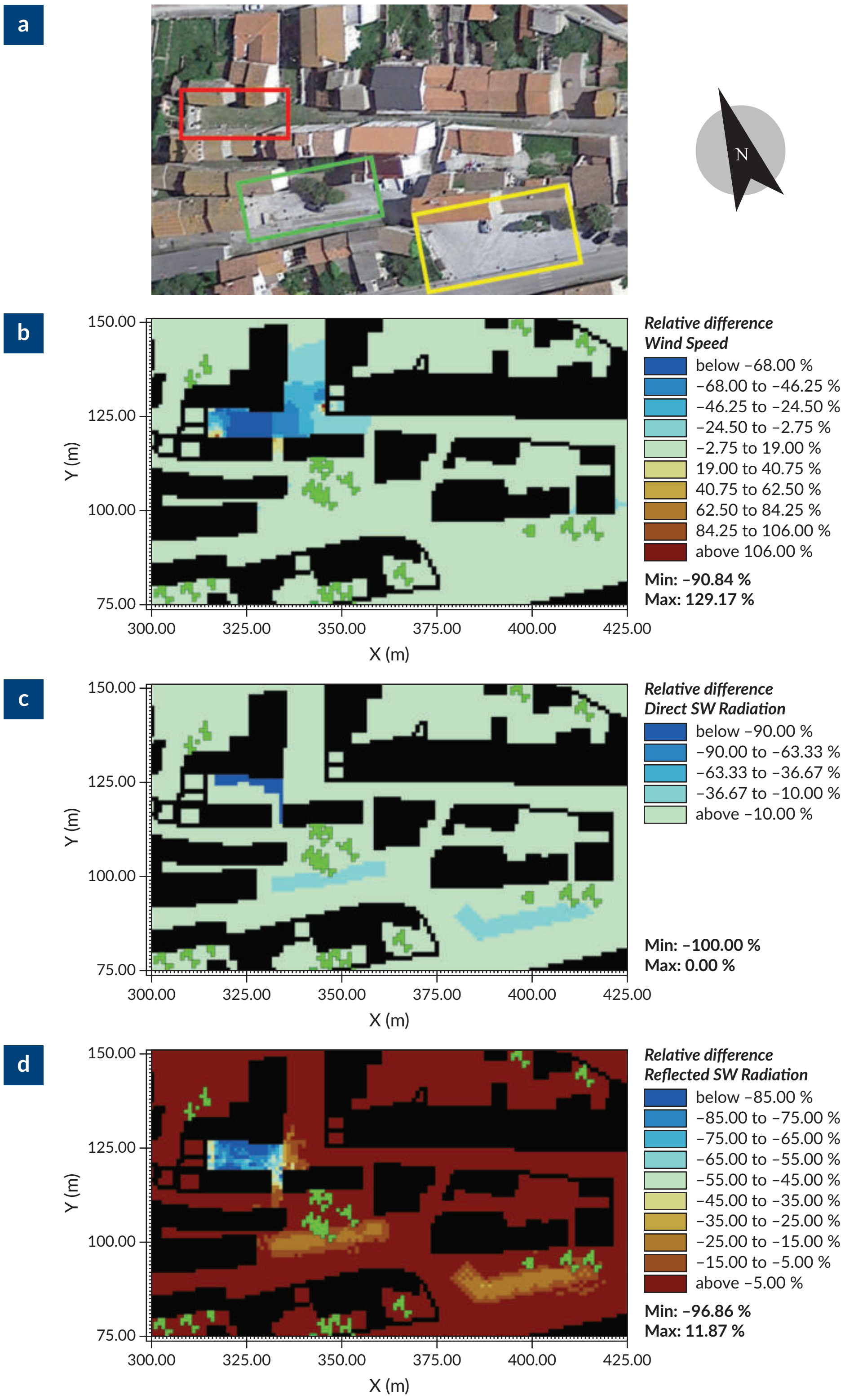


Figure 10. Microclimate analysis after the mitigation interventions (LAD = 0.5 m^2/m^3, no spray) at 14:00 of July 12, 2024: (a) orthophoto of the analysed area; (b) relative difference between the microclimate driver of wind speed before and after the intervention; (c) relative difference between the microclimate driver of direct solar radiation before and after the intervention; (d) relative difference between the microclimate driver of reflected solar radiation before and after the intervention. Note: all values at 1.5 m above the ground. Sources: (a) graphic elaboration by authors from Google Earth; (b)–(e) graphic elaboration by the authors.

4. Conclusions and Remarks

This contribution explored the application of the integrated UMD methodology to the in-depth analysis of historical urban contexts and their microclimatic dynamics, focusing on the case study of the small historical village of Osidda. Three main objectives were identified:

- The elaboration of an in-depth urban fabric and stratigraphic analysis, through the direct analysis of the settlement's characteristics (a combination of archival and bibliographic research), and the urban stratigraphic method, permitting the identification of the areas of historical and cultural significance, as well as the focus intervention areas.
- The assessment, through computational fluid dynamics and microclimate simulations, of microclimatic behaviour and thermal outdoor comfort conditions in the local built environment on a typical critical summer day; the identified issues lead to the selection of a set of mitigation interventions for the focus areas, selected through the integrated UMD methodology.
- The assessment of the effectiveness of the selected mitigating interventions, through quantitative comparisons among the key variables of thermal outdoor comfort, to evaluate the capability of the mitigation interventions to foster sustainable urban reactivation and heritage conservation strategies.

The results of the urban fabric analysis identified cultural values and critical issues. Traditional masonry buildings, which represent half of the total building stock, are generally in better condition thanks to modifications, even when using inconsistent building techniques and industrial materials, as they ensure ongoing use and maintenance. Although some abandoned historical buildings are in an advanced state of decay, often reaching structural instability, others are well preserved thanks to past interventions and now host various services. The urban fabric analysis led to the identification of three focus areas: Delogu Square, a space with a strong historical identity but still unrealised potential; and Bonapace Square and Dei Caduti Square, cores of public life and service centres. These three focus areas identify a path that, from the main street (Corso Garibaldi), invites the user to enter the historic core of the village, which is often less experienced. The creation of this path can encourage the use of urban spaces and their inclusion in integrated strategies of conservation, restoration, and reactivation. Moreover, stratigraphic analysis on the focus areas allowed the identification of three chronological phases and the tracing of the settlement's evolution over time. It revealed that, even with recent modifications, such as new structures and the raising of the existing ones, the squares maintain their traditional morphology and function as public spaces.

The analysis of the microclimate and outdoor thermal comfort in the present situation on a typical critical summer day highlights a high degree of discomfort, leading to physiological stress caused by the heat. Moreover, even though Osidda is a small village, its compact structure and building materials lead to an urban heat island phenomenon, usually more typical of larger urban settlements. This analysis revealed that, in this case, the primary contributor to thermal discomfort is the solar radiation. Therefore, shading mitigation interventions were selected as the most suitable to mitigate the high levels of thermal stress, and were designed to remain compatible with the historic built environment, with a place-based approach. Enhancing thermal outdoor comfort improves the liveability of public spaces and, consequently, could help foster social reactivation.

The effectiveness of these mitigating interventions was subsequently assessed through a comparison between the PMV thermal comfort index in the current state and that after the mitigation interventions. Results showed that sun sails are much more effective than the green-covered pergolas, although the latter also improved thermal outdoor comfort. Therefore, the geometrical shading using sun sails proved to be the most effective mitigation strategy in this specific urban context. The addition of water sprays led to further minor improvements, but sustainability concerns linked to water consumption make them not recommended in geographical areas affected by drought. While the proposed interventions have proven effective in improving thermal comfort, they should be understood as reversible solutions, designed to minimise physical impact on the historical built environment. Their temporary nature highlights the challenges in identifying long-term design strategies that are both climatically effective and culturally appropriate.

The findings of the present study have highlighted the thermal comfort behaviour of Osidda, a historical village characterised by a compact and stratified urban fabric. The features of the urban morphology significantly contribute to the current adverse thermal conditions. While these same characteristics once functioned effectively under lower historical temperature regimes, they now intensify thermal stress in the context of contemporary climate conditions.

Moreover, improving thermal comfort in specific areas of the urban fabric (seen as potential future hubs of social life) is crucial for enhancing living conditions in historical villages, fragile and marginalised contexts threatened by depopulation. Thus, this specialised yet adaptable methodology may support sustainable urban reactivation and heritage conservation strategies, contributing to the resilience and sustainability of historical settlements in the context of climate change.

Acknowledgments

The models in ENVI-met were developed with the help of Martina Ferraro, a master’s student in sustainable building design at the University of Cagliari.

Funding

This project was partially funded by the University of Cagliari, by Sapienza University of Rome, and by Politecnico di Milano through the National PhD Program “Heritage Science.”

Conflict of Interests

The authors declare no conflict of interests.

Data Availability

Data are available from the corresponding author upon request.

LLMs Disclosure

LLM tools were used for grammar and style improvement.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

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