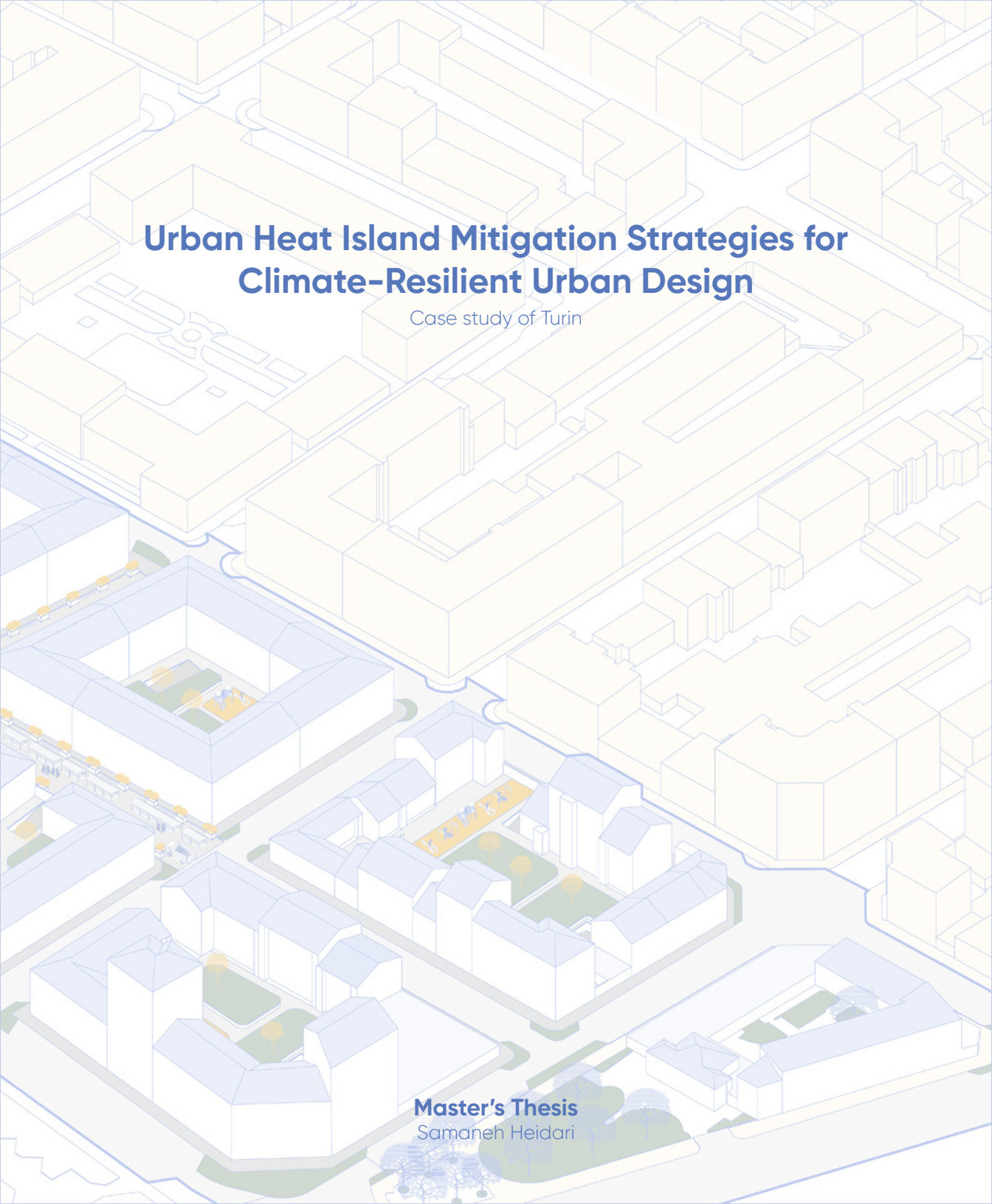
Urban Heat Island Mitigation Strategies for Climate-Resilient Urban Design

Case study of Turin



Master's Thesis

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Politecnico di Torino

Urban Heat Island Mitigation Strategies for Climate Resilient Urban Design

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Dedication

- To Iran a land of beauty, contradiction, resilience, and unfinished dreams.
- To my family, whose love has remained close even from far away, for their endless support, patience, and belief in me, even across the distance.
- To everyone I have had to leave behind, and to every place that still feels like home.
- And to myself for having the courage to leave, to begin again, and to keep going.

With hope for a future in which **Iran** can be a place of peace, dignity, freedom, and opportunity for its people.

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Preface

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0.1 Glossary

Albedo

The ability of a surface that allows it to reflect solar radiation, measured between 0 and 1, 0 being full absorption and 1 being full reflectivity) (Lopez-Cabeza et al, 2022)

Adaptation

Adjustments in natural or built environments in response to the expected or actual outcomes of climate change (Intergovernmental Panel on Climate Change, 2001).

Aspect Ratio (Urban Canyon)

The ratio between the height of buildings and the width of the street. It affects solar exposure, shading, and ventilation (Emmanuel, 2021).

Emissivity

The ability of a surface to emit absorbed heat. Materials with low emissivity retain heat,
while high-emissivity materials release it more quickly (Musikant, 2003).

Local Climate Zones (LCZ)

A classification system used to standardize the description of urban and rural landscapes based on surface cover, structure, and function. Useful in UHI studies (Stewart, 2012; Oke, 2012).

Microclimate

The set of atmospheric conditions (e.g., temperature, humidity, wind, solar radiation) in a small, specific area that can differ significantly from the surrounding regional climate, often influenced by urban form, vegetation, and surface materials. (Oke, 1987).

Mitigation

Interventions that deal with the causes of climate change, such as to reduce the emission sources (Locatelli, 2011).

Nature based Solutions (NbS)
Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN, 2016).

Psychological Equivalent Temperature (PET)
The air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Erell et al., 2011).

Thermal Comfort
The condition of mind that expresses satisfaction with the thermal environment, influenced by factors such as air temperature, humidity, radiant temperature, clothing, and activity level (ISO 7730:2005).

Urban Morphology
The study of urban form that examines the formation and transformation of cities, towns and villages (Chen, 2014).

Urban Heat Island (UHI)
An urban or metropolitan area where the temperature is significantly higher compared to that of its surroundings, commonly associated with intense human activities (Taha, 2004).

0.2 Abstract

Urban areas are increasingly affected by rising temperatures and more frequent heat events, making the improvement of outdoor environmental conditions an important challenge for contemporary urban design. At the same time, many existing urban districts contain underused or poorly organised spaces that could provide opportunities for environmental and social improvement without requiring major changes to the established urban fabric. This research investigates how existing spatial resources can be reconfigured to address both urban regeneration and climate-related challenges.

The research focuses on the Barrier di Milano district of Turin, Italy, where the existing urban fabric is characterised by dense blocks, mixed uses, internal courtyards, scattered garages, and service spaces, with extensive impervious surfaces and limited areas of continuous vegetation. Within this context, the thesis explores the potential of transforming underused internal spaces within existing urban blocks into green and multifunctional public spaces while preserving the existing urban morphology. The research is structured around three interconnected objectives: improving the spatial efficiency of existing urban blocks through the reorganisation of scattered garages; transforming the released internal spaces into green and multifunctional areas that enhance environmental and social quality; and evaluating the extent to which these strategies can improve local microclimatic conditions and outdoor thermal comfort.

The methodology combines urban and morphological analysis, climate-responsive design strategies, and ENVI-met simulation. The initial analysis examines the existing building fabric, internal block spaces, circulation, garages and service structures, vegetation, surface materials, street geometry, and climate vulnerability of the study area. Relevant precedent studies are used to identify transferable strategies involving vegetation, shading, surface materials, permeability, and spatial reorganisation. The identified needs and the suggested design strategies have also been carried out considering the existing public and semi-public spaces, including the open market. Based on these findings, a design intervention is

developed that reorganises scattered garages and recovers internal space for new green and multifunctional uses while maintaining the existing urban morphology.

The environmental performance of the existing and proposed conditions is evaluated using ENVI-met, focusing on potential air temperature, surface temperature, and outdoor thermal comfort through the Physiological Equivalent Temperature (PET) indicator. The simulations demonstrate spatial variations in thermal conditions associated with urban morphology, surface materials, vegetation, solar exposure, and shading. The comparison between the existing and proposed conditions indicates localized improvements in the most thermally affected areas, with reductions of up to 16.38 K in PET, 15.45 K in surface temperature, and 3.18 K in potential air temperature at selected locations and times. These results indicate that the proposed combination of vegetation, shading, and climate-responsive surface materials can improve local thermal conditions, particularly within the redesigned internal block spaces, although the improvements are not uniform across the entire study area.

The findings demonstrate that the regeneration of underused internal public spaces can provide an opportunity to address spatial inefficiency, improve environmental and social quality, and enhance outdoor thermal comfort. Rather than replacing or substantially modifying the existing urban morphology, the proposed approach works within the existing structure by reorganising fragmented functions and reallocating recovered space toward greener, more multifunctional, and climate-responsive public and semi-public spaces. The research highlights the potential of combining spatial reorganisation, green infrastructure, thermally responsive materials, and shading as an integrated strategy for improving the environmental performance and resilience of existing urban neighbourhoods.

Keywords: Urban regeneration; underused urban spaces; urban morphology; green public space; multifunctional public space; public and semi-public spaces; Heat Island; microclimate; thermal comfort; ENVI-met; PET; Turin; Barrier di Milano district.

0.3 Introduction

Cities are increasingly exposed to the environmental consequences of climate change, with rising temperatures and more frequent heat events creating significant challenges for urban health, comfort, and resilience (IPCC, 2022). The effects of extreme heat are not distributed uniformly within cities. Urban form, land cover, building density, surface materials, vegetation, solar exposure, and air movement can create substantial differences in thermal conditions between streets, open spaces, and neighbourhoods (Oke et al., 2017; Perini & Magliocco, 2014). Consequently, understanding climate change at the urban scale requires attention not only to regional climatic trends but also to the microclimatic conditions experienced by people within specific urban environments (Perini & Magliocco, 2014).

The Urban Heat Island (UHI) effect represents one of the most important manifestations of this relationship between climate and urban form. The replacement of natural surfaces with buildings, asphalt, concrete, and other impervious materials alters the surface energy balance and contributes to heat storage and reradiation (Oke et al., 2017; IPCC, 2021). At the same time, dense urban morphology can modify solar exposure and ventilation, while insufficient vegetation reduces opportunities for shading and evapotranspirative cooling (Perini & Magliocco, 2014; IPCC, 2021). These processes interact differently according to the geometry and characteristics of individual urban spaces, meaning that their thermal performance cannot be adequately described through a single average temperature or a city wide assessment (Perini & Magliocco, 2014; Puche et al., 2023).

The consequences of urban overheating extend beyond environmental performance. Outdoor thermal conditions directly influence the usability and perceived quality of public space and can affect human health and well-being, particularly during periods of extreme heat (Ahmed et al.,

2024; IPCC, 2022). This makes urban heat mitigation relevant to the broader objectives of sustainable development. The present research therefore relates its investigation to Sustainable Development Goal 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), linking the environmental performance of urban spaces with questions of health, resilience, and climate adaptation (United Nations, 2015; Ahmed et al., 2024).

Within this broader context, urban microclimate provides an important scale of analysis. Microclimatic conditions are shaped by the interaction between atmospheric variables and the physical characteristics of the built environment. Building height and spacing, street orientation, aspect ratio, surface properties, vegetation, shading, and openness can influence air temperature, radiation, wind, and humidity (Oke et al., 2017; Ali-Toudert & Mayer, 2006). The concept of Local Climate Zones (LCZs) provides an additional framework for understanding how recurring combinations of urban morphology and land cover characteristics influence thermal behaviour (Stewart & Oke, 2012).

Climate responsive urban design consequently requires more than the application of individual technologies. The literature and precedent studies examined in this thesis demonstrate that vegetation, cool materials, shading structures, permeability, and modifications to public space configuration can influence different components of the thermal environment. However, their effectiveness depends on the spatial and climatic context in which they are introduced (Klemm et al., 2019; Zölch et al., 2016; Di Napoli et al., 2021). The four precedent cases examined in Barcelona, Rome, Teramo, and Valencia demonstrate this principle through different combinations of surface modification, vegetation, shading, urban space reconfiguration, and environmental simulation (Ambrosini et al., 2014; Ahmed et al., 2024; Sola-Caraballo et al., 2024). Together, they establish a methodological basis for comparing existing and proposed conditions using measurable microclimatic indicators.

This research applies these principles to Turin, a dense urban centre located within the Po Valley and influenced by its regional climatic and topographical conditions. Turin's urban environment contains areas where dense built form, extensive impervious surfaces, limited vegetation, and restricted ventilation contribute to increased vulnerability to urban heat (Garzena et al., 2018; Oke et al., 2017). The spatial distribution of UHI risk is also associated with social and demographic characteristics, demonstrating that heat risk is not solely a physical environmental phenomenon but a socio spatial issue (IPCC, 2022).

The research therefore focuses on a defined area within the Barriera di Milano district of Turin, examining the relationship between urban morphology, surface materials, vegetation, street geometry, solar exposure, and pedestrian level thermal conditions (Oke et al., 2017; Stewart & Oke, 2012). The analysis does not seek to replace the existing urban structure. Instead, it explores how targeted climate responsive interventions can improve the environmental performance of an existing urban setting while maintaining its morphology and functional characteristics. This is particularly important for active public spaces and market environments, where spatial flexibility and everyday use impose practical constraints on the introduction of permanent interventions (Di Napoli et al., 2021; Klemm et al., 2019).

The study adopts a sequential methodology. First, a scientific and theoretical framework is established through literature concerning UHI, microclimate, thermal comfort, adaptation and mitigation, and analytical and simulation tools. Second, relevant built and research based precedents are examined to identify transferable climate responsive strategies. Third, the study area is analysed through urban and morphological mapping, including building characteristics, street geometry, land use, surface conditions, vegetation, and UHI vulnerability. Finally, an existing condition model is developed and evaluated using ENVI-met, followed by the development and simulation of a proposed intervention scenario for the public open market spaces and underused internal areas of the urban blocks.

The proposed intervention considers spatial reorganisation, vegetation, surface materials, and pedestrian conditions while maintaining the existing building fabric and urban morphology. Its effects are evaluated through air temperature, surface temperature, wind speed, and Physiological Equivalent Temperature (PET). These indicators allow the microclimatic response of the intervention and its implications for pedestrian thermal comfort to be assessed (Bruse & Fleer, 1998; Erell et al., 2011).

The central premise of the thesis is therefore that the transformation of underused internal urban spaces can simultaneously address spatial inefficiency, environmental degradation, and urban heat vulnerability (UN-Habitat, 2023; IPCC, 2022). Rather than modifying the established morphology of the urban block, the research proposes to work within its existing structure by reorganising fragmented functions and reallocating recovered space toward green, multifunctional, and climate responsive public and semi-public spaces. In this way, spatial regeneration and environmental performance are considered as interconnected objectives, with the effectiveness of the proposed transformation evaluated through its potential contribution to outdoor thermal comfort and local microclimatic improvement (Erell et al., 2011; Bowler et al., 2010).

0.4 Research Questions

The research investigates how existing urban blocks in the Barrier di Milano district of Turin can be adapted to improve their spatial, environmental, and social performance without altering the fundamental morphology of the existing urban fabric. Particular attention is given to the underused internal spaces of urban blocks, where scattered garages and warehouse structures occupy valuable ground that could potentially support more diverse environmental and public functions. The study therefore explores the possibility of reorganising these existing functions in order to release internal block areas and transform them into greener and more multifunctional spaces.

This approach considers urban regeneration not as a process of replacing the existing fabric, but as a process of reorganising and reprogramming existing spatial resources. The proposed transformation combines spatial reorganisation with green infrastructure, permeable and thermally responsive surfaces, vegetation, and opportunities for social use. Such interventions are considered in relation to the existing morphology, accessibility, circulation, and functional requirements of the urban block. This is particularly relevant to climate responsive design because urban morphology, surface materials, vegetation, shading, and the configuration of open spaces influence pedestrian-level microclimatic conditions and outdoor thermal comfort.

Accordingly, the research is structured around one main research question and three complementary sub research questions:

Main Research Question

How can underused internal spaces within existing urban

blocks be transformed into green and multifunctional public and semi-public spaces while preserving the existing urban morphology?

Sub-Research Questions

1.How can the reorganisation of scattered garages improve the spatial efficiency of existing urban blocks?

2.How can the released internal spaces be transformed into green and multifunctional spaces that improve environmental and social quality?

3.To what extent can these spatial transformations, through changes in vegetation and surface materials, improve the microclimatic conditions and outdoor thermal comfort of the existing urban block?

The research questions establish a direct relationship between spatial reorganisation, environmental design, and microclimatic performance. The first question addresses the spatial and functional problem of scattered garages and underused internal areas. The second shifts from spatial efficiency to the architectural and landscape transformation of the released spaces, considering greenery, multifunctionality, and public space quality. The third evaluates the environmental consequences of these transformations through microclimatic simulation, particularly in relation to potential air temperature, surface temperature, and outdoor thermal comfort. The use of ENVI-met provides a comparative framework for evaluating the existing and proposed conditions and for assessing whether the spatial transformation can produce measurable environmental improvements.

0.5 Methodology

This research adopts a multi-scale and comparative methodology to investigate how underused internal spaces within existing urban blocks can be transformed into green and multifunctional public spaces while preserving the existing urban morphology. The research begins with the collection of spatial data from the Municipal Technical Map, Geoportal of Turin, and Google Maps. These data are used to analyse the urban context in terms of land use, activity distribution, circulation networks, vegetation, public spaces, and urban services.

Based on this analysis, a representative urban block characterised by underused internal spaces, scattered garages, and limited vegetation is selected as the case study. A design intervention is then developed by reorganising these spaces and transforming the released areas into green and multifunctional spaces while maintaining the existing urban structure.

The environmental performance of the existing and proposed scenarios is evaluated using ENVI-met. The analysis focuses on Potential Air Temperature, Surface Temperature, Wind Speed, and Physiological Equivalent Temperature (PET). The results are compared to assess the influence of urban morphology, orientation, surface materials, and vegetation on local microclimatic conditions and outdoor thermal comfort.

Finally, the results are synthesised to identify the most effective spatial and environmental strategies, addressing the research question of how underused internal urban spaces can be transformed to improve both spatial efficiency and environmental quality.

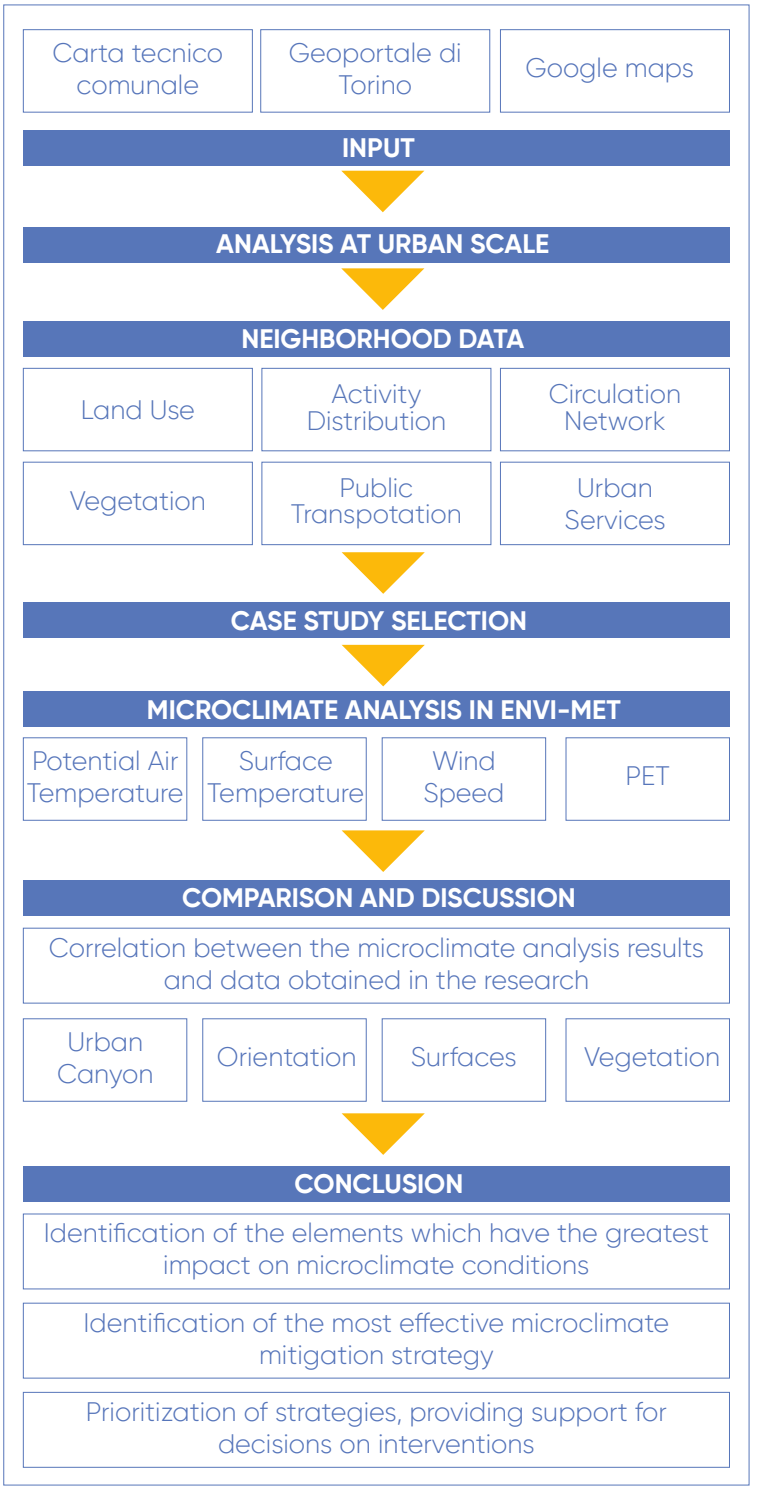


Figure 1. Methodological framework of the research. Source: Author's elaboration.

01 Turin Case Study

Scientific Background

1.1 Sustainable Development Goals

1.1.1 Goal 3: Good health and well-being

1.1.2 Goal 11: Sustainable cities and communities

1.1.3 Goal 13: Climate Action

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1.1 Sustainable Development Goals

In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, establishing 17 Sustainable Development Goals (SDGs) as a global framework for addressing interconnected environmental, social, and economic challenges. The Agenda provides a framework from 2015 to 2030 aimed at improving human well-being while ensuring that development does not compromise the ability of future generations to meet their needs (United Nations, 2015). The SDGs are interconnected, reflecting the fact that environmental conditions, public health, social equity, and urban development cannot be addressed independently.

For this reason, sustainable urban development requires an integrated approach that considers the relationships between environmental quality, human health, climate resilience, and the built environment. Within this framework, SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) are particularly relevant to this research. Together, these goals establish a framework for creating urban environments that are healthier, more resilient, and better adapted to the impacts of climate change.

The figure 1 illustrates the relationship between the 17 Sustainable Development Goals and the three goals most directly relevant to this research: SDG 3, SDG 11, and SDG 13. These goals are interconnected through the environmental

and social challenges associated with urban heat. Increasing temperatures, heatwaves, and the Urban Heat Island (UHI) effect can affect thermal comfort and public health, increase energy demand, and reduce the resilience of urban environments. In response, improving urban microclimatic conditions can contribute simultaneously to the objectives of these three goals by supporting healthier living environments, more sustainable and resilient cities, and greater capacity for climate adaptation. The framework therefore positions urban heat and microclimate as a common interface between health, urban sustainability, and climate action, establishing the broader sustainability context for the climate responsive urban design strategies investigated in this thesis.

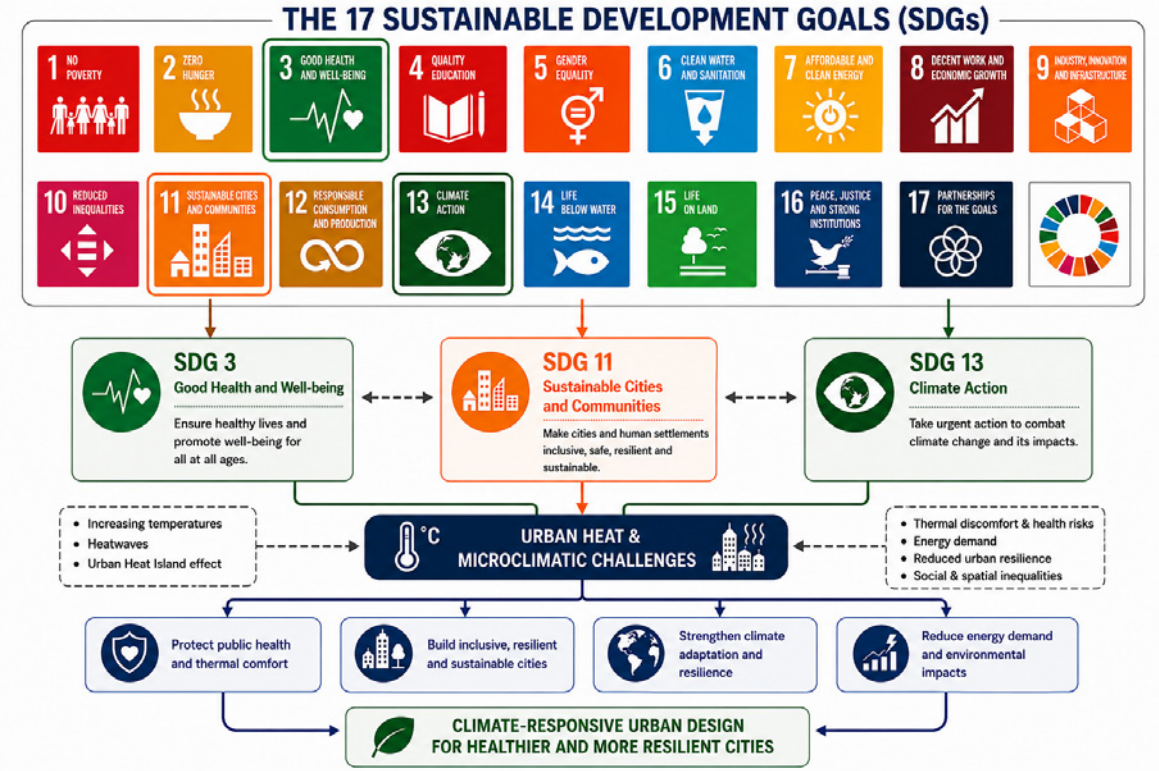


Figure 1 The Sustainable Development Goals and their relevance to the research framework, highlighting SDG 3, SDG 11, and SDG 13 in relation to urban heat and microclimatic challenges. Source: Author's elaboration based on United Nations (2015)

1.1.1 SDG 3: Good Health and Well-being

SDG 3 aims to ensure healthy lives and promote well-being for all at all ages. Although the goal encompasses a broad range of health priorities, its relevance to urban design is particularly evident through the relationship between the physical environment and human health. The quality and configuration of urban spaces can influence opportunities for physical activity, Physiological well-being, social interaction, exposure to environmental hazards, and vulnerability to extreme climatic conditions (United Nations, 2016; United Nations, 2025).

The World Health Organization (WHO) recognizes the urban environment as an important determinant of health and well-being. In particular, urban green spaces such as parks, playgrounds, and residential vegetation can provide multiple health benefits by supporting physical activity, Physiological restoration, and social interaction, while also reducing exposure to environmental stressors such as air pollution, noise, and excessive heat (WHO, 2016). These relationships demonstrate that the quality of urban space should not be considered solely as an ecological or spatial issue, but also as an important component of public health.

The relationship between the urban environment and health is mediated, in part, by local microclimatic conditions, which are also influenced by global and regional climate conditions. The physical characteristics of urban areas including urban form and density, vegetation, surface materials, shading, permeability, and anthropogenic heat can modify air temperature, surface temperature, radiant conditions, humidity, and airflow. These environmental variables determine the thermal conditions experienced by people at pedestrian level and therefore influence the degree of heat exposure within urban spaces.

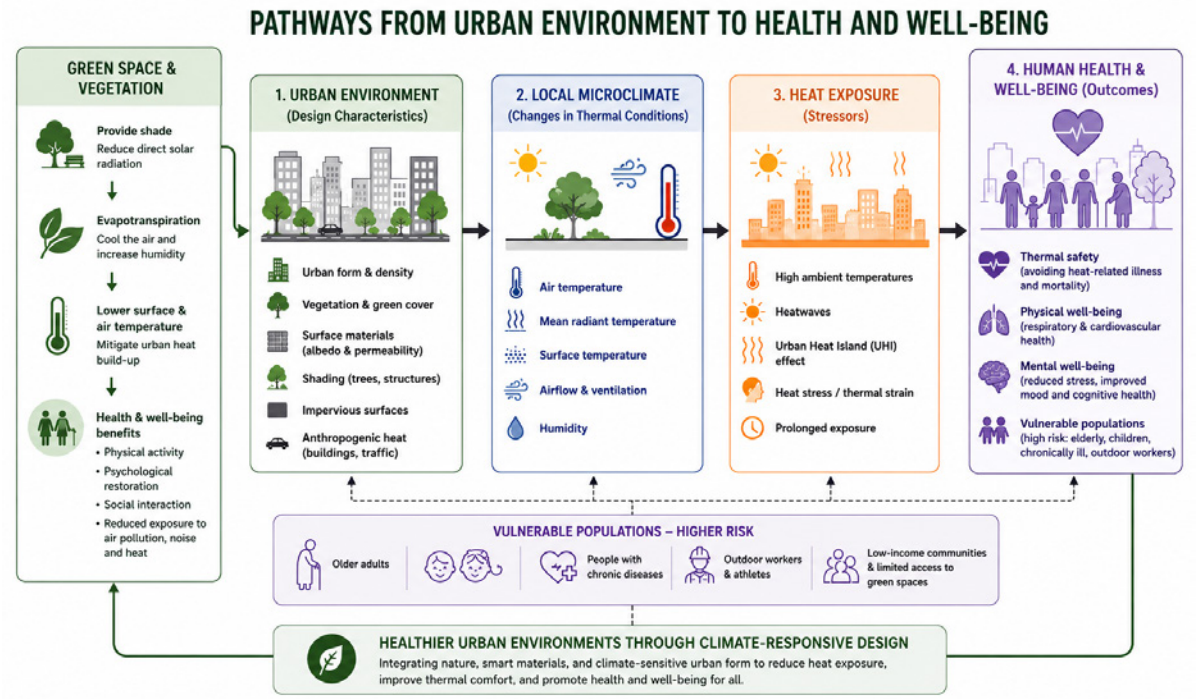


Figure 2 Pathways from the urban environment to health and well-being, illustrating the influence of urban design characteristics and green space on local microclimatic conditions, heat exposure, and human health outcomes. Source: Author's elaboration.

The figure 2 illustrates the pathway through which characteristics of the urban environment can influence human health and well-being. Urban form and density, vegetation, surface materials, shading, impervious surfaces, and anthropogenic heat affect the local microclimate by modifying solar exposure, heat storage, evapotranspiration, and airflow. These processes influence air temperature, mean radiant temperature, surface temperature, humidity, and ventilation conditions. Under increasingly warm climatic conditions, these microclimatic characteristics can contribute to different levels of heat exposure, including exposure to high ambient temperatures, heatwaves, and the Urban Heat Island (UHI) effect. The resulting thermal conditions can affect thermal

safety, physicaland mental well-being, and the vulnerability of particular population groups. Conversely, vegetation and green spaces can provide shade and evaporative cooling while supporting physical activity, Physiological restoration, and social interaction (WHO, 2016). The figure 2 therefore conceptualizes urban environmental design as an important pathway through which heat exposure and its potential health impacts can be influenced.

Among these environmental challenges, excessive urban heat represents a significant concern for public health. The combination of increasing background temperatures, more frequent heatwaves, and the Urban Heat Island effect can increase the intensity and duration of heat exposure in cities. Urbanization can intensify these conditions through the replacement of vegetation and permeable surfaces with impervious materials that absorb and store solar radiation. At the same time, building geometry, reduced ventilation, and anthropogenic heat from buildings, transportation, and other urban activities can further modify local thermal conditions. Consequently, thermal conditions within densely built urban areas can differ substantially from those of surrounding rural or less-developed environments.

The health implications of heat exposure are not distributed equally across the population. Vulnerable groups, including older adults and people with existing health conditions, may be particularly susceptible to heat related health effects (Smargiassi et al., 2009; Basagaña et al., 2011). Exposure can become especially significant when high temperatures persist over extended periods or occur simultaneously with other

environmental stressors. More broadly, the combination of climate change and urban heat can increase risks to thermal safety and reduce the capacity of urban spaces to provide comfortable outdoor environments (Sarofim et al., 2016).

This relationship is particularly important in public spaces, where people are directly exposed to outdoor climatic conditions. Thermal comfort is therefore an important interface between urban environmental quality and health. The experience of heat at pedestrian level depends not only on air temperature but also on radiant conditions, wind, humidity, and the characteristics of surrounding surfaces and vegetation. Consequently, strategies aimed at improving urban thermal conditions should address the spatial and physical characteristics that determine these variables rather than focusing on air temperature alone.

From an urban design perspective, this highlights the potential of climate responsive interventions to reduce heat exposure and improve the health and usability of public spaces. Strategies such as increasing vegetation and tree canopy, providing shade, introducing appropriate surface materials, improving permeability, and modifying urban form can influence local microclimatic conditions and reduce thermal stress. Such interventions can therefore contribute to the objectives of SDG 3 by supporting healthier outdoor environments while simultaneously improving the comfort, accessibility, and everyday usability of urban public spaces.

1.1.2 SDG 11: Sustainable Cities and Communities

SDG 11 aims to make cities and human settlements inclusive, safe, resilient, and sustainable. The rapid growth of urban populations and the increasing concentration of social, economic, and infrastructural activities within cities have intensified the environmental pressures associated with urban development. These pressures include population growth, demand for infrastructure and services, unequal access to resources and public spaces, and increasing exposure to climate related hazards (United Nations, 2025). As a result, achieving sustainable urban development requires not only the provision of adequate infrastructure and services, but also the capacity of urban environments to respond to environmental risks and changing climatic conditions.

Urban resilience is closely related to the physical and spatial organization of cities. The distribution and configuration of buildings, streets, public spaces, vegetation, and infrastructure can influence how environmental risks are experienced across different parts of the urban fabric. These risks are also socially uneven: differences in socio-economic conditions, access to green and public spaces, and the quality of the built environment can affect the capacity of communities to adapt to climate related stresses. Sustainable urban planning therefore needs to consider both the physical characteristics of urban areas and the social dimensions of resilience.

At the neighborhood scale, urban form and the quality of public space play an important role in determining local environmental conditions. Building density and height, street geometry and orientation, surface materials, vegetation,

shading, and the availability and accessibility of open spaces influence solar exposure, heat storage, airflow, and natural cooling. These characteristics can consequently affect air and surface temperatures and the degree of exposure to urban heat. Climate responsive planning provides an opportunity to manage these relationships by integrating environmental considerations directly into the spatial organization and design of urban areas.

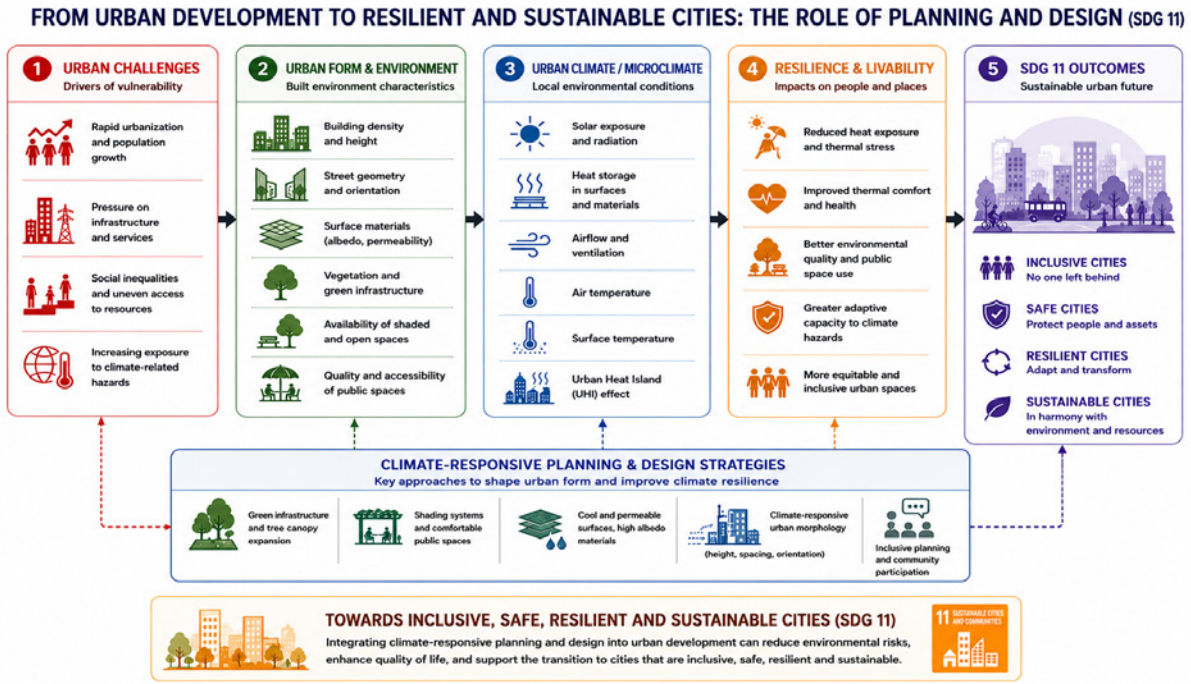


Figure 3 Relationship between urban development, built environment characteristics, urban climate, and urban resilience, illustrating the role of climate responsive planning and design in supporting the objectives of SDG 11. Source: Author's elaboration.

The figure 3 illustrates the pathway through which urban development and planning decisions can influence urban climate and, consequently, the resilience and livability of cities. Rapid urbanization, population growth, pressure on infrastructure, social inequalities, and exposure to climate related hazards represent important drivers of urban

vulnerability. These pressures interact with physical characteristics of the built environment, including building density and height, street geometry, surface materials, vegetation, shading, and the configuration of public and open spaces. Such characteristics influence local climatic processes, including solar exposure, heat storage, ventilation, air temperature, surface temperature, and the intensity of the Urban Heat Island (UHI) effect. Climate responsive planning and design can intervene in this relationship through green infrastructure, tree canopy expansion, shaded public spaces, cool and permeable surfaces, and climate responsive urban morphology. By reducing heat exposure, improving thermal comfort and environmental quality, and increasing adaptive capacity, these interventions can contribute to more inclusive, safe, resilient, and sustainable urban environments.

The relationship between SDG 11 and urban climate is particularly significant in the context of the Urban Heat Island effect. Urban development can modify the surface energy balance and atmospheric conditions through the concentration of buildings and impervious surfaces, the reduction of vegetation, and changes in airflow and radiation exchange. Consequently, different urban configurations can produce substantially different thermal conditions within the same city. Urban planning and design can therefore either intensify or mitigate local heat accumulation depending on the characteristics and spatial organization of the built environment.

From this perspective, climate responsive urban planning represents an important component of urban resilience.

Green infrastructure and tree canopy can provide shade and evaporative cooling; appropriate surface materials can influence heat absorption and storage; shaded and well-designed public spaces can reduce direct thermal exposure; and urban morphology can affect solar access and ventilation. These measures should not be considered as isolated interventions, but as interconnected components of a broader planning approach that responds to local environmental conditions while maintaining the social and functional role of urban spaces.

For this research, SDG 11 provides the broader urban-planning and resilience framework within which microclimate sensitive urban design is examined. This perspective shifts the focus from considering urban heat solely as a climatic phenomenon toward understanding how the spatial configuration and physical characteristics of neighborhoods can influence environmental quality and climate resilience. Accordingly, the analysis of urban morphology, vegetation, surface materials, shading, and public space configuration provides the basis for identifying design strategies capable of improving local microclimatic conditions while supporting the broader objectives of sustainable and resilient urban development.

1.1.3 SDG 13: Climate Action

SDG 13 calls for urgent action to combat climate change and its impacts. Climate change represents a major challenge to sustainable development, as increasing temperatures and changes in the frequency and intensity of extreme weather events can affect ecosystems, infrastructure, economies, and human health.

Addressing these impacts requires complementary approaches to climate change mitigation and adaptation, supported by coordinated action at international, national, regional, and local levels (United Nations, 2025).

The Paris Agreement, adopted under the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 and entering into force in 2016, established an international framework for strengthening the global response to climate change. While limiting greenhouse gas emissions remains essential for reducing the magnitude of future climate change, adaptation is equally important because many climate related impacts are already occurring and are experienced directly at the local level. Climate adaptation therefore requires strategies capable of reducing vulnerability and exposure while increasing the capacity of communities and urban systems to respond to changing climatic conditions.

Cities have a particularly important role in this process. The concentration of population, buildings, infrastructure, economic activities, and energy consumption makes urban areas both significant contributors to greenhouse-gas emissions and highly exposed to climate related hazards. At the same time, the physical characteristics of cities can modify the local expression of climatic conditions. Dense built environments, extensive impervious surfaces, limited vegetation, and altered airflow can intensify heat accumulation and contribute to higher thermal exposure. Urban climate adaptation therefore requires approaches that respond to local environmental conditions and integrate climate considerations into planning and design processes.

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The Paris Agreement, adopted under the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 and entering into force in 2016, established an international framework for strengthening the global response to climate change. While limiting greenhouse gas emissions remains essential for reducing the magnitude of future climate change, adaptation is equally important because many climate related impacts are already occurring and are experienced directly at the local level. Climate adaptation therefore requires strategies capable of reducing vulnerability and exposure while increasing the capacity of communities and urban systems to respond to changing climatic conditions.

Cities have a particularly important role in this process. The concentration of population, buildings, infrastructure, economic activities, and energy consumption makes urban areas both significant contributors to greenhouse gas emissions and highly exposed to climate related hazards. At the same time, the physical characteristics of cities can modify the local expression of climatic conditions. Dense built environments, extensive impervious surfaces, limited vegetation, and altered airflow can intensify heat accumulation and contribute to higher thermal exposure. Urban climate adaptation therefore requires approaches that respond to local environmental conditions and integrate climate considerations into planning and design processes.

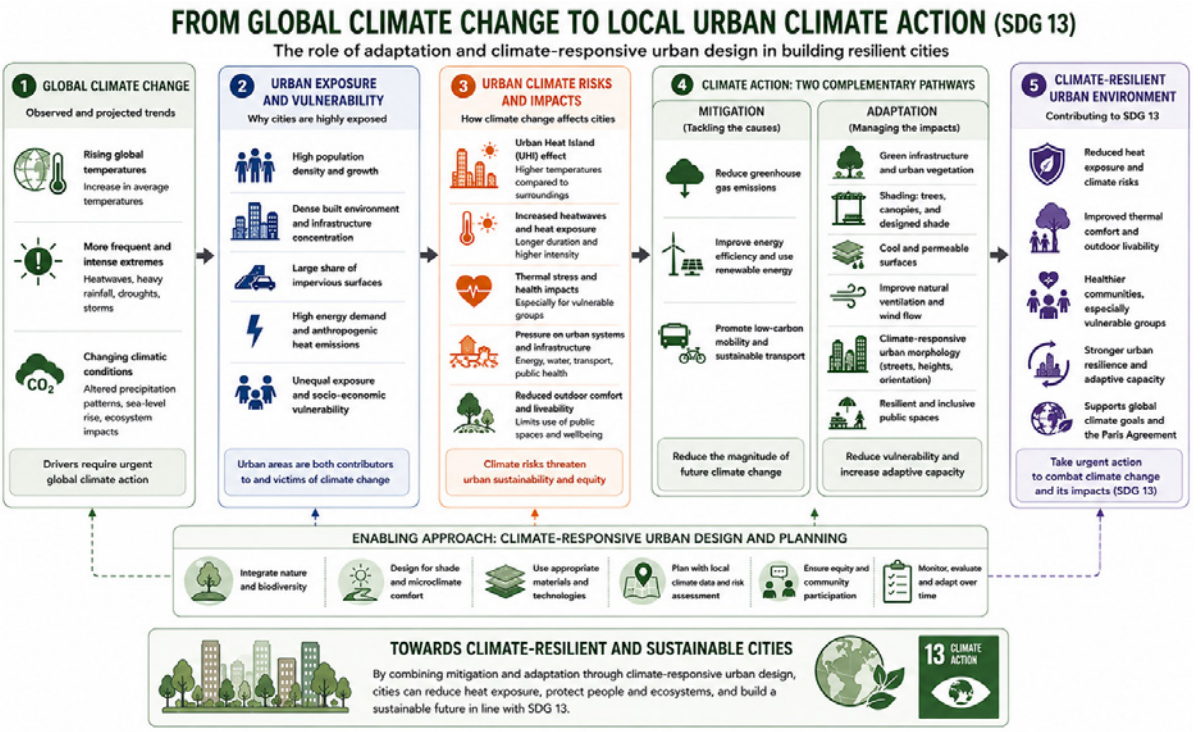


Figure 4. From global climate change to local urban climate action, illustrating the relationship between climate change, urban exposure, heat related risks, mitigation and adaptation, and climate responsive urban design. Source: Author, based on IPCC (2022) and United Nations (2025).

The figure 4 illustrates the pathway from global climate change to local urban climate action and highlights the complementary roles of mitigation and adaptation. Global temperature increases and changing climatic conditions interact with the physical and social characteristics of urban areas, where high population densities, extensive built surfaces, infrastructure concentration, and unequal exposure can increase vulnerability to climate related hazards. These conditions can contribute to urban climate risks including the Urban Heat Island (UHI) effect, increased heatwave exposure, thermal stress, and reduced outdoor comfort. Climate action can respond through

two complementary pathways: mitigation, which addresses the causes of climate change by reducing greenhouse gas emissions, and adaptation, which addresses its impacts by reducing vulnerability and increasing adaptive capacity. At the urban scale, adaptation can include green infrastructure, shading, cool and permeable surfaces, improved ventilation, climate responsive urban morphology, and resilient public spaces. The figure therefore establishes the connection between global climate objectives and the spatial and physical interventions through which cities can respond to local climate risks.

Within this framework, Urban Heat Island mitigation represents an important component of local urban climate adaptation. Rising background temperatures associated with climate change can be amplified by the thermal characteristics of urban environments, increasing heat exposure and placing additional pressure on the thermal resilience of cities. The interaction between regional climate warming and local urban conditions means that the effects of heat cannot be understood solely at the global or regional scale. Urban morphology, surface characteristics, vegetation, shading, and airflow can influence the magnitude and spatial distribution of heat at the neighborhood and pedestrian scales. Consequently, urban design provides an opportunity to address climate related heat risks through interventions that modify local microclimatic conditions.

Climate responsive urban design can therefore contribute to adaptation by influencing the environmental processes that determine heat exposure. Vegetation and green infrastructure

can provide shade and evaporative cooling; shading structures and appropriate building configurations can reduce direct solar exposure; cool and permeable surfaces can modify heat storage and surface conditions; and urban morphology and street configuration can influence solar access and airflow. These interventions can be combined according to the climatic and spatial characteristics of individual urban contexts rather than being applied as isolated measures. Such an approach is particularly important in existing urban areas, where adaptation strategies must respond to established urban morphology, infrastructure, land uses, and public-space functions.

Consequently, integrating microclimatic considerations into urban planning and design can support the objectives of SDG 13 by strengthening the adaptive capacity of urban environments. Understanding how urban morphology, vegetation, surface materials, shading, and open space configuration influence local climatic conditions allows adaptation strategies to be tailored to specific neighborhood conditions. In this sense, climate responsive urban design translates the broader objectives of climate adaptation into spatial and physical interventions at the local scale. For the present research, this provides the basis for investigating how targeted urban design strategies can modify urban microclimatic conditions, reduce heat exposure, and contribute to more climate resilient urban environments.

1.1.3.1 Sustainable Development Goals and Urban Heat Challenges

The relationship between climate change, urbanization,human health, and the Urban Heat Island (UHI) effect demonstrate that urban heat is not an isolated environmental phenomenon. Rather, it represents a multidimensional urban challenge involving thermal exposure, public health, energy demand, air quality, infrastructure, outdoor activity, and social vulnerability (Shahmohamadi et al., 2011; He et al., 2021; Kamel et al., 2024). The increasing frequency of heatwaves and the intensification of urban overheating can therefore affect not only the thermal conditions of individual spaces, but also the broader environmental quality, livability, and resilience of cities.

The Sustainable Development Goals provide an integrated framework for understanding these interconnected impacts. As established in the preceding sections, SDG 3 connects urban environmental conditions with health and well-being, SDG 11 addresses the development of inclusive, safe, resilient, and sustainable urban environments, and SDG 13 emphasizes climate action and adaptation to climate related impacts. Urban heat lies at the intersection of these objectives because the factors that contribute to overheating are simultaneously environmental, spatial, social, and climatic.

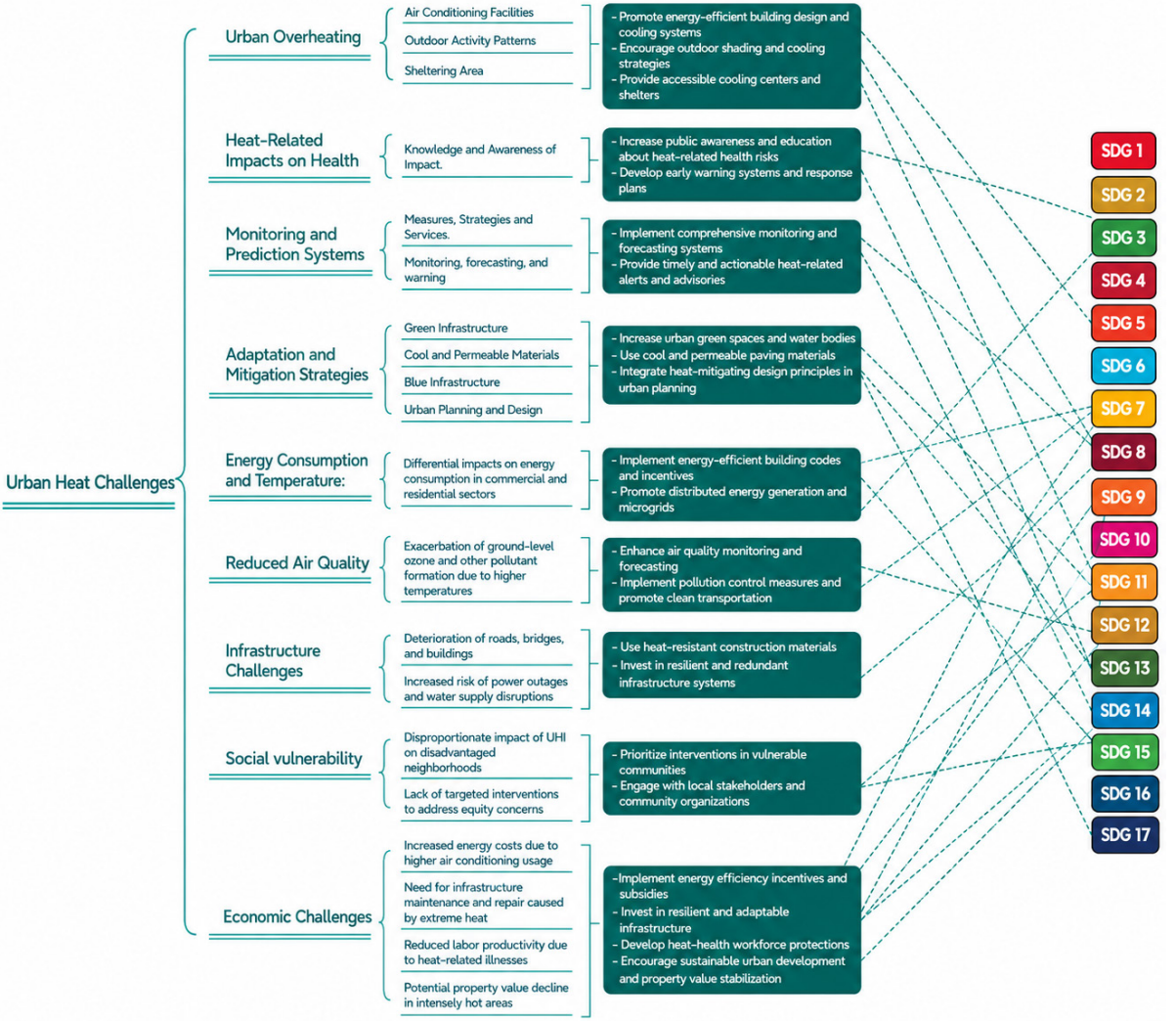


Figure 5. Relationship between Sustainable Development Goals and urban heat challenges, illustrating the connections between urban overheating, heat related health impacts, energy consumption, air pollution, infrastructure, social vulnerability, and corresponding mitigation and adaptation strategies. Source: Ahmed et al. (2024).

The framework presented in Figure 5 demonstrates how the different dimensions of urban heat can be connected to complementary sustainability objectives. Urban overheating and the UHI effect can increase heat exposure and affect human health and outdoor thermal comfort, directly relating to SDG 3. At the same time, excessive heat can reduce the

usability and livability of public spaces, increase pressure on infrastructure and energy systems, and contribute to inequalities in environmental exposure, linking the issue to SDG 11. From a climate perspective, increasing temperatures and more frequent extreme heat events strengthen the need for adaptation strategies, connecting urban heat mitigation to SDG 13. The figure consequently demonstrates that urban heat should be addressed through integrated rather than isolated interventions, combining environmental, spatial, technological, and social responses (Ahmed et al., 2024).

The figure also emphasizes that urban heat mitigation can generate benefits across several sustainability objectives simultaneously. Green infrastructure and vegetation can provide shade and evaporative cooling while contributing to healthier and more attractive public spaces. Cool and reflective materials can reduce solar heat absorption, while appropriate urban planning and spatial configuration can influence solar exposure, heat storage, and airflow. Climate responsive public spaces can consequently contribute to improved thermal comfort and health, while also strengthening the adaptive capacity of urban environments. Ahmed et al. (2024) similarly identify greenery and vegetation, roof treatments, material properties, water features, and urban geometry among the principal strategies investigated in the literature for addressing urban heat.

An important implication of this framework is that the effectiveness of heat mitigation strategies depends on their integration within the existing urban context. Urban heat cannot be addressed through a single intervention because

its intensity and spatial distribution result from the interaction between urban morphology, surface characteristics, vegetation, climatic conditions, and human activity. Consequently, strategies should be selected according to the characteristics and constraints of each urban environment, particularly in existing neighborhoods where the spatial structure and functional uses of public spaces must be maintained.

For the purposes of this thesis, this relationship establishes the broader sustainability framework for investigating urban microclimate and heat mitigation through urban design. Rather than considering the UHI effect solely as a climatic phenomenon, the research approaches urban heat as a cross cutting urban design, health, resilience, and climate-adaptation challenge. This perspective provides the basis for examining how changes to urban morphology, vegetation, surface materials, shading, and public-space configuration can influence local microclimatic conditions and contribute to healthier, more resilient, and more sustainable urban environments.

1.1.3.2 Urban Microclimate Challenges

A microclimate refers to the climatic conditions occurring within a relatively small and spatially defined area, where environmental conditions may differ from those of the surrounding climate (Oke, 2012). In urban environments, these conditions are strongly influenced by the interaction between atmospheric processes and the physical characteristics of the built environment. Building geometry, vegetation, surface materials, topography, water, human activities, and the

spatial configuration of streets and open spaces can modify the exchange of radiation, heat, moisture, and air, resulting in significant local variations in air temperature, surface temperature, wind, humidity, and radiant conditions.

Climate and atmospheric processes operate across different spatial scales, from planetary and regional phenomena to conditions occurring around individual buildings and urban open spaces (Oke et al., 2017). As illustrated in Figure 6, these scales can be understood progressively from the planetary and regional scales, through the city and neighbourhood scales, to the building and pedestrian scales (Oke et al., 2017).. While larger scales describe broader climatic conditions that establish the background environment of a city, smaller scales are increasingly influenced by the physical characteristics of the local environment. This distinction is particularly important in urban studies because climatic conditions can vary considerably within relatively short distances as a result of differences in urban morphology, vegetation, surface characteristics, and exposure.

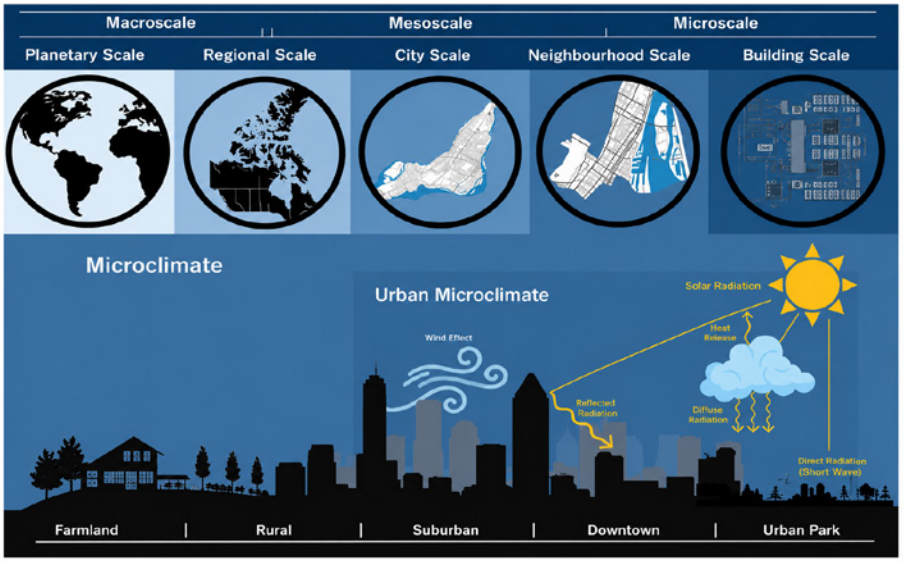


Figure 6. Climatic spatial scales and the urban microclimate, illustrating the transition from planetary and regional climatic conditions to city, neighborhood, and building scales, and the interaction of solar radiation, wind, heat release, and urban surfaces within the urban microclimate.
Source: Orlanski, (1975)

The figure 6 illustrates how climatic conditions are expressed across different spatial scales and highlights the urban microclimate as the interface between broader climatic processes and the physical characteristics of individual urban environments. At the planetary and regional scales, climatic conditions establish the broader atmospheric context within which cities operate. At the city and neighborhood scales, urbanization begins to modify these conditions through changes in land cover, building density, vegetation, and surface properties.

At the building and open space scales, the interaction between solar radiation, reflected and diffuse radiation, heat release, wind, and urban surfaces produces highly localized environmental conditions. The figure therefore demonstrates that urban microclimate is not independent of the larger climate system, but represents the local expression of broader climatic conditions as they interact with the built environment. The urban microclimate is particularly influenced by the spatial configuration and material characteristics of the urban environment. Building height and density, street orientation, the relationship between building height and street width, and the distribution of open spaces determine the amount of solar radiation received and the potential for shading and airflow. The arrangement of buildings can also influence wind movement and the exchange of heat within streets and open spaces. These effects are further modified by vegetation, which can provide shade and influence local radiation and moisture conditions through evapotranspiration.

Surface characteristics are another important component of urban microclimate. Urban materials differ in their ability to

absorb, reflect, store, and release solar energy, meaning that changes in surface properties can influence local thermal conditions. Impervious surfaces can store heat during periods of solar exposure and release it later, while permeable and vegetated surfaces can alter heat and moisture exchanges.
Urban surfaces can absorb, reflect, store, and release solar energy, meaning that changes in surface properties can influence local thermal conditions. Impervious surfaces can store heat during periods of solar exposure and release it later, while permeable and vegetated surfaces can alter heat and moisture exchanges. The interaction between surface materials, solar radiation, vegetation, and surrounding buildings therefore contributes to spatial differences in surface and air temperatures within the urban environment (Oke et al., 2017). This phenomenon is particularly evident at night with the nocturnal UHI.

As shown in Figure 6, these processes occur simultaneously with wind and atmospheric heat exchange. Building geometry and urban density can obstruct, channel, or accelerate airflow, while the thermal characteristics of surfaces influence the release of stored heat into the surrounding atmosphere. Solar radiation is also modified by the geometry of buildings and vegetation through direct shading, reflection, and changes in radiant exposure. Consequently, urban microclimate results from the combined interaction of radiation, heat storage and release, vegetation, airflow, and the physical configuration of the urban environment rather than from a single environmental variable (Oke et al., 2017).

These interactions are closely related to the formation of the Urban Heat Island (UHI) effect. The concentration of buildings and

impervious surfaces, reduction of vegetation, modification of airflow, and release of anthropogenic heat can alter the urban energy balance and contribute to higher temperatures in built-up areas compared with their surrounding environments (Hadavi et al., 2021). The UHI can therefore be understood as an important manifestation of the cumulative effects of urbanization on local climatic conditions. However, the intensity and spatial distribution of urban heat are not uniform; they vary according to urban morphology, land cover, surface properties, vegetation, and the climatic conditions of the specific location.

Understanding these relationships is essential for urban heat mitigation and climate-responsive urban design. Because urban microclimate is strongly influenced by physical characteristics that can be modified through design, interventions involving vegetation, shading, surface materials, building configuration, and open space structure can potentially alter local thermal conditions. At the pedestrian level, these modifications influence the environmental conditions directly experienced by people and therefore have implications for outdoor thermal comfort and the usability of public spaces.

For the present research, urban microclimate provides the critical link between the physical characteristics of the study area and the environmental conditions experienced at pedestrian level. The neighborhood and open-space scales shown in Figure 6 are particularly relevant because they represent the spatial range at which urban morphology, vegetation, surface materials, and shading interact to produce localized thermal conditions. This provides the theoretical basis for examining how changes to these elements can modify the local microclimate and contribute to urban heat mitigation.

1.2 Microclimate

Following the sustainability framework established in Section 1.1, it is necessary to examine the physical and environmental processes that contribute to urban heat and influence the climatic conditions of urban spaces. Urban overheating results from the interaction between background climatic conditions, urban morphology, land cover, surface materials, vegetation, atmospheric processes, and human activities. Understanding these relationships provides the scientific basis for assessing how the built environment modifies local climatic conditions and how urban design can respond to heat related challenges.

This chapter examines the Urban Heat Island (UHI) phenomenon, Local Climate Zones (LCZ), urban morphology, urban canyon geometry, ventilation, and outdoor thermal comfort. These concepts are closely interconnected: the spatial configuration and physical characteristics of the urban environment influence radiation exchange, heat storage, shading, and airflow, which in turn affect local microclimatic conditions and the thermal environment experienced by people at pedestrian level. Establishing these relationships is therefore essential for understanding the mechanisms of urban overheating and identifying the physical parameters that can be addressed through climate-responsive urban design.

1.2.1 Urban Heat Island (UHI)

The Urban Heat Island (UHI) is a climatic phenomenon in which urban areas experience higher temperatures than their surrounding rural or less developed environments. It results from the interaction of urban land cover, built form, surface properties, vegetation, anthropogenic heat emissions, and atmospheric conditions. Urbanization replaces natural and permeable surfaces with buildings, roads, pavements, and other impervious materials, modifying the surface energy balance through changes in the absorption, storage, and release of solar energy. At the same time, the geometry of the built environment influences radiation exchange, shading, and airflow, while anthropogenic activities such as transportation, buildings, industry, and air conditioning systems introduce additional heat into the urban environment (Oke, 1982; Zhou et al., 2014).

The intensity of the UHI is not spatially uniform. It varies according to the characteristics of the urban fabric and surrounding landscape, as well as meteorological conditions and time of day. Differences in building density and height, vegetation cover, surface materials, sky view factor, and urban geometry can produce substantial variations in temperature within the same urban area. These spatial variations are particularly relevant at the neighborhood and street scales, where the interaction between urban form and atmospheric processes determines the thermal conditions experienced at pedestrian level.

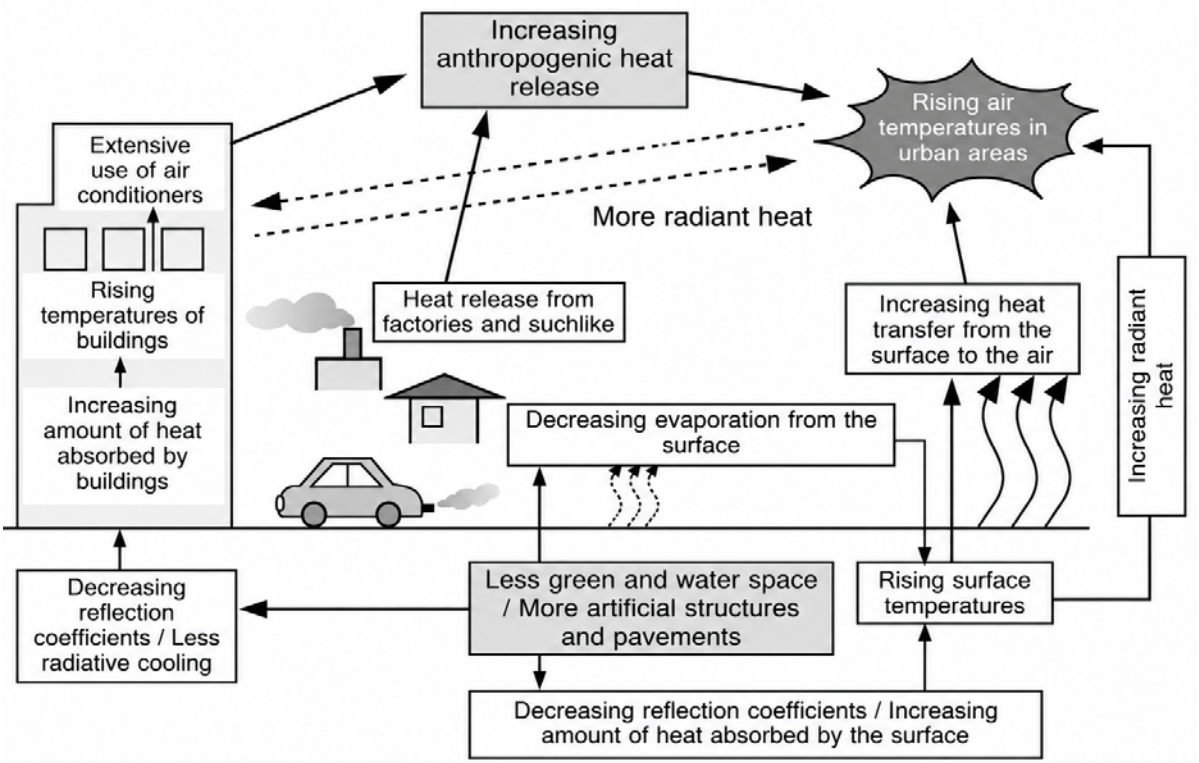


Figure 7. Main physical and anthropogenic processes contributing to the formation and intensification of the Urban Heat Island (UHI). Source: Yamamoto (2006)

The Figure 7 illustrates the interconnected processes through which urbanization contributes to the development of the UHI. The replacement of vegetation and water surfaces with artificial structures and pavements can reduce evaporative cooling and alter surface reflectivity. Changes in surface properties can also increase the amount of solar energy absorbed and stored within the urban fabric. In addition, anthropogenic heat released by buildings, transportation, industrial activities, and air conditioning systems adds further heat to the urban environment. These processes interact through radiative, conductive, and convective heat exchanges, contributing to elevated surface and air temperatures. The figure therefore emphasizes that urban overheating results from the combined

effects of land-cover change, surface characteristics, anthropogenic heat, and atmospheric processes rather than from a single cause.

The spatial expression of the UHI can be represented by comparing temperature conditions along a transect extending from a rural or less developed area through an urban environment and back toward the surrounding rural area. As illustrated in Figure 8, temperature generally increases toward more intensely urbanized areas, although the magnitude and spatial distribution of this difference depend on local land cover, urban morphology, vegetation, and meteorological conditions. The temperature difference between an urban area and its surrounding non urban environment is commonly used to characterize the intensity of the urban heat island, although the magnitude and timing of the phenomenon vary according to the climatic variable being considered and the spatial and temporal scale of observation.

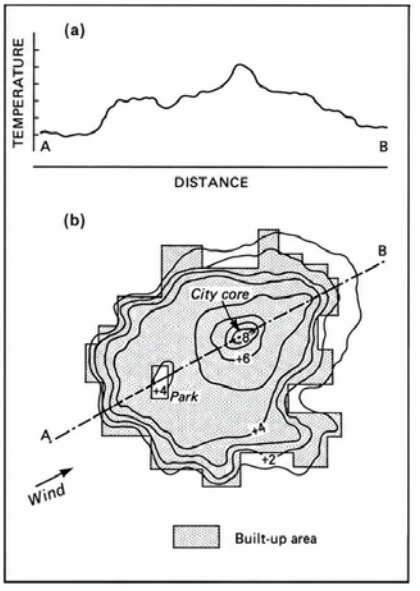


Figure 8. Spatial representation of the Urban Heat Island, showing (a) a generalized temperature profile across an urban area and (b) the spatial distribution of temperature within a built-up area, including the localized cooling influence of an urban park. Source: Oke (1982).

The figure 8 demonstrates the spatial variability of the UHI within an urban environment. The temperature profile in (a) illustrates the increase in temperature toward the more intensely urbanized area, while the spatial distribution in (b) shows that temperature is not uniform across the urban fabric. The presence of an urban park, for example, is associated with a localized reduction in temperature compared with the surrounding built-up area. These variations demonstrate that the intensity of urban heat depends on land cover, urban morphology, vegetation, and local atmospheric conditions.

The formation of the UHI can also be understood through the urban surface energy balance. Urban surfaces receive incoming shortwave solar radiation, part of which is reflected while the remainder is absorbed. The absorbed energy may be stored within buildings and surface materials, converted into sensible and latent heat fluxes, or exchanged with the atmosphere.

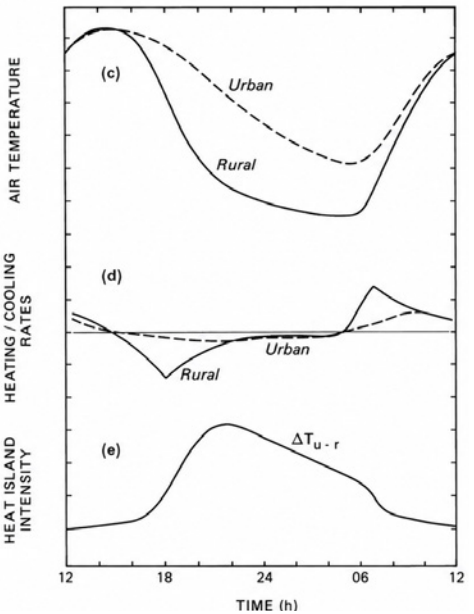


Figure 9. Diurnal evolution of the Urban Heat Island, showing (c) urban and rural air temperatures, (d) corresponding heating and cooling rates, and (e) the resulting urban–rural temperature difference (ΔT_{u-r}). Source: Oke (1982).

The figure 9 illustrates the temporal development of the UHI through the contrasting thermal responses of urban and rural environments. During the daytime, the urban and rural environments respond differently to solar heating, while after sunset the urban environment generally cools more slowly than the rural environment. These differences in heating and cooling rates contribute to the characteristic increase in the urban rural temperature difference during the evening and night. The figure therefore demonstrates that UHI intensity is a dynamic phenomenon governed not only by differences in temperature, but also by differences in the rate at which urban and rural environments gain and lose heat.

The consequences of urban overheating extend beyond temperature differences alone. Elevated urban temperatures can increase cooling demand and associated energy consumption, intensify heat exposure, and contribute to thermal discomfort and heat related health risks. During periods of extreme heat, the combination of high background temperatures and the UHI can increase the intensity and duration of heat exposure, particularly in densely built areas with limited vegetation and shading. Urban heat can also interact with atmospheric and air quality conditions, while increased cooling demand may place additional pressure on urban energy systems (Goggins et al., 2012; Ward et al., 2016).

Among the physical characteristics influencing urban thermal conditions, surface materials and their thermal properties are particularly relevant to urban design. Surface albedo determines the proportion of incoming solar radiation that is reflected, while thermal properties such as heat capacity (Oke et al., 2017).

and emissivity influence the storage and release of heat. Consequently, pavements, roofs, façades, and other urban surfaces can contribute differently to the urban surface energy balance depending on their material properties and exposure conditions (Doulos et al., 2004; Baldinelli et al., 2024). These characteristics are particularly important when considering heat mitigation interventions involving cool or reflective materials.

However, UHI intensity cannot be attributed to surface materials alone. Urban morphology, vegetation, sky view factor, building geometry, airflow, and anthropogenic heat interact with surface properties to determine local thermal conditions. This interaction explains why areas with similar surface materials can nevertheless experience different thermal environments because of differences in building configuration, shading, ventilation, or vegetation.

For the present research, the UHI is therefore understood as the result of interacting climatic, morphological, material, vegetative, and anthropogenic processes. Understanding these relationships provides the basis for examining the spatial structure of the urban environment through Local Climate Zones, urban morphology, street canyon geometry, and microclimatic variables. These concepts are essential for identifying the physical characteristics that contribute to urban heat and for evaluating how climate responsive urban design can modify local thermal conditions.

The spatial variability of the UHI is closely related to differences in the physical structure and surface characteristics of urban

areas. A standardized framework for describing these differences is therefore useful for comparing urban environments according to their morphological and land cover characteristics. Local Climate Zones (LCZs) provide such a framework by classifying urban and non urban areas according to their physical and surface properties.

1.2.2 Local Climate Zones (LCZ)

The Local Climate Zone (LCZ) classification system was introduced by Stewart and Oke (2012) to provide a standardized framework for describing urban and non urban landscapes according to their physical characteristics and their relevance to local climate. The classification was developed in response to the limitations of the conventional urban rural distinction, which often groups highly different urban environments under the single category of "urban." Differences in building height, density, spacing, vegetation, surface cover, and construction materials can produce substantially different thermal environments within the same city. LCZs provide a common framework for describing and comparing these differences in urban climate studies.

The LCZ system consists of 17 standard classes, divided into two main groups: 10 built types (LCZ 1–10) and 7 land-cover types (LCZ A–G). The built types are primarily distinguished by characteristics such as building height, building density, spacing, and the degree of openness of urban fabric. The land-cover types describe areas dominated by different forms of vegetation, bare surfaces, or water. Each LCZ therefore represents a characteristic combination of surface structure and cover rather than a specific land use function.

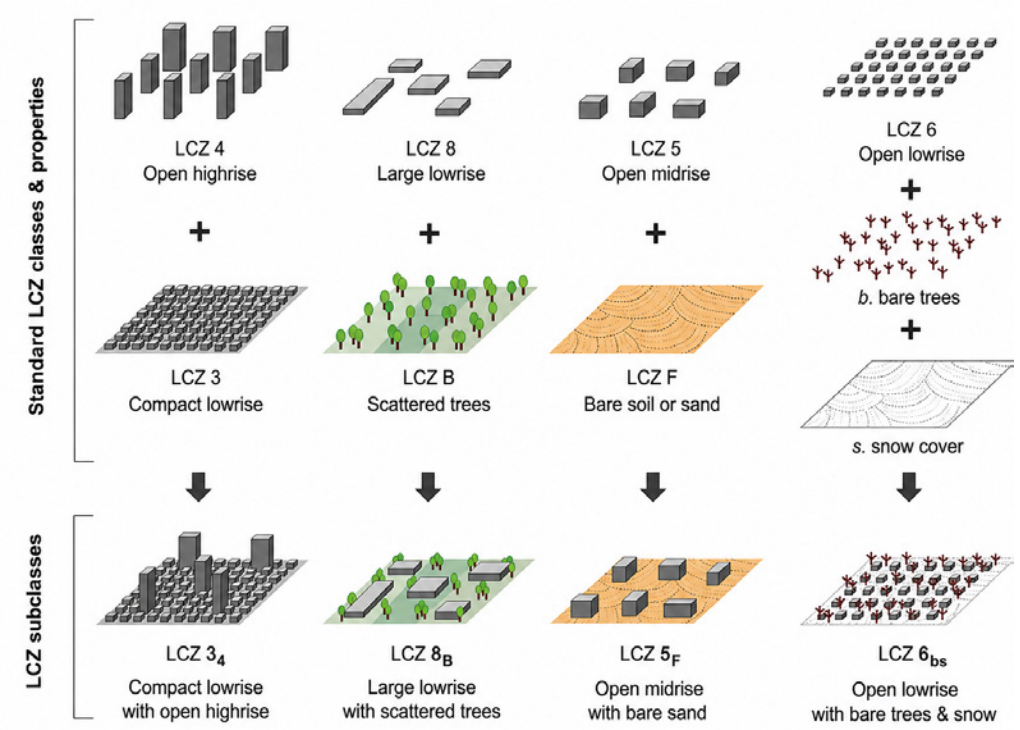


Figure 10. Examples of standard Local Climate Zone (LCZ) classes and their subclasses, illustrating combinations of built form characteristics and land cover properties within the LCZ classification framework. Source: Stewart and Oke (2012).

The figure 10 illustrates the diversity and compositional variability represented within the LCZ framework. The standard classes describe characteristic combinations of built form and land cover, while the subclasses demonstrate how additional land cover characteristics can be associated with a dominant built or land cover type. This representation is particularly useful for understanding the heterogeneous nature of real urban environments, where building morphology and surface cover may occur in combination rather than as completely independent conditions.

The classification is based on a set of geometric, surface cover, and environmental characteristics that describe the physical

structure of each zone. Important parameters include building height, building surface fraction, building spacing, impervious and previous surface fractions, vegetation characteristics, sky view factor, and the geometric relationship between buildings and open spaces. These characteristics influence the local exchange of radiation, heat, moisture, and momentum and consequently contribute to differences in air temperature and other microclimatic conditions. Subsequent evaluations of the LCZ framework have demonstrated measurable thermal contrasts between different LCZ classes, with building height and spacing, pervious surface fraction, tree density, and soil moisture among the factors influencing thermal differences (Stewart & Oke, 2012; Leconte et al., 2015).

An important advantage of the LCZ framework is that it enables comparison between urban areas that may have very different physical configurations. Conventional land-use classifications primarily describe the function of an area, such as residential, commercial, industrial, or recreational use, but do not necessarily capture the physical characteristics that control local climate. Two residential areas, for example, may have substantially different building heights, densities, vegetation cover, and surface characteristics and may therefore exhibit different thermal conditions. LCZ classification provides a more climate oriented description of these physical differences (Stewart & Oke, 2012).

The relationship between LCZ and temperature has been investigated using both observational and remote-sensing approaches. Air temperature observations can be used to examine thermal differences between LCZ classes, while satellite-derived land surface temperature (LST) provides spatially continuous information that can be used to investigate the relationship between surface temperature and LCZ (Bechtel et al., 2015; Leconte et al., 2015).

However, air temperature and land surface temperature represent different components of the urban thermal environment and should not be treated as interchangeable variables. Research combining LCZ classification with temperature observations has demonstrated that thermally distinct conditions can occur between different LCZ classes, supporting the value of the classification for urban climate analysis (Stewart & Oke, 2012; Leconte et al., 2015).

The LCZ framework is therefore particularly useful for investigating spatial differences in urban thermal conditions and potential heat exposure. Rather than treating an entire city as a single homogeneous urban environment, LCZ classification allows areas with different physical configurations and climatic characteristics to be distinguished. This is particularly relevant for neighbourhood scale studies, where variations in building density, urban geometry, vegetation, and surface cover can influence the local microclimate and the intensity of heat exposure (Stewart & Oke, 2012).

Identifying the LCZ characteristics of the study area helps establish the relationship between existing urban morphology, surface cover, and potential thermal conditions. It also provides a basis for comparing the baseline and proposed design conditions within their broader urban context. In combination with detailed site-scale analysis and microclimatic simulation, LCZ classification can therefore support the identification of areas that may be more susceptible to heat accumulation and thermal stress. The use of LCZ in this thesis should therefore not be understood as a substitute for detailed site scale microclimatic analysis (Stewart & Oke, 2012; Leconte et al., 2015).

Rather, it provides a contextual classification framework that links the broader characteristics of the urban fabric to the local environmental conditions examined through subsequent morphological analysis and ENVI-met simulation. This establishes a direct transition from the classification of the urban environment to specific physical characteristics, such as building configuration, street geometry, vegetation, and surface materials that influence urban microclimate.

1.2.3 Urban Morphology

Urban morphology refers to the physical form and spatial organization of the built environment, including the street network, block structure, buildings, open spaces, and land-use patterns. These components evolve over time as cities develop and transform, producing different configurations of density, building form, street geometry, and surface cover. From an urban climate perspective, morphology is important because the geometry and material composition of the urban fabric influence solar exposure, radiation exchange, heat storage, shading, and airflow, thereby contributing to spatial variations in urban microclimatic conditions (Oke, 2012; Grimmond, 2007).

The relationship between urban morphology and climate is particularly relevant to the Urban Heat Island (UHI) effect. The arrangement and composition of buildings and surfaces influence the amount of solar radiation received and stored within the urban fabric, as well as the rate at which heat is released to the atmosphere. Surface properties such as albedo, thermal capacity, emissivity, and moisture availability

further modify these processes. Consequently, differences in building density, height, spacing, street orientation, vegetation, and surface cover can produce substantially different thermal conditions within the same urban area (Dihkan et al., 2015; Hu et al., 2010).

The integration of urban morphology into climate analysis has therefore become increasingly important for connecting urban climatology with planning and design. Rather than treating climatic conditions as independent from the physical structure of cities, contemporary urban climate research increasingly uses measurable morphological parameters to investigate how spatial configurations influence local environmental conditions. This approach provides a basis for translating climatic knowledge into planning and design decisions and is particularly relevant at the neighborhood and street scales, where morphological characteristics can be directly related to pedestrian level microclimate.

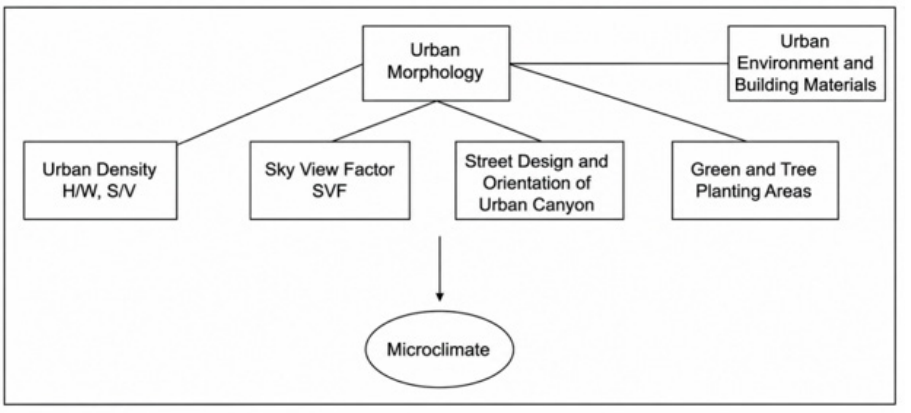


Figure 11. Examples of standard Local Climate Zone (LCZ) classes and their subclasses, illustrating combinations of built-form characteristics and land cover properties within the LCZ classification framework. Source: Stewart and Oke (2012).

The figure 11 illustrates the main urban form and environmental characteristics through which the built environment influences local microclimatic conditions. Urban density and the relationship between building height and street width affect the spatial enclosure and exposure of urban spaces, while the Sky View Factor (SVF) influences the amount of visible sky and consequently the exchange of shortwave and longwave radiation. Street design and orientation further affect solar exposure and airflow, while vegetation and tree planting can provide shade and modify evapotranspiration. Surface and building material properties influence the absorption, storage, and release of heat. These factors interact rather than acting independently, contributing collectively to the spatial variability of urban microclimate.

Among these morphological characteristics, building height, street width, and their relationship are particularly important at the pedestrian level. The ratio between building height and street width, commonly expressed as the height-to-width ratio (H/W), is a key descriptor of urban canyon geometry. The orientation of the street relative to prevailing wind directions also affects the movement and exchange of air within the urban fabric. Studies using numerical simulations have shown that differences in canyon orientation and configuration can influence both temperature and ventilation conditions, demonstrating the importance of considering morphology and wind conditions together rather than independently (Rafail-Kouklis et al., 2021).

1.2.3.1 Urban Canyon

An urban canyon is the spatial environment formed by a street

or pathway enclosed by surrounding buildings. Its geometry creates a distinct local environment in which solar radiation, longwave radiation, heat storage, and airflow are strongly influenced by the surrounding building surfaces. The relationship between building height and street width, together with street orientation and building arrangement, determines the degree of solar exposure and the potential for ventilation within the canyon (Emmanuel, 2005; Santamouris, 2015).

The H/W ratio is therefore an important descriptor of urban-canyon geometry. Increasing building height relative to street width generally reduces the amount of sky visible from street level and can increase shading during periods of direct solar exposure. At the same time, deeper or more enclosed canyons can restrict air exchange depending on wind direction, building arrangement, and the presence of openings. The thermal effect of canyon geometry is consequently not unidirectional: greater enclosure can provide daytime shading while potentially reducing longwave radiative loss and ventilation under certain atmospheric conditions. The thermal performance of an urban canyon therefore depends on the interaction between geometry, orientation, solar position, wind conditions, and surface properties.

The figure 12 illustrates how the geometry of the urban canyon modifies the exchange and accumulation of heat within the built environment. The presence of surrounding buildings limits the visible portion of the sky and can increase the number of interactions between incoming solar radiation and urban surfaces through multiple reflections. Urban materials absorb and store part of this energy, while long wave radiation is

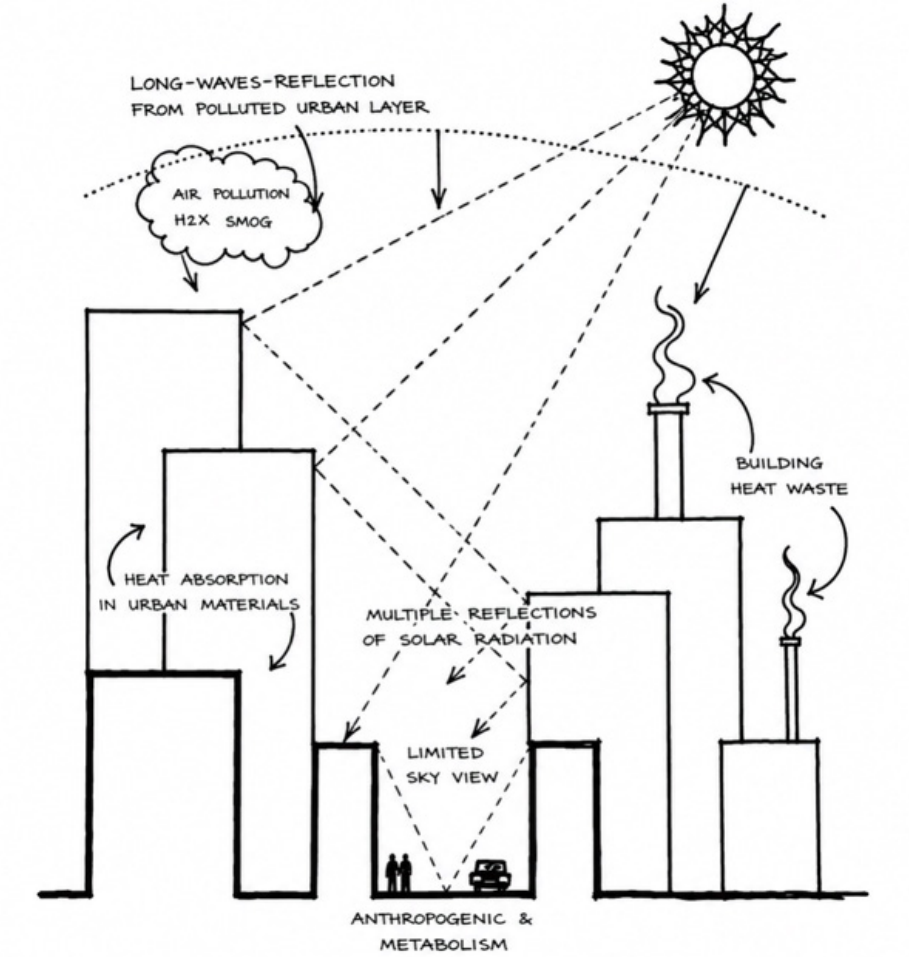


Figure 12. Examples of standard Local Climate Zone (LCZ) classes and their subclasses, illustrating combinations of built form characteristics and land cover properties within the LCZ classification framework. Source: Stewart and Oke (2012).

exchanged between building surfaces and the atmosphere. At the same time, anthropogenic and metabolic activities, together with waste heat from buildings, contribute additional heat to the urban environment. These processes demonstrate that the thermal conditions within an urban canyon result from the combined effects of geometry, radiation, material properties, and anthropogenic heat rather than from air temperature alone.

The relationship between morphology and microclimate becomes particularly evident when considering ventilation. Wind is an important component of urban climatology because it contributes to the transport and redistribution of heat, moisture, and pollutants. The geometry of buildings and streets can accelerate, redirect, channel, or obstruct airflow, thereby influencing the removal of accumulated heat from urban spaces. In densely built environments, insufficient ventilation can reduce convective heat exchange and contribute to the persistence of elevated temperatures, while appropriately configured openings and pathways can support air movement and natural cooling (Fernando et al., 2010; Buccolieri et al., 2010).

Urban ventilation is therefore not determined solely by the presence or absence of wind. It depends on the interaction between regional wind conditions and the three dimensional geometry of the urban fabric. Building height, spacing, orientation, street width, surface roughness, and the configuration of openings between blocks can all influence airflow patterns. Computational approaches such as Computational Fluid Dynamics (CFD) and urban microclimate models can be used to investigate these relationships and evaluate how changes in urban configuration affect wind flow and thermal conditions.

The figure 13 illustrates the multi scale nature of urban atmospheric processes and the connection between larger scale atmospheric circulation and pedestrian level microclimate. At the mesoscale, the urban area modifies the atmospheric boundary layer and interacts with surrounding rural and

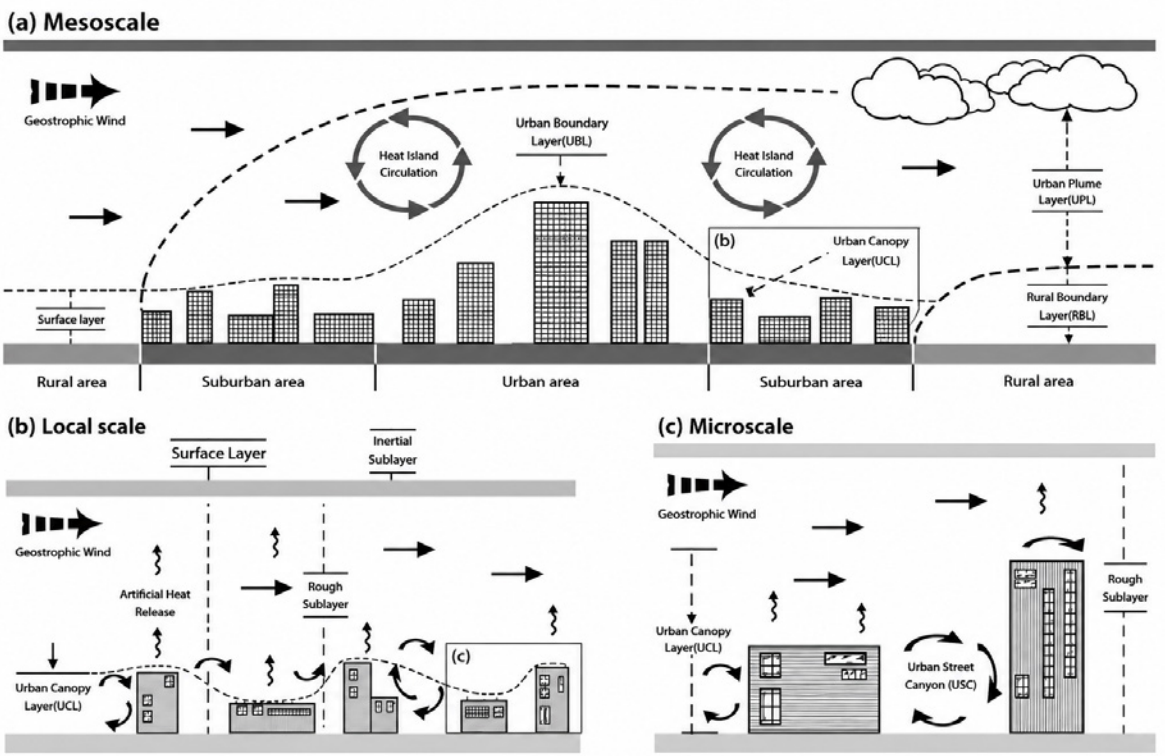


Figure 13. Multi scale atmospheric processes in urban environments, illustrating the interaction between mesoscale, local scale, and microscale atmospheric processes and their influence on the urban canopy and street canyon environment. Source: Oke (1987).

suburban environments. At the local scale, the interaction between wind, surface roughness, anthropogenic heat, and the Urban Canopy Layer influences the distribution and transport of heat within the urban environment. At the microscale, building geometry and street canyon configuration further modify airflow and heat exchange close to the ground, where outdoor thermal conditions are directly experienced by pedestrians. The figure therefore demonstrates that urban microclimate is influenced by processes operating across multiple spatial scales rather than being determined solely by individual buildings or surfaces.

For urban design, this multi-scale relationship is important because modifications made at the neighborhood or street scale occur within a broader atmospheric context. Building configuration, street geometry, vegetation, and surface materials can modify local radiation and airflow, but their effects are also influenced by prevailing wind conditions and the surrounding urban structure. Consequently, the assessment of urban microclimate requires consideration of both the physical characteristics of the study area and the atmospheric conditions under which they interact. This provides the basis for using site scale microclimatic simulation to investigate how proposed urban design interventions modify local environmental conditions.

For the present research, urban morphology provides the physical framework through which the relationship between the built environment and local microclimate can be examined. Building height and density, street width and orientation, urban canyon geometry, vegetation, surface materials, and the configuration of open spaces are particularly relevant because they can influence solar exposure, shading, heat storage, radiation exchange, and airflow. These parameters correspond directly to the characteristics that can be represented and modified within the study area and subsequently evaluated through microclimatic simulation. The comparison between existing and proposed conditions can therefore be interpreted not only as a change in spatial configuration, but also as a change in the environmental processes associated with that configuration. This establishes the theoretical connection between urban morphology, microclimate simulation, and the climate-responsive design strategies investigated in the

following stages of the thesis.

The combined effects of solar radiation, air and surface temperatures, humidity, and wind ultimately determine the thermal conditions experienced by people in outdoor spaces. Understanding how these environmental variables interact with human physiological responses therefore requires a shift from the physical characterization of urban morphology to the assessment of outdoor thermal comfort.

1.2.4 Thermal Comfort

Outdoor thermal comfort refers to the degree to which people perceive the thermal conditions of an outdoor environment as acceptable or comfortable. Unlike indoor environments, outdoor spaces are exposed to continuously changing environmental conditions, including solar radiation, air temperature, humidity, wind, and long wave radiation. These conditions interact with human physiological characteristics and behavioural factors, such as metabolic activity, clothing, and exposure duration, producing variations in thermal sensation and thermal stress (Givoni, 1979; Chen et al., 2011).

Thermal comfort is particularly relevant to the quality and usability of public open spaces, where people are directly exposed to the surrounding microclimate. The thermal conditions of streets, squares, markets, parks, and other outdoor spaces can influence people's willingness to remain in and use these environments. Consequently, urban microclimate is an important component of outdoor environmental quality, particularly in areas exposed to elevated temperatures and heatwaves. Improving thermal conditions can therefore

contribute not only to individual comfort but also to the usability, livability, and social function of public spaces.

Outdoor thermal comfort is determined by the interaction of environmental and personal variables. The principal environmental variables include air temperature, mean radiant temperature (MRT), relative humidity, and wind speed. Among these, radiation is particularly important in outdoor environments because direct and reflected solar radiation, together with long wave radiation emitted by surrounding surfaces, can substantially influence the heat exchange between the human body and its surroundings. Personal variables, particularly clothing insulation and metabolic activity, also affect the human energy balance and therefore influence thermal sensation.

For this reason, thermal comfort cannot be adequately evaluated using air temperature alone. Two urban spaces with similar air temperatures may produce substantially different thermal sensations if they differ in solar exposure, shading, surface temperatures, or wind conditions. This is particularly relevant to urban design, where changes in building configuration, vegetation, shading, and surface materials can modify several environmental variables simultaneously.

The figure 14 illustrates the conceptual relationship between the physical characteristics of the urban environment, local microclimatic conditions, human physiological response, and outdoor thermal comfort. Urban form and density, street geometry and orientation, vegetation, surface and material properties, and anthropogenic heat influence the microclimatic

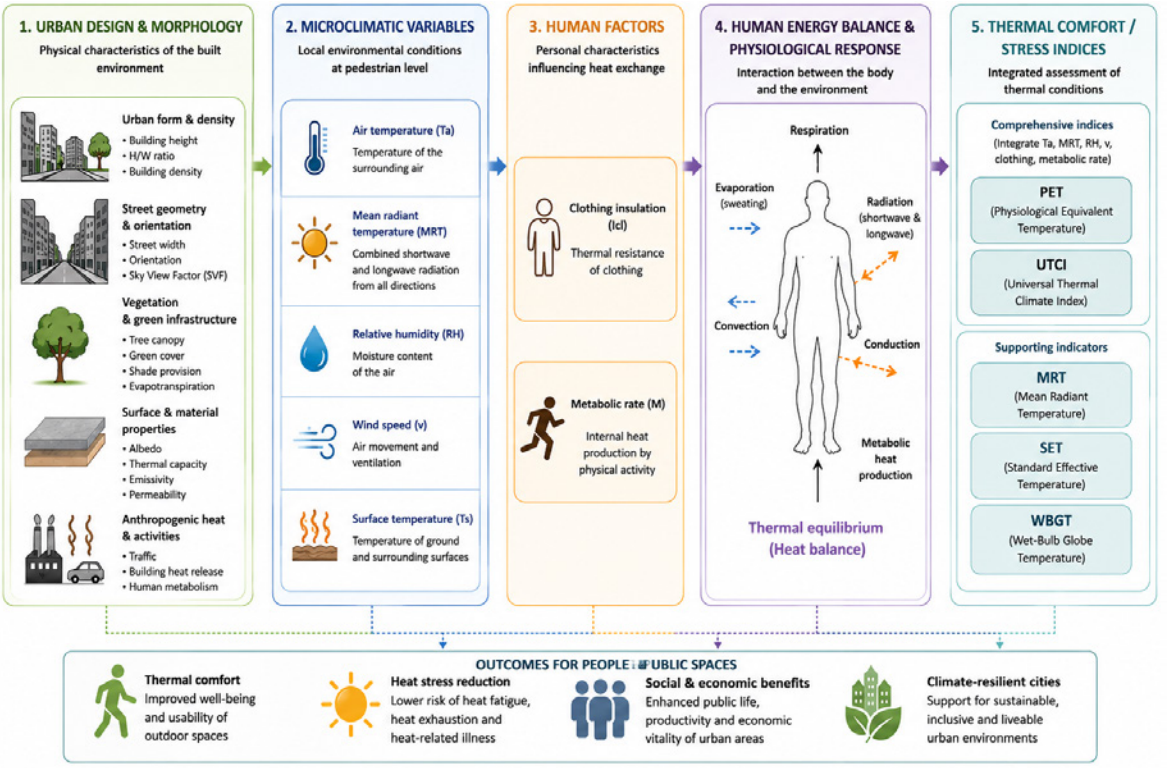


Figure 14. Conceptual framework linking urban design and morphology to outdoor thermal comfort, illustrating the relationships between urban form characteristics, microclimatic variables, human factors, physiological heat balance, and thermal comfort and heat stress indices. Source: Author's elaboration.

conditions experienced at pedestrian level. These conditions are characterized by variables such as air temperature, mean radiant temperature (MRT), relative humidity, wind speed, and surface temperature. The resulting environmental conditions interact with personal factors, particularly clothing insulation and metabolic activity, to determine the exchange of heat between the human body and its surroundings. The resulting physiological response can then be assessed using integrated thermal comfort indices, particularly the Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI), while MRT and complementary indices such as SET and WBGT provide additional information about the thermal environment and heat stress. The framework therefore

establishes a direct connection between climate responsive urban design, pedestrian level microclimate, and human thermal experience, providing the conceptual basis for evaluating the effectiveness of urban heat mitigation strategies investigated in this thesis.

1.2.4.1 Thermal Comfort Assessment

Because outdoor thermal conditions are influenced by multiple interacting variables, several thermal comfort and heat stress indices have been developed to express the combined effect of environmental conditions on the human body. These indices are based on different assumptions and physiological models and therefore are not directly interchangeable. Among the indicators relevant to outdoor urban environments are the Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), Mean Radiant Temperature (MRT), Standard Effective Temperature (SET), and Wet-Bulb Globe Temperature (WBGT).

1.2.4.2 Physiological Equivalent Temperature (PET)

The Physiological Equivalent Temperature (PET) is a widely used index for evaluating outdoor thermal conditions. It is based on the human energy balance and expresses a complex outdoor thermal environment as an equivalent air temperature in a reference indoor environment. PET is defined as the air temperature of a reference environment in which the human body would experience the same physiological conditions, particularly comparable core and skin temperatures, as under the actual outdoor conditions (Höppe, 1999).

PET integrates the effects of several meteorological variables,

including air temperature, mean radiant temperature, relative humidity, and wind speed, together with personal parameters such as clothing and metabolic activity. This allows the combined thermal influence of radiation, air movement, humidity, and air temperature to be expressed through a single temperature based indicator. PET is therefore particularly useful for comparing the thermal conditions of different outdoor spaces and for identifying areas of thermal stress within urban environments.

An important advantage of PET for urban microclimate studies is its intuitive temperature based interpretation. Rather than describing thermal stress only through separate environmental variables, PET expresses the combined physiological effect as an equivalent temperature that can be related to familiar temperature conditions. This makes it useful for communicating the thermal implications of urban design interventions involving shading, vegetation, surface materials, and changes in urban geometry.

1.2.4.3 Universal Thermal Climate Index (UTCI)

The Universal Thermal Climate Index (UTCI) is another comprehensive indicator developed specifically for assessing human thermal stress under outdoor conditions. UTCI is based on a multi-node physiological model and represents the equivalent temperature of a reference environment that would produce the same physiological response as the actual outdoor conditions. The index considers the effects of air temperature, wind speed, humidity, and radiation and incorporates the physiological response of the human body to changing thermal conditions (Jendritzky et al., 2012).

Unlike indices based primarily on a single environmental parameter, UTCI is designed to represent a wide range of outdoor thermal stresses, including conditions associated with cold and heat. Its physiological basis makes it particularly useful for assessing thermal stress across different climatic conditions and for comparing outdoor environments using a standardized framework (Bröde et al., 2012). Both PET and UTCI are therefore relevant to urban microclimate research because they integrate several environmental variables into a human centred assessment. However, they are based on different physiological models and assumptions and should not be interpreted as numerically equivalent measures of thermal comfort. The choice of index should consequently reflect the objectives, available environmental variables, and modelling framework of the study (Höppe, 1999; Bröde et al., 2012).

1.2.4.4 Mean Radiant Temperature (MRT)

Mean Radiant Temperature (MRT) differs from PET and UTCI because it is not, by itself, a thermal comfort index. Instead, it is a key environmental parameter describing the radiative thermal environment experienced by a person. MRT represents the uniform temperature of an imaginary enclosure that would produce the same net radiant heat exchange with the human body as the actual surrounding surfaces and radiation field (ISO 7726, 1998).

MRT is particularly important in outdoor environments because the human body receives radiation from multiple directions, including direct solar radiation, diffuse sky radiation, and long wave radiation emitted or reflected by surrounding buildings and ground surfaces. Consequently, changes in shading,

surface temperature, building geometry, vegetation, and material properties can substantially modify MRT even when air temperature changes only slightly.

This makes MRT especially relevant to the present research. Changes in surface materials, vegetation, building configuration, and shading can modify the radiative environment experienced at pedestrian level, which can subsequently influence PET and other thermal comfort indicators. MRT therefore provides an important physical link between urban design interventions and human thermal perception.

1.2.4.5 Other Thermal Indices

Other indices have also been developed for assessing thermal conditions. Standard Effective Temperature (SET) combines environmental and physiological variables to express thermal conditions through an equivalent temperature based on a standardized reference environment (Gagge et al., 1986). It has been applied in both indoor and outdoor thermal comfort research but is less central to the present analysis.

The Wet-Bulb Globe Temperature (WBGT) is primarily a heat stress indicator developed to evaluate conditions involving air temperature, humidity, radiant heat, and air movement. It is widely used in occupational and sports settings where heat exposure and physiological stress are important concerns. However, its application is less directly suited to the detailed spatial analysis of urban microclimate and pedestrian thermal comfort undertaken in this research.

The distinction between these indices is important because

thermal comfort and heat stress are related but not identical concepts. An index developed primarily for occupational heat stress assessment should not automatically be treated as equivalent to an outdoor thermal comfort index designed to represent the human energy balance under spatially variable urban conditions (ISO 7243, 2017; Höppe, 1999; Bröde et al., 2012).

For the present thesis, thermal comfort provides the human centred component of the urban microclimate assessment. The preceding sections have established that urban morphology, street canyon geometry, vegetation, surface materials, radiation, and airflow influence local environmental conditions. These environmental changes ultimately affect the thermal conditions experienced by pedestrians.

The ENVI-met modelling framework used in this research allows environmental variables relevant to thermal comfort to be assessed at pedestrian level, while its BIO-met component can be used to calculate thermal comfort indicators such as PET and UTCI. The ENVI-met output workflow used for the simulations specifically identifies PET and UTCI as thermal comfort indices that can be calculated from the simulated microclimatic conditions.

Among these indicators, PET is particularly relevant to the present study because it integrates air temperature, humidity, wind, and radiation within a human energy balance framework and can therefore reflect the combined effects of the urban design interventions investigated in this thesis. PET outputs can also be examined spatially and at selected points, allowing differences between areas with different surface materials,

vegetation, and urban configurations to be evaluated.

The assessment of thermal comfort therefore provides a final link between urban form, microclimatic processes, and human experience. While variables such as air temperature, surface temperature, radiation, and wind describe the physical conditions of the urban environment, thermal comfort indicators integrate these factors from the perspective of the human body. This human centered perspective is essential for evaluating climate responsive urban design strategies, as the effectiveness of an intervention should be assessed not only by its ability to modify individual microclimatic variables, but also by its capacity to improve the thermal conditions experienced by people in outdoor spaces. Ultimately, this provides a basis for evaluating whether changes in urban morphology, vegetation, shading, and surface materials can translate into meaningful improvements in pedestrian thermal comfort.

1.3 Microclimate Adaptation and Mitigation Strategies

The preceding sections established the relationship between urban heat, urban morphology, local microclimate, and outdoor thermal comfort. These relationships demonstrate that thermal conditions in urban spaces are influenced not only by background climatic conditions but also by the physical characteristics of the built environment, including building configuration, street geometry, vegetation, surface materials, shading, and the availability of open spaces. Consequently, improving urban thermal conditions requires strategies that respond both to the broader impacts of climate change and to the specific characteristics of the urban environment.

Urban climate responses can broadly be understood through the complementary concepts of adaptation and mitigation. Although these approaches differ in their objectives and mechanisms, they can overlap at the urban scale and generate multiple environmental benefits. Strategies that increase vegetation, provide shade, modify surface materials, improve urban ventilation, reduce anthropogenic heat, or enhance building energy performance can contribute to reducing heat exposure while supporting broader climate objectives.

The effectiveness of these strategies, however, is strongly dependent on local context and spatial configuration. A measure that reduces surface temperature under one climatic

or morphological condition may produce a different outcome elsewhere. (Oke et al., 2017) Similarly, individual interventions can involve environmental trade offs. Increasing surface reflectivity, for example, can reduce solar heat absorption but may also increase reflected shortwave radiation at pedestrian level. (Erell et al., 2014) Vegetation can provide shade and evaporative cooling, while its density and configuration can also influence local airflow. (Bowler et al., 2010) Climate responsive urban design should therefore consider the interaction between urban morphology, material properties, vegetation, atmospheric conditions, and human thermal comfort, rather than relying on a single universal solution. (Oke et al., 2017)

This section reviews the principal strategies relevant to improving urban thermal conditions at the neighborhood and pedestrian scales. It first distinguishes adaptation from mitigation and then examines surface and material based solutions, green infrastructure, building integrated strategies, and Nature based Solutions (NbS). Together, these approaches provide the theoretical basis for understanding and evaluating the climate responsive urban design strategies investigated later in this thesis.

1.3.1 Mitigation and Adaptation

Adaptation and mitigation represent two complementary approaches to addressing climate change and its impacts. According to the Intergovernmental Panel on Climate Change (IPCC), adaptation refers to the process of adjustment to actual or expected climate and its effects, with the aim of moderating harm or taking advantage of potential beneficial opportunities (IPCC, 2022). In urban environments, adaptation

infrastructure, and urban systems to climatic hazards and increasing their capacity to cope with changing environmental conditions.

In the context of urban heat, adaptation measures primarily seek to reduce exposure and vulnerability to elevated temperatures and heat stress. Such measures can include increasing shaded areas, planting trees, incorporating water sensitive features, improving the design and accessibility of public spaces, providing cooler urban environments, and implementing heat action or early warning systems. These interventions primarily address the consequences of climate change by modifying the conditions experienced by people and urban systems at the local scale.

In contrast, climate change mitigation addresses the underlying causes of climate change. The IPCC defines mitigation as human intervention to reduce greenhouse gas emissions or enhance greenhouse gas sinks (IPCC, 2022). In urban environments, mitigation can involve improving building energy efficiency, reducing energy demand, increasing the use of renewable energy, improving building envelopes, reducing operational emissions, and selecting materials and technologies with lower environmental impacts.

The distinction between adaptation and mitigation therefore lies primarily in what each approach seeks to address. Adaptation responds to the impacts and risks associated with climate change, whereas mitigation seeks to reduce the processes that contribute to climate change. The two approaches also differ in their spatial and temporal characteristics. Adaptation is often place specific and

can provide relatively immediate benefits to local communities, whereas mitigation generally requires longer term action and produces benefits through the gradual reduction of greenhouse gas emissions and their associated climate effects (IPCC, 2007; Klein et al., 2007; Biesbroek et al., 2008).

Dimension	Climate-change mitigation	Climate adaptation	Integrated adaptation–mitigation approach
Primary objective	Reduce greenhouse-gas emissions or enhance carbon sinks	Reduce vulnerability and exposure to climate impacts	Address climate impacts while reducing emissions and supporting long-term resilience
Main focus	Causes of climate change	Consequences and risks of climate change	Interaction between climate risks, emissions, and urban resilience
Temporal perspective	Primarily long-term	Often immediate to medium-term	Combines immediate responses with long-term strategies
Spatial scale	Local to global	Primarily local and regional	Multi-scale, linking local interventions with broader climate objectives
Urban focus	Energy efficiency, renewable energy, low-carbon buildings, sustainable transport	Heat adaptation, shading, vegetation, cooling spaces, water-sensitive design	Integrated urban design combining thermal adaptation, resource efficiency, and low-carbon development
Relationship to urban heat	Reduces energy demand, emissions, and potentially anthropogenic heat	Reduces heat exposure, thermal vulnerability, and heat stress	Combines reduced heat exposure with reduced energy demand and broader environmental benefits
Examples relevant to urban design	Energy-efficient buildings, cool roofs, renewable energy, low-carbon materials	Trees, shading, permeable surfaces, cooling public spaces, water-sensitive landscapes	Green infrastructure combined with energy-efficient buildings, climate-responsive surfaces, shading, and multifunctional public spaces
Primary scale of benefit	Reducing energy demand, anthropogenic heat, and environmental impacts	Improving pedestrian thermal conditions and reducing heat exposure	Combining microclimate-sensitive urban design with broader resilience and environmental objectives

Table 2. Principal differences between climate adaptation and mitigation
Source: Author's synthesis based on IPCC (2007, 2022), Klein et al. (2007), Biesbroek et al. (2008), and Pollo and Trane (2021).

The table 2 highlights that climate change mitigation and adaptation differ in their primary objectives, spatial and temporal characteristics, and mechanisms of action, while also demonstrating the potential for integrated approaches. In urban environments, adaptation measures can provide relatively immediate and place specific benefits by reducing exposure and vulnerability to climatic hazards, whereas mitigation contributes to longer term reductions in greenhouse gas emissions and associated climate impacts.

Despite these differences, the two approaches should not be considered independent or mutually exclusive. Individual urban interventions can contribute to both objectives. Urban vegetation, for example, can reduce pedestrian heat exposure through shading and evapotranspiration while also providing broader environmental benefits. Similarly, energy efficient buildings can reduce greenhouse gas emissions while decreasing cooling demand and associated waste heat. An integrated approach can therefore strengthen urban resilience while addressing climate risks at different spatial and temporal scales.

This interaction is particularly relevant to urban heat, which results from the combined influence of broader climatic conditions and local urban characteristics. Increasing background temperatures and more frequent heatwaves can increase heat exposure, while building density, street geometry, surface properties, vegetation, shading, and anthropogenic heat can further modify local thermal conditions. These characteristics influence how solar radiation is absorbed, stored, reflected, and released within the urban environment

and therefore affect the thermal conditions experienced at pedestrian level.

Within this context, urban heat mitigation can be understood as the set of interventions that modify the physical processes responsible for local heat accumulation or reduce thermal exposure within the urban environment. Common approaches include high albedo and permeable surfaces, green infrastructure, shading, water-sensitive design, improved urban ventilation, and energy efficient buildings. These strategies influence different components of the urban energy balance, including surface temperature, radiation exchange, evapotranspiration, airflow, and anthropogenic heat release.

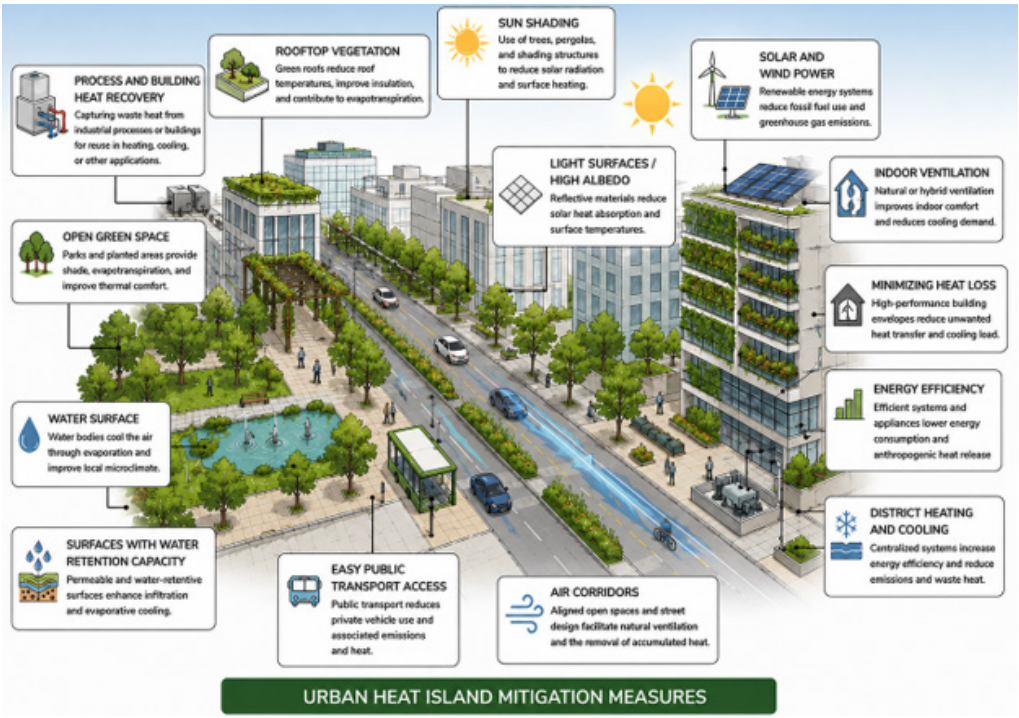


Figure 15. Urban climate adaptation and Urban Heat Island mitigation measures across the urban environment, illustrating strategies related to shading, vegetation, surface properties, water management, ventilation, energy efficiency, heat recovery, public transport, and renewable energy. Adapted from Ichinose, Matsumoto and Kataoka (2008).

The figure 15 illustrates the range of urban climate strategies that can contribute to reducing heat exposure, mitigating Urban Heat Island effects, and improving the environmental performance of urban areas. The strategies include sun shading, rooftop and ground level vegetation, open green spaces, light and high albedo surfaces, water surfaces, water retentive and permeable surfaces, and air corridors.

These measures can influence urban thermal conditions through mechanisms such as reducing solar heat absorption, providing shade, supporting evapotranspiration and evaporative cooling, improving infiltration, and facilitating the movement and removal of accumulated heat. The figure also illustrates complementary building and infrastructure scale measures, including heat recovery, improved energy efficiency, reduced heat loss, indoor ventilation, district heating and cooling, renewable energy generation, and accessible public transport. Together, these interventions demonstrate that climate responsive urban design involves coordinated actions across buildings, surfaces, vegetation, water systems, transportation, and energy infrastructure rather than relying on a single cooling strategy.

The relevance of these strategies depends on the climatic, morphological, and functional characteristics of the urban environment. Their effectiveness is therefore not uniform across all locations, and individual interventions may produce different outcomes depending on factors such as solar exposure, urban geometry, vegetation density, surface properties, wind conditions, and water availability. For this reason, climate responsive urban design requires the selection and

combination of strategies according to local conditions and the specific environmental objectives of the intervention.

The distinction between adaptation and mitigation provides the broader framework for evaluating these strategies. Adaptation oriented interventions primarily seek to reduce heat exposure and improve the capacity of urban spaces and communities to cope with elevated temperatures, whereas climate change mitigation measures additionally address energy consumption, greenhouse gas emissions, or other drivers of climate change. In practice, however, many urban interventions provide benefits across both categories. The classification should therefore be understood as a distinction between their primary objectives rather than as a strict separation between different types of interventions.

For the present research, the emphasis is placed primarily on local adaptation and urban heat mitigation through modifications to the physical environment. The proposed interventions involve changes to elements such as surface materials, vegetation, shading, and open space configuration while maintaining the principal function and morphology of the study area. Their effectiveness can therefore be evaluated through changes in pedestrian level microclimatic conditions and outdoor thermal comfort.

The following subsections examine the main categories of strategies relevant to this approach, beginning with surface and material based solutions, followed by green infrastructure, building integrated strategies, and Nature based Solutions. These categories are not mutually exclusive; rather, they

represent complementary approaches that can be combined according to the morphological, climatic, functional, and spatial characteristics of an urban environment.

1.3.2 Surface and Material-Based Solutions

The thermal performance of urban surfaces is strongly influenced by their radiative, thermal, and hydrological properties. Among these characteristics, solar reflectance, or albedo, is particularly important because it determines the proportion of incoming shortwave solar radiation that is reflected rather than absorbed by a surface. Materials with higher albedo can therefore absorb less solar energy and, under appropriate conditions, achieve lower surface temperatures than darker, low albedo materials (Nazarian et al., 2019; Santamouris, 2013).

The relevance of material-based strategies to Urban Heat Island (UHI) mitigation is particularly evident in streets, plazas, pedestrian areas, parking spaces, and other urban surfaces where impervious materials occupy a substantial proportion of the ground plane. Modifying the thermal and radiative properties of these surfaces can alter the local surface energy balance and influence the exchange of heat and radiation between the ground, buildings, and surrounding atmosphere. However, material performance cannot be assessed through albedo alone. Thermal capacity, thermal conductivity, emissivity, permeability, moisture availability, surface condition, and solar exposure also influence how much heat is absorbed and stored, how rapidly it is released, and how the surface interacts with the surrounding environment.

Although many conventional building materials have relatively high long wave emissivity, variations in solar reflectance can substantially influence daytime surface temperatures and the radiative environment. This distinction is particularly important at pedestrian level, where reflected shortwave radiation can influence mean radiant temperature (MRT) and, consequently, outdoor thermal comfort. Therefore, a material that reduces its own surface temperature does not necessarily produce an equivalent improvement in the thermal conditions experienced by pedestrians.

1.3.2.1 Pavements

Reflective, or "cool," pavements are among the most widely investigated material based strategies for reducing urban surface temperatures. They generally use materials or coatings with increased solar reflectance, allowing a greater proportion of incoming solar radiation to be reflected rather than absorbed. Increasing pavement albedo can consequently reduce surface temperatures and sensible heat release from the pavement to the surrounding atmosphere (Synnefa et al., 2006; Qin, 2015; Rossi et al., 2014; Santamouris, 2013).

Cool pavements can be implemented through high albedo aggregates, specially formulated surface materials, or reflective coatings applied to existing pavements. This makes them particularly relevant to existing urban areas where the spatial configuration and function of streets, plazas, or pedestrian spaces need to be maintained while their thermal performance is improved. In such contexts, modifying the surface characteristics can provide a relatively direct intervention without requiring major changes to the overall

urban morphology.

However, the thermal benefits of cool pavements should not be interpreted solely in terms of reduced surface temperature. Increasing surface reflectance can also increase the amount of shortwave radiation reflected toward pedestrians, adjacent façades, or windows. Under particular solar and geometrical conditions, this may increase radiant exposure and glare at pedestrian level or contribute to additional heat gains in surrounding buildings (Levinson & Akbari, 2010; Santamouris, 2013; Taleghani, 2018). Consequently, high reflectance does not automatically translate into improved outdoor thermal comfort. This distinction is particularly important because pedestrian thermal comfort is determined by the combined effects of air temperature, humidity, wind, and radiation, rather than by surface temperature alone.

The effectiveness of cool pavements at the neighborhood scale is also strongly dependent on the extent of the treated surface, urban geometry, atmospheric conditions, solar exposure, and surrounding materials. Field studies and reviews indicate that changes in air temperature may be relatively small or spatially variable, even when substantial reductions in pavement surface temperature are achieved (LBNL, 2019; Santamouris, 2013). The surrounding urban morphology therefore plays an important role in determining whether a material intervention produces a meaningful improvement in the broader microclimatic environment.

Permeable and water-retentive pavements provide an additional approach to modifying urban surface conditions.

By allowing infiltration and retaining moisture within or beneath the surface, these systems can support evaporative cooling when sufficient water is available. Their performance therefore depends on both the physical properties of the material and the availability of moisture. In addition to their potential thermal benefits, permeable surfaces can contribute to stormwater management and reduce surface runoff. Combining appropriate reflectivity with permeability can therefore provide multiple environmental functions within the same intervention.

The long term effectiveness of pavement based strategies also depends on maintenance and material durability. Surface soiling and wear can reduce solar reflectance over time, while some reflective coatings may require periodic maintenance or reapplication. Furthermore, the environmental performance of a pavement should be considered over its entire life cycle, including material production, embodied energy, durability, maintenance requirements, and associated greenhouse gas emissions. Consequently, a material with favourable initial thermal properties does not necessarily provide the greatest overall environmental benefit if its durability and lifecycle impacts are unfavourable (Qin, 2015; Giorio et al., 2023).

For these reasons, pavement selection should be based on a multi criteria assessment rather than on albedo alone. In pedestrian environments, surface temperature, reflected radiation, shading conditions, permeability, moisture availability, durability, and thermal comfort should be considered simultaneously. This is particularly relevant to the present research, where modification of pavement

characteristics represents one of the principal design interventions. The effects of the proposed material changes are therefore evaluated through pedestrian level microclimatic conditions rather than through surface temperature alone.

1.3.2.2 Façades

Building façades also contribute to the urban thermal environment because they form a substantial part of the three dimensional urban surface and continuously interact with solar and long wave radiation. Their thermal behaviour is influenced by solar reflectance, emissivity, thermal properties, orientation, and exposure. As urban development becomes increasingly dense and vertical, façades represent an increasingly important component of the urban surface exposed to solar radiation.

During daytime conditions, solar reflectance is generally the dominant factor influencing façade surface temperature, while emissivity has a more limited influence under strong solar exposure. During nighttime conditions, however, emissivity becomes more important because long-wave radiative exchange plays a greater role in the cooling of façade surfaces (Santamouris et al., 2011). Although modifying emissivity can influence building thermal performance, changes in solar reflectance are generally considered an important strategy for reducing daytime façade heating (Alonso et al., 2016).

Studies have demonstrated the potential of high-reflectance façade materials and coatings to reduce façade surface temperatures. Bishara et al. (2017), for example, reported that high reflectance pigments could substantially reduce façade

surface temperatures compared with low reflectance coatings. Other research has also indicated that façade retrofits can reduce building energy consumption and contribute to improved thermal performance (Hong et al., 2022; Xu, 2019). The potential benefits therefore extend beyond the immediate surface temperature of the façade to include building energy performance and the wider urban thermal environment.

As with pavements, however, façade reflectivity should be considered within the broader urban radiation environment. Reflected shortwave radiation can be redirected toward neighbouring buildings, streets, or pedestrians, meaning that increasing reflectance does not necessarily produce a uniform improvement in outdoor thermal conditions. The effect depends on façade orientation, building geometry, solar position, surrounding surfaces, and the distribution of radiation within the urban canyon. Research has also indicated that high reflectance façades can influence pedestrian thermal conditions, with Taleghani et al. (2021) reporting an improvement in neighborhood scale PET associated with high reflectance façade surfaces during summer conditions.

For the present research, façade interventions are less directly relevant than surface modifications because the proposed design primarily addresses the public realm and pedestrian environment. Nevertheless, façade properties remain an important component of the urban energy balance and help explain the interaction between building surfaces, solar radiation, and pedestrian level microclimate. Their consideration is therefore important for understanding the broader thermal context within which surface based

interventions operate.

Overall, material based strategies demonstrate that urban heat mitigation cannot be reduced to the selection of materials with a single favourable property. The thermal performance of urban surfaces results from the interaction between albedo, emissivity, thermal properties, moisture, permeability, shading, urban geometry, solar exposure, and radiation exchange. A material that reduces surface temperature may therefore have different consequences for pedestrian thermal comfort depending on its location and surrounding conditions. For this reason, material interventions should ultimately be evaluated through their effects on the wider urban microclimate and on pedestrian level thermal comfort indicators, particularly MRT and PET, rather than through surface temperature alone.

For the present thesis, this distinction is particularly important because the proposed intervention modifies the characteristics of the public realm while maintaining its principal urban function. The evaluation of the intervention therefore considers whether changes in surface materials contribute to improved pedestrian level thermal conditions when combined with the existing and proposed vegetation, shading, and urban morphology. This provides the basis for assessing material based strategies through microclimatic simulation and establishes the transition to the following section on green infrastructure, where vegetation and tree canopy are examined as complementary mechanisms for urban heat mitigation.

1.3.3 Green Infrastructure

Green infrastructure refers to the integration of vegetation and ecological elements into the urban environment to provide environmental, social, and climatic functions. In the context of urban heat mitigation, vegetation can modify local microclimatic conditions through several interconnected mechanisms, particularly shading, evapotranspiration, modification of surface characteristics, and interaction with airflow. These processes can reduce solar exposure and surface heating while contributing to improved thermal conditions at pedestrian level.

Trees are particularly important within urban green infrastructure because their canopies intercept incoming solar radiation and create shaded areas beneath and around them. Shading reduces the amount of direct solar radiation reaching pedestrians, buildings, and ground surfaces and can therefore substantially influence the radiative environment. This is especially relevant to outdoor thermal comfort because reducing direct solar exposure can lower the radiant load experienced by pedestrians. At the same time, vegetation contributes to cooling through evapotranspiration, whereby water is transferred from vegetation and soil to the atmosphere as water vapour. This process can dissipate a portion of the available energy as latent heat and contribute to lower surface and air temperatures when sufficient moisture is available.

The cooling performance of vegetation depends strongly on species characteristics, canopy size, density, spatial arrangement, water availability, and the surrounding urban morphology (Bowler et al., 2010). Consequently, vegetation

should not be evaluated simply according to its total quantity or percentage of green cover. The configuration of trees and other planted elements determines the extent, continuity, and intensity of shade and influences the relationship between cooling and ventilation. The position of vegetation relative to buildings, streets, pedestrian paths, and open spaces is therefore an important component of climate responsive urban design.

The spatial arrangement of trees is particularly relevant to their microclimatic performance. Studies have indicated that groups or clusters of trees can create larger and more continuous shaded areas and enhance the combined effects of shading and evapotranspiration compared with isolated trees under appropriate conditions (Shashua-Bar & Hoffman, 2000). Clustered vegetation can therefore provide a more continuous reduction in solar exposure and contribute to the formation of localized cooler areas within the urban environment. However, the effectiveness of clustering depends on the specific configuration of the site and the relationship between vegetation, buildings, and pedestrian spaces.

Vegetation also interacts with the urban wind environment. Tree canopies and planted areas can act as porous aerodynamic elements that modify wind speed, direction, and turbulence. Depending on their density and spatial arrangement, vegetation can reduce wind speed, redirect airflow, or provide protection from hot air movement, with potential implications for pedestrian thermal comfort (Bowler et al., 2010). This interaction demonstrates that vegetation density must be considered together with the existing wind conditions and urban morphology. While vegetation can provide valuable

shade and protection from excessive heat, excessively dense planting may restrict beneficial airflow in some urban configurations.

The relationship between vegetation and thermal comfort is therefore highly context-dependent. Dense vegetation can provide substantial shading and cooling, but its effectiveness may be reduced if planting configurations obstruct ventilation or limit air movement. Conversely, sparse vegetation may provide less overall cooling but can be strategically positioned to provide targeted shade while maintaining important ventilation paths. The optimal vegetation configuration should therefore be determined according to the climatic conditions, urban morphology, spatial function, and specific thermal objectives of the site rather than by maximizing vegetation density alone.

Beyond its direct influence on thermal conditions, increased vegetation can provide broader environmental and social benefits. Green infrastructure can contribute to improved air quality, reduced glare, ecological connectivity, recreational opportunities, Physiological restoration, and reduced vulnerability to heat related health impacts (Gorsevski et al., 1998; Mullaney et al., 2015; Lau et al., 2016; Frumkin et al., 2010; Tan et al., 2015). Vegetation can therefore contribute simultaneously to environmental quality, public health, and the usability of urban public spaces. These additional benefits reinforce the role of green infrastructure as a multifunctional component of sustainable urban development rather than solely as a heat mitigation measure. Trees can also influence the energy performance of adjacent buildings by reducing

solar exposure through canopy shading. Depending on tree species, canopy density, building configuration, and climatic conditions, shading from trees can contribute to reductions in building cooling demand (Akbari et al., 2001). The potential energy benefits therefore depend on the spatial relationship between vegetation and buildings and should not be assumed to be uniform across different urban contexts.

Green infrastructure can be implemented through a wide range of spatial interventions, including street trees, parks, pocket gardens, planted courtyards, green roofs, rooftop gardens, vegetated corridors, and smaller scale planters. The appropriate form of intervention depends on available space, existing urban morphology, functional requirements, maintenance capacity, water availability, and the intended use of the space. In dense urban environments, smaller and strategically positioned planting elements can therefore complement larger green spaces by providing targeted shade and localized environmental benefits.

The spatial and functional requirements of public spaces are particularly important when integrating vegetation into active urban environments. In areas with permanent or temporary activities, excessive planting can interfere with circulation, visibility, accessibility, maintenance, and the functional use of the space. Green infrastructure should therefore be integrated in a way that improves environmental performance without compromising the primary social and spatial functions of the urban environment.

This consideration is particularly relevant to the present research. The study area includes an active public market in which the central space must remain accessible to market activities, pedestrian movement, and temporary commercial uses. Consequently, permanent vegetation occupying the central functional area would not be appropriate. Instead, vegetation is integrated strategically around and within the surrounding public realm through a limited number of trees and movable planting elements, allowing shading and environmental benefits to be provided while preserving flexibility, accessibility, and market functionality.

The design approach therefore considers vegetation as a spatial and microclimatic strategy rather than simply an increase in green coverage. The location, canopy characteristics, density, and relationship of planting to pedestrian areas and surrounding built form are considered in relation to shading, solar exposure, airflow, and thermal comfort. This approach is particularly relevant to the microclimatic simulation undertaken in this thesis, where the effects of vegetation are evaluated together with changes in surface materials and urban spatial configuration rather than as an isolated intervention.

Overall, green infrastructure represents a complementary approach to material based heat mitigation. Whereas surface interventions primarily modify the radiative and thermal properties of the urban ground plane, vegetation can additionally provide shade, evapotranspirative cooling, and modification of local airflow. The combination of these mechanisms can contribute to improved pedestrian level thermal conditions while also providing broader environmental

and social benefits. For this reason, the integration of appropriately configured vegetation with surface and spatial interventions provides an important component of climate responsive urban design and establishes the basis for the following discussion of building integrated strategies.

1.3.4 Building-Integrated Strategies

Buildings are both contributors to and potential components of urban climate mitigation. Their energy consumption, material properties, heat storage, and waste heat emissions influence the surrounding urban environment, while their roofs and façades provide opportunities for reducing energy demand and improving thermal performance. Consequently, building-integrated strategies can contribute to climate mitigation and, under appropriate conditions, to the reduction of urban heat accumulation. Nevertheless, these factors are among the most influential variables at the urban local scale, particularly when considering anthropogenic heat released by buildings and human metabolism.

The concept of green buildings has emerged as an important approach to improving the environmental performance of the built environment. Green building strategies integrate architectural design, material selection, energy efficient systems, and environmental technologies to reduce resource consumption and associated environmental impacts. In relation to urban heat, these strategies can influence both building scale thermal performance and the wider urban energy balance by reducing operational energy demand, modifying surface characteristics, increasing vegetative cover, and reducing the amount of anthropogenic heat released into the urban environment (Santamouris, 2014; Akbari et al., 2001;

Salvati et al., 2019). Improving building energy efficiency is particularly relevant during periods of elevated outdoor temperature. At the urban local scale, it is therefore important to consider the effects of anthropogenic heat, including heat released by buildings and human metabolism. Reducing cooling demand can decrease electricity consumption and, depending on the energy system and building technology, reduce the amount of waste heat released from mechanical cooling systems into the surrounding urban environment. Improvements to the building envelope, including insulation, solar control, glazing performance, and shading, can further reduce heat transfer between indoor and outdoor environments. These strategies primarily contribute to building scale energy performance but can also support broader urban climate objectives.

The thermal properties of building surfaces are another important component of building integrated climate strategies. Reflective or cool roofs and façades can increase solar reflectance and reduce the amount of shortwave radiation absorbed by building surfaces. This can lower surface temperatures and potentially reduce heat transfer into buildings. The effectiveness of reflective surfaces, however, depends on solar exposure, orientation, surrounding geometry, and the interaction of reflected radiation with neighbouring buildings and outdoor spaces. Their contribution should therefore be considered as part of the wider urban radiation environment rather than as an isolated material intervention.

Vegetated building elements provide an additional approach. Green roofs and vegetated façades can modify the thermal behaviour of buildings through shading and evapotranspiration while also providing ecological and environmental benefits. Green roofs can reduce direct solar exposure of roof surfaces

and, when sufficient moisture is available, contribute to evaporative cooling. Vegetated façades can similarly provide shading and modify the surface energy balance of building envelopes. These strategies can therefore complement conventional energy efficiency measures while contributing to the environmental quality of the surrounding urban environment.

Low carbon materials and construction approaches provide another dimension of building integrated climate action. Reducing the embodied environmental impacts of construction materials can contribute to climate change mitigation over the building life cycle, while appropriate material selection can also influence thermal storage and surface behaviour. However, the relationship between material properties and urban thermal performance depends on the specific building configuration, climate, and surrounding urban morphology. Consequently, material selection should be evaluated together with operational energy performance, durability, and lifecycle impacts rather than through a single thermal characteristic.

The relationship between building integrated strategies and urban microclimate is strongly influenced by urban morphology. Building height, density, spacing, orientation, façade exposure, and the configuration of surrounding streets and open spaces determine how buildings interact with solar radiation and airflow. Modifications to roofs and façades may therefore produce different outcomes depending on the geometry and density of the surrounding urban fabric. Similarly, the benefits of building energy efficiency or reduced waste heat may extend beyond individual buildings but are influenced by the intensity and spatial distribution of building energy use across the neighborhood.

Recent research has further emphasized the potential contribution of green building strategies to urban heat mitigation through the combined effects of improved energy efficiency, reduced waste heat, reflective surfaces, and vegetated building components (Rastinifard et al., 2024). These approaches demonstrate that buildings can play an important role within broader urban climate strategies, particularly when building scale interventions are coordinated with changes to streets, open spaces, vegetation, and surface materials.

Nevertheless, building integrated strategies should not be considered independently from the public realm. The thermal conditions experienced at pedestrian level result from the interaction between building surfaces, ground materials, vegetation, solar radiation, wind, and the configuration of open spaces. A highly efficient building envelope, for example, does not necessarily improve pedestrian thermal comfort if the surrounding public space remains highly exposed to solar radiation and lacks shading. Conversely, interventions in streets and open spaces can complement building scale measures by modifying the outdoor thermal environment in which buildings are located.

For the present research, building integrated strategies are therefore considered primarily as complementary components of the broader urban heat mitigation framework. The design intervention investigated in this thesis focuses predominantly on the public realm common open spaces, including surface materials, vegetation, shading, and open space configuration, rather than on modifications to existing building envelopes or energy systems. Existing building scale measures are consequently not the principal interventions evaluated

through the microclimatic simulation. Nevertheless, their consideration is important for understanding the wider interaction between buildings, anthropogenic heat, radiation, and urban microclimate. This distinction allows the research to maintain a clear focus on neighborhood scale and pedestrian level interventions while acknowledging that the thermal performance of urban spaces is embedded within a larger building street environment system. The following section therefore moves from building scale strategies toward Nature based Solutions, which integrate vegetation, water, soil, and ecological processes into urban design and can operate across multiple spatial scales.

1.3.5 Nature-Based Solutions

Nature based Solutions (NbS) are defined as actions to protect, sustainably manage, and restore natural or modified ecosystems in ways that address societal challenges while simultaneously providing human well being and biodiversity benefits (IUCN, 2016). Within the urban context, NbS provide a framework for integrating ecological processes into the built environment to address environmental and social challenges associated with climate change, urbanisation, and environmental degradation. Their relevance to urban climate adaptation lies in their ability to work with natural processes rather than relying exclusively on conventional engineered infrastructure.

In relation to urban heat, NbS can contribute to thermal regulation through mechanisms including shading, evapotranspiration, water retention, and modification of surface characteristics. Urban forests, street trees, green roofs,

wetlands, rain gardens, restored waterways, and other green and blue infrastructures can influence the local surface energy balance and, under suitable conditions, contribute to lower surface and air temperatures (EEA, 2021). Vegetation can intercept solar radiation and provide shade, while evapotranspiration transfers heat from the surface and vegetation into the atmosphere through water vapour. These processes can be particularly relevant to outdoor thermal conditions at the pedestrian level.

Beyond thermal regulation, NbS can provide a range of additional environmental and social benefits. Vegetated and water sensitive systems can support biodiversity, improve stormwater management, contribute to carbon sequestration, enhance ecological connectivity, and create more attractive and usable public environments. Consequently, NbS are increasingly considered multifunctional approaches to urban resilience rather than interventions designed exclusively for temperature reduction (Kabisch et al., 2016).

A key characteristic of NbS is therefore their multifunctionality. Unlike a single-purpose technical intervention, an NbS intervention can address several urban challenges simultaneously. For example, a rain garden can combine stormwater management with vegetation, habitat provision, and potential microclimatic benefits; a tree corridor can provide shade while supporting pedestrian mobility and ecological connectivity; and a pocket park can combine recreation, vegetation, biodiversity, and local thermal regulation. This multifunctional character allows NbS to contribute simultaneously to environmental, social, and, where

appropriately planned, economic objectives (Frantzeskaki, 2019).

The effectiveness of NbS, however, is strongly dependent on contextual integration. Their performance is influenced by landscape structure, urban morphology, climatic conditions, soil characteristics, water availability, vegetation type, spatial configuration, and maintenance practices (Demuzere et al., 2014). The thermal effect of a tree, for example, depends not only on the presence of vegetation but also on canopy size, density, solar exposure, surrounding buildings, wind conditions, and available water. Similarly, the performance of green or blue infrastructure can vary according to its spatial relationship with streets, buildings, and other open spaces NbS should therefore be understood as context-dependent design strategies rather than universally transferable solutions.

This contextual dimension is particularly important in dense urban environments, where the introduction of ecological infrastructure must coexist with existing circulation systems, buildings, infrastructure, and public space functions. NbS do not necessarily require the complete transformation of an urban area. Instead, they can be integrated incrementally into existing urban structures through interventions such as pocket parks, tree corridors, rain gardens, permeable landscapes, green roofs, and the restoration of existing ecological systems.

The figure below illustrates a transition from an original landscape to a degraded condition and subsequently to a restored condition, in which ecological restoration measures are combined with infrastructure and conservation strategies.

The figure demonstrates two important characteristics of NbS identified by the IUCN: first, that NbS can complement conventional infrastructure and other interventions; and second, that natural areas or conservation measures established for another purpose can also contribute to addressing societal challenges through NbS approaches (IUCN, 2016).



Figure 16. Hypothetical scenario illustrating the use of Nature-based Solutions in conjunction with infrastructure development and protected area conservation. Source: IUCN (2016).

The figure 16 illustrates a hypothetical transition from an original landscape to a degraded condition and subsequently to a restored condition, showing how Nature based Solutions can be implemented alongside infrastructure development and protected area conservation. The figure demonstrates that NbS are not necessarily independent interventions; rather, ecological restoration can be combined with conventional infrastructure and conservation measures to address environmental pressures while maintaining or enhancing ecosystem functions (IUCN, 2016).

Although the example is presented at a broader landscape scale, the underlying principle is transferable to urban environments. Green corridors, vegetated streets, pocket parks, rain gardens, and water sensitive landscapes can similarly combine ecological processes with existing urban infrastructure. In this way, NbS can contribute to climate adaptation while also supporting biodiversity, water management, public space quality, and other urban functions.

For the present research, the multifunctional and context sensitive character of NbS is particularly relevant. The case study area is an active urban public environment in which accessibility, circulation, market activity, and existing spatial functions must be maintained. Consequently, the objective is not to maximise the amount of vegetation or replace the existing urban structure with a predominantly green landscape. Instead, nature based interventions are considered as targeted elements within the existing public realm, selected according to their spatial feasibility and potential contribution to microclimatic improvement.

This approach is consistent with the broader objective of the research, in which vegetation, shading, surface materials, and open space configuration are considered together. In this context, trees and planted areas can provide shade and evapotranspirative cooling, while permeable or water sensitive landscape elements can support additional environmental functions. Their effectiveness is evaluated in relation to the surrounding urban morphology and the functional requirements of the public space rather than as isolated ecological interventions.

While Nature based Solutions provide a broad framework for integrating ecological processes into urban adaptation, their implementation at the neighborhood scale requires principles that can be translated into spatially explicit and measurable criteria. In this respect, urban greening frameworks can help move from general objectives concerning access to nature and vegetation toward more tangible considerations of visual contact, tree canopy provision, and proximity to green space. One such framework is the 3–30–300 principle, proposed by urban forestry researcher Cecil Konijnendijk. The principle recommends that people should be able to see at least three large trees from their everyday environments, that neighborhoods should aim for approximately 30% tree canopy cover, and that residents should have access to a high quality, publicly accessible green space within approximately 300 m (Konijnendijk, 2021).

The three components address different spatial dimensions of urban greening. The "3" concerns visual contact with vegetation at the individual level; the "30" addresses tree canopy

provision at the neighborhood scale; and the "300" considers the spatial accessibility of high quality public green space. Together, these criteria provide a simple framework for evaluating not only the quantity of urban vegetation but also its distribution, visibility, and relationship to everyday urban life.

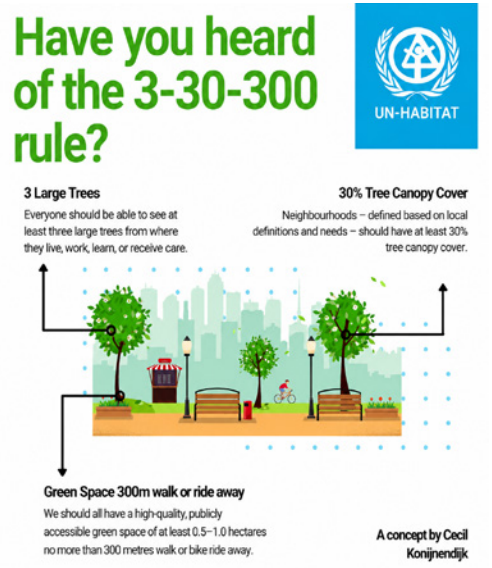


Fig. 16 3-30-300 Regulation By Dr. Konijnendijk, Source: 2024 World Cities Report on strategies to build nature and resilience into our cities

Figure 17. The 3–30–300 principle for urban greening, illustrating the recommended relationship between visual access to trees, neighborhood tree canopy cover, and proximity to high quality public green space. Source: Konijnendijk (2021); adapted from UN-Habitat, World Cities Report (2024).

The figure 17 illustrates the three components of the principle and their relationship to different scales of urban greening. The "3" refers to the recommendation that people should be able to see at least three large trees from places where they live, work, learn, or receive care. The "30" refers to a target of at least 30% tree canopy cover at neighborhood scale, while the "300" refers to access to a high quality, publicly accessible green space within approximately 300 m walking or cycling distance. The principle therefore connects everyday visual exposure to vegetation with neighborhood scale canopy provision and physical accessibility to green space. The 3–30–300 principle should not, however, be interpreted as a universal performance standard that can be applied independently of

and morphological conditions. The feasibility of achieving a particular canopy percentage or distance threshold depends on factors such as urban density, land availability, existing vegetation, street morphology, infrastructure, land ownership, and the functional requirements of public spaces. Its value therefore lies primarily in providing a reference framework for assessing the distribution, visibility, and accessibility of urban nature, rather than as a fixed prescription for every urban context.

For the present research, the 3–30–300 principle is consequently used as a conceptual reference rather than as a fixed design requirement. The case study area contains an established urban structure and an active public market with specific spatial and functional constraints. The proposed intervention therefore does not seek to achieve a 30% canopy threshold through extensive tree planting. Instead, the principle reinforces the importance of strategically positioning vegetation so that its benefits including shade, visual contact with nature, and improved access to green elements are distributed in relation to pedestrian activity and existing urban functions.

In this sense, NbS within the present research are understood not as a complete replacement of the existing urban fabric, but as strategically integrated ecological interventions capable of complementing surface materials, shading, and spatial reconfiguration. This interpretation establishes a direct conceptual link between the broader nature based framework and the specific microclimatic interventions evaluated later in the thesis.

1.3.6 Synthesis: Climate-Responsive Urban Design

The strategies discussed in this section demonstrate that urban heat mitigation and climate adaptation cannot be addressed through a single intervention or universal solution. Different strategies influence different components of the urban thermal environment. Surface and material interventions can modify solar absorption, heat storage, permeability, and radiative exchange; green infrastructure can provide shading and evapotranspiration cooling; building integrated measures can reduce energy demand and anthropogenic heat release; and Nature based Solutions can combine thermal regulation with ecological, hydrological, and social functions.

The effectiveness of these strategies is strongly influenced by urban morphology and local environmental conditions. Building density and height, street geometry, sky view factor, solar exposure, wind conditions, vegetation configuration, surface properties, and water availability can all modify the performance of individual interventions. Consequently, climate responsive urban design should be understood as a process of context specific integration and evaluation, rather than as the application of isolated measures.

This principle is particularly relevant to the present research. The proposed intervention does not seek to transform the existing urban fabric completely, but instead introduces targeted modifications to surface materials, vegetation, shading, and open space conditions while maintaining the functional and morphological characteristics of the existing market environment. The selection of these strategies is therefore guided by their compatibility with the site, their potential

influence on pedestrian level as well as residential blocks microclimatic conditions, and their capacity to improve thermal comfort.

The theoretical framework developed in this chapter establishes the relationship between urban heat, urban morphology, microclimatic processes, thermal comfort, and climate responsive design strategies. These relationships provide the basis for the subsequent analysis of the selected case study, where the existing urban conditions and the proposed design intervention are examined through site specific analysis and microclimatic simulation.

1.4 Analytical Tools and Climate Modeling

1.4.1 The importance of utilizing climate modeling tools

Numerical models are essential tools for analyzing urban climate for engineers, architects, urban planners, and policymakers. This is because climate sensitive urban planning needs to be predictive to account for different urban forms and climates (Erell, 2008). Numerical models enable built environment professionals to compare different urban design alternatives (Toparlar et al, 2017) Also, numerical models have the potential to simulate the study areas under varying meteorological conditions.

The development of simulation models can thus provide suitable urban planning measures based on the knowledge of urban human biometeorology (Lee et al., 2016). Recent years have witnessed an increased research interest in urban climate at varied spatial scales (Lauzet, et al., 2019). Numerical models can be broadly categorized into three categories on the basis of spatial scale (Mirzaei, 2015).

Building scale models focus on isolated buildings, thermal comfort, indoor air quality, etc. These Building Energy Models (Prataviera, et al., 2021) are based on energy balance applied to the building volume. Micro scale models focus on the neighborhood scale and are mostly used in thermal

comfort studies. The interaction between the building and its surroundings is the basis of the development of microclimate models. Different model types ranging from simple geometrical models to complex Computational Fluid Dynamic and Large Eddy Simulation models can be categorized to micro scale models. These models are mostly utilized by scientists and architects.

City scale models are much coarser in resolution and are used to evaluate urban scale policies to mitigate heat island effects. For parameterization of various urban features, such as vegetation and building density at the meso scale, single and multi layer urban canopy models are often applied (Kwok, et al., 2021). With regards to urban micro climate and heat island considerations, several commercial tools/models are available, namely: RayMan (Wang et al., 2024), ENVI-met and CitySim (Miller et al., 2018). RayMan is mainly used for radiation calculation and human thermal comfort assessment, with more attention on thermal comfort in specific locations rather than the micro-climatic system in an urban space. According to (Lin et al., 2024), ENVI-met shows high accuracy in local climate simulation, but incurs high computation cost in handling large scale urban blocks. CitySim is more oriented to building energy consumption simulation and does not fully assess the overall impact of climate change (Wang et al., 2024).

Among available tools, the ENVI-met model is widely regarded as one of the most effective for simulating the spatial distribution of thermal parameters across diverse climatic contexts and urban morphologies, including variations in building configurations and vegetation types (Zhang et al

2022; Kotharkar et al., 2024).

ENVI-met has demonstrated strong performance in numerous studies assessing the thermal exchange processes between vegetation, buildings, and the ground surface under different scenarios. For instance, it has been employed to simulate the thermal benefits of trees (Morakinyo et al.,2018). evaluate the cooling effects of different green roofs16, and analyze the thermal environment in specific urban spaces such as parks17 and school courtyards18. Moreover, its application in community scale thermal comfort studies (Crank et al., 2023) highlights its value in shaping public space design and renewal ENVI-met.

1.4.2 ENVI-met

ENVI-met is a Computational Fluid Dynamics 3D microclimate modeling software based on the fundamental laws of fluid dynamics and thermodynamics (Sharmin et al. 2017). It was designed by Professor M. Bruse in 1994 and has been under constant development and scientific expansion ever since. The software uses an urban weather generator to predict the meteorological parameters based on which the most probable weather conditions are recreated (Bande et al. 2019).

It reconstructs the microclimate dynamics of the urban environment through the interaction between climate variables, vegetation, surfaces and built environment (Bruse and Fleer 1998). ENVI-met simulates the atmosphere processes such as air flow, air temperature, humidity, turbulence, radiation fluxes and calculates the indexes and factors of comfort in the urban area such as Physiological Equivalent Temperature, Predicted Mean Vote, Universal Thermal Comfort Index, and many others (Trane et al. 2023).

The software is grid based and has high temporal and spatial resolution, allowing accurate microclimate analysis up to a street level. Due to holistic approach and complexity of the calculations, ENVI-met has certain limitations, mostly regarding the computation time with high space resolution and wide simulation domains, and the high temporal resolution of meteorological data needed (30-minute timesteps for full forcing mode) (Trane et al., 2023).

02

Best Practices

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2.2 Overview

2.1 Design and Research practices

The case studies presented in this section were selected to examine the relationship between urban design interventions and measurable microclimatic outcomes. Rather than focusing exclusively on architectural appearance or urban regeneration, the analysis considers how specific modifications to the physical environment can influence thermal conditions at the pedestrian and neighborhood scales.

Four cases are examined: the Superblocks intervention in the Sant Antoni area of Barcelona; Viale Carlo Felice Gardens in Rome; the historical centre of Teramo; and the Virgen del Carmen neighborhood in Valencia. Although they differ in scale, morphology, climate, and intervention type, all four provide relevant precedents for understanding strategies to reduce urban heat and improve outdoor thermal conditions.

The cases have been selected because they collectively address several of the principal variables identified in the theoretical framework. These include surface properties and albedo, vegetation and green infrastructure, shading, street configuration, permeability, building related interventions, and changes in public space use and circulation. Several of the studies also employ numerical microclimatic modelling to compare existing and proposed conditions, allowing design interventions to be related to measurable environmental

changes.

The first case, the Sant Antoni Superblocks in Barcelona, is particularly relevant to the present research because it combines the transformation of a market related urban environment with changes in traffic circulation, pavement materials, vegetation, shading, and public space configuration. Its ENVI-met assessment provides a direct example of how an existing urban condition can be compared with a redesigned scenario through pedestrian level climatic indicators.

The second case, Viale Carlo Felice Gardens in Rome, demonstrates the combined application of vegetation, shading structures, cool paving materials, and water-related interventions within an open public space. Its comparison between existing and redesigned conditions provides a useful reference for understanding how multiple interventions can be tested together through thermal comfort indicators.

The third case, the historical center of Teramo, provides a different perspective by examining mitigation within a compact historical urban fabric. The comparison between a base case, a high albedo "cool" case, and a green roof scenario illustrates how different interventions can produce different levels of microclimatic improvement within a constrained urban morphology.

The fourth case, the Virgen del Carmen neighborhood in Valencia, extends the analysis to a larger residential context and incorporates future climate conditions. The study is particularly relevant because it compares alternative scenarios involving pavement modification, increased permeability,

vegetation, and additional shading, demonstrating how the performance of design strategies can change under different climatic conditions and times of day.

Taken together, these cases provide a comparative evidence base for the design decisions developed later in this thesis. The analysis focuses on four main questions:

- what physical design strategies were introduced;
- which microclimatic mechanisms were targeted;
- which environmental or thermal comfort indicators were used to evaluate the intervention;
- what measurable changes were reported.

The following subsections therefore examine each case individually, beginning with its urban and climatic context, followed by the existing condition, the design interventions, the microclimatic assessment, and the reported results. This structure enables distinguishing between the design strategy itself and its measured environmental performance, while also identifying aspects that may be transferable to the Turin case study.

2.1.1 Super Blocks (Sant Antoni area)

Location: Barcelona, Spain **Year:** 2019
Architect: Leku Studio **Area:** 16180 m^2

The Superblocks program represents a city scale urban strategy that reorganizes traffic circulation to reclaim street space for pedestrians, vegetation, public activities, and improved environmental conditions. For this thesis, the analysis focuses specifically on the Sant Antoni area in Barcelona, where changes to the urban environment have been examined through before and after microclimatic simulations. The case is particularly relevant because the intervention combines modifications to traffic circulation, street configuration, pavement materials, vegetation, shading, and public space use, allowing the effects of several complementary strategies to be evaluated together.

The Sant Antoni area is located within Barcelona's dense urban fabric, where a regular street grid is combined with a relatively high proportion of impervious surfaces and intensive urban activity. Within this context, the Superblock intervention represents a neighborhood scale transformation embedded in a broader urban network of streets, open spaces, and green infrastructure. Before the intervention, carriageways, parking areas, and conventional pavement occupied a significant part of the public realm. The extensive use of dark and impervious surfaces contributed to heat absorption and storage, while the limited availability of shade increased exposure to direct solar radiation at pedestrian level.

The Superblocks approach responds to these conditions by redirecting through traffic toward the perimeter of the intervention area and transforming selected internal streets

into lower speed, pedestrian oriented public spaces. The strategy therefore represents more than a traffic management intervention; it involves a broader reprogramming of the public realm in which environmental and social objectives are integrated with changes to urban circulation.

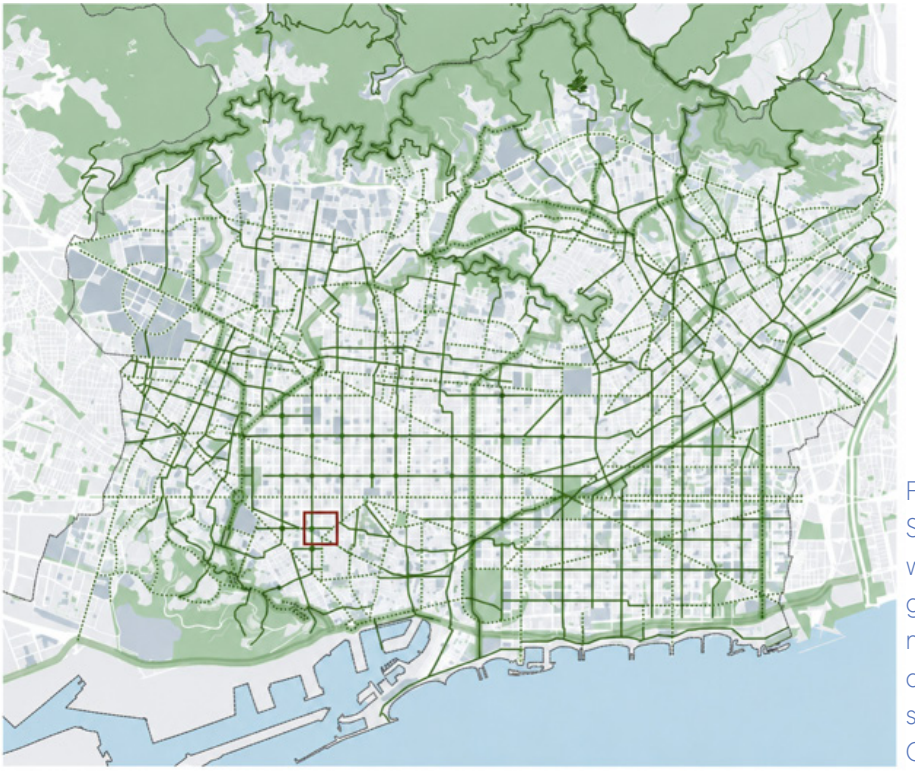


Figure 18. Location of the Sant Antoni Superblock within Barcelona's urban green infrastructure network, with the study area indicated by the red square. Source: Barcelona City Council.

The figure 18 situates the Sant Antoni study area within the broader urban structure of Barcelona and illustrates the distribution of green corridors and connected open spaces across the city. The red square identifies the location of the intervention within the dense urban fabric, highlighting the relationship between the relatively compact study area and the wider network of green infrastructure. This broader spatial context is relevant to the interpretation of the intervention because the thermal performance of a neighborhood scale public space is influenced not only by its immediate morphology, but also by

its relationship to surrounding vegetation, open spaces, and urban environmental networks. The figure therefore establishes the city scale context of the Sant Antoni Superblock before the subsequent figures examine its local spatial transformation and microclimatic interventions.

The local transformation of the Sant Antoni public realm is particularly important for understanding how the Superblock strategy translates its broader urban objectives into physical changes at street level. Figure 19 compares the same urban environment before and after the intervention.



Figure 19. Before and after comparison of the Sant Antoni Superblock, showing the transformation from a vehicle dominated street environment to a pedestrian oriented public space with vegetation, shaded areas, and flexible urban use elements. Source: Archdaily

The figure 19 illustrates the physical transformation of the Sant Antoni public realm before and after the Superblock intervention. The preintervention condition is characterized by a large impervious road surface, extensive vehicular circulation, and limited pedestrian oriented space. Following the intervention, the same urban setting incorporates planted areas, trees, shaded spaces, pedestrian routes, and flexible public space elements. The comparison demonstrates how

the intervention simultaneously modifies the functional use, surface condition, vegetation cover, and shading environment of the street. These changes are particularly relevant from a microclimatic perspective because they alter solar exposure, surface heat absorption, and the availability of shaded areas at pedestrian level.

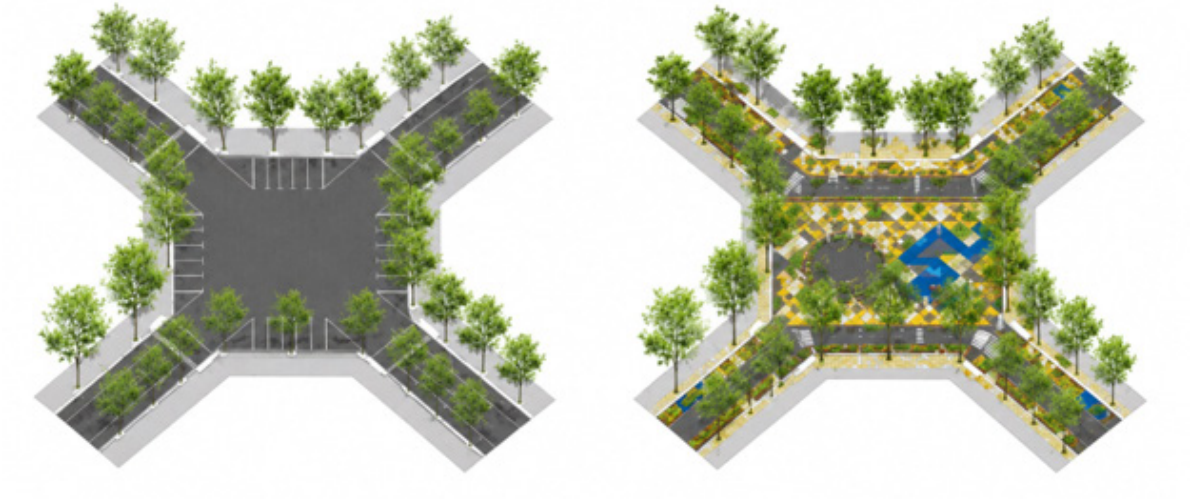


Figure 20. Schematic comparison of the Sant Antoni Superblock before and after the intervention, illustrating the transformation of the street and public space configuration through increased vegetation, modified surface treatments, pedestrian oriented areas, and reorganization of the central space. Source: Leku Studio project webpage

The figure 20 provides a schematic representation of the spatial transformation shown in the previous photographic comparison. The preintervention configuration is dominated by vehicular circulation, parking, and extensive impervious surfaces, while the post intervention condition introduces a more diversified public space structure with planted areas, pedestrian oriented surfaces, trees, and activity spaces. The comparison demonstrates that the Superblock intervention involved not only a reduction in vehicular dominance but also a reorganization of the relationship between movement, vegetation, surface materials, and public space functions.

From a microclimatic perspective, these changes are relevant because they modify the proportion of exposed impervious surfaces, the availability of shade, and the spatial distribution of vegetation within the intervention area. Building on this spatial transformation, the principal design strategies can be identified according to their contribution to surface temperature reduction, shading, vegetation provision, and the reconfiguration of pedestrian space.

2.1.1.1 Design Strategies

The Sant Antoni intervention combines several strategies that are directly relevant to climate responsive urban design. These strategies are considered below according to their principal effects on urban morphology, surface conditions, vegetation, shading, and public space functionality.

Reprogramming the Street Section

One of the principal interventions was the transformation of internal streets around the Sant Antoni Market from predominantly traffic oriented spaces into pedestrian oriented public areas. Selected streets were pedestrianized and the distinction between carriageways and sidewalks was reduced through more continuous ground planes.

This reconfiguration increased the amount of space available for pedestrian movement, social activities, events, and market related uses. From a climatic perspective, the reduction of vehicle dominated surfaces created opportunities for introducing vegetation, shading elements, and alternative pavement materials while simultaneously reducing the spatial dominance of traffic.

The implementation of these principles can be observed at street level, where changes to surface treatment, pedestrian space, and vegetation are integrated within the existing urban structure. The figure 21 illustrates this condition.



Figure 21. Streets and public spaces around the Sant Antoni Market after the implementation of the intervention, illustrating the reconfigured pedestrian oriented street environment Source: Leku studio webpage

The figure 21 illustrates the street level implementation of the Superblock strategy and shows how the intervention operates within an existing dense urban environment. The image demonstrates the use of distinctive surface markings to visually define pedestrian oriented areas and organize movement, while existing mature trees provide substantial canopy cover and shade. The intervention maintains vehicular circulation on the surrounding street while reallocating portions of the public realm toward pedestrian activity and social use. From a climate responsive perspective, the combination of tree canopy, shaded areas, and modified surface treatment is

particularly relevant because it can influence solar exposure, radiant conditions, and the thermal behavior of the urban surface. The figure also demonstrates that the intervention does not require the complete removal of vehicular infrastructure; instead, it reorganizes the relative balance between movement, public activity, and environmental functions within the existing street structure.

Beyond the reorganization of circulation and surface markings, the intervention also sought to increase the environmental and social quality of the reclaimed public space through vegetation, shading, and flexible elements. The figure 22 illustrates this condition in the redesigned Sant Antoni public realm.

A second strategy involved replacing darker surface treatments with lighter and more reflective ground finishes. The intervention reduced the presence of dark surfaces around the market and introduced materials with higher solar reflectance.

Increasing surface reflectance can reduce the proportion of incoming shortwave radiation absorbed by the pavement and therefore reduce surface heating under exposed daytime conditions. However, as discussed in Chapter 1, the effect of increased albedo on pedestrian thermal comfort depends on the surrounding geometry and radiation environment. The Sant Antoni case therefore provides a useful example of evaluating reflective surfaces in combination with other interventions rather than treating albedo as an isolated solution.



Figure 22. Redesigned public space within the Sant Antoni Superblock, showing the integration of tree canopy, planted areas, shaded seating, pedestrian oriented space, and flexible urban furniture. Source: Leku studio webpage

The figure 22 illustrates the redesigned public space and demonstrates how the Superblock intervention combines environmental and social functions within the same urban space. Mature tree canopies provide extensive areas of shade, while planted areas and additional vegetation are integrated with seating and other flexible urban furniture. The resulting space supports pedestrian movement, resting, and social interaction while reducing direct exposure to solar radiation in shaded areas. From a microclimatic perspective, the combination of tree canopy, vegetation, and shaded public space areas is particularly relevant because it can modify the pedestrian radiant environment and contribute to thermal comfort during hot daytime conditions. At the same time, the image demonstrates that climate responsive interventions can be integrated with every day public-space activities rather than functioning as separate environmental installations.

The relationship between the environmental interventions and the existing market structure can be examined more clearly through the spatial and architectural representation of the project. The figure 23 illustrates the organization of the intervention in plan and elevation.

2.1.1.2 Shading and Vegetation

Vegetation and shading were introduced through trees, planters, flowerbeds, and lightweight shading structures.. These elements created localized shaded areas while introducing vegetation into previously hard surfaced public spaces.

Trees provide shade by intercepting direct solar radiation and can additionally contribute to evaporative cooling when sufficient water is available. The combination of vegetation and shading structures therefore reduces pedestrian exposure to direct radiation while potentially modifying surface and air temperatures in localized areas. By reducing direct solar radiation, shading can also lower mean radiant temperature (MRT), which is an important component of outdoor thermal comfort. The arrangement of these elements is also important because vegetation can influence airflow depending on its density and spatial configuration (Bowler et al., 2010; Lee et al., 2013).

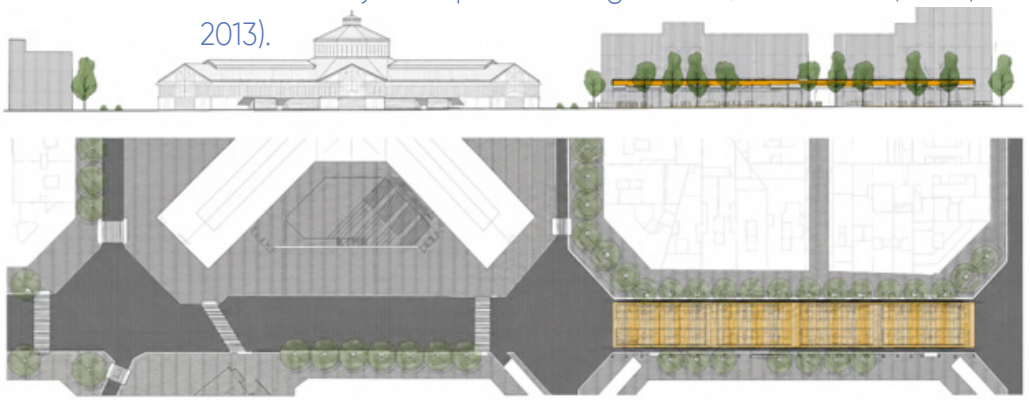


Figure 23. Plan and elevation of the Sant Antoni Superblock public realm, illustrating the relationship between the market building, surrounding streets, tree lined edges, pedestrian areas, and the linear shaded structure introduced along the public space. Source: Leku studio webpage

The figure 23 provides a plan and elevation based representation of the spatial organization of the Sant Antoni intervention. The drawing illustrates the relationship between the existing market building and the surrounding public realm, including the reconfigured street spaces, pedestrian areas, and continuous rows of trees along the edges of the intervention. The elevation further demonstrates how vegetation and the linear horizontal structure contribute to the definition and shading of the public space. From a microclimatic perspective, the spatial arrangement of trees is particularly relevant because the position and continuity of tree canopies determine the distribution of shade and the degree of solar exposure experienced at pedestrian level. The figure therefore complements the photographic evidence by showing how vegetation, shading elements, circulation space, and the market function are integrated within the same urban configuration.

2.1.1.3 Flexible and Modular Urban Furniture

The intervention also incorporated flexible and modular urban furniture. A reversible design "kit" composed of patterns, signage, and modular elements supports phased implementation and allows public space configurations to be adjusted according to different activities and requirements.

Although these elements have a less direct influence on the urban energy balance than vegetation or pavement materials, they are relevant to climate responsive design because they demonstrate how environmental interventions can be incorporated without permanently compromising the functional flexibility of an active public space.

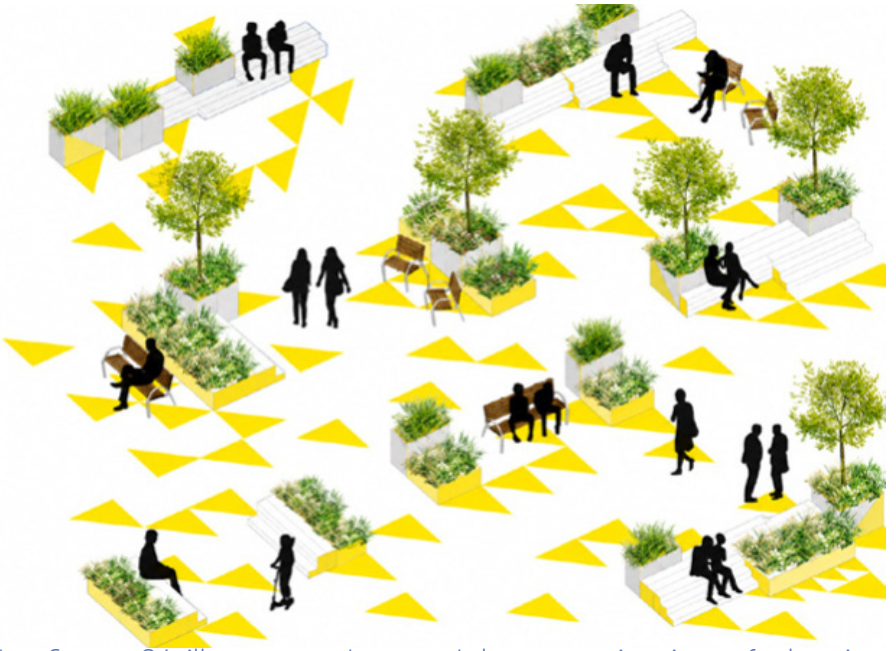


Figure 24. Schematic representation of modular planting, seating, and flexible public space elements within the redesigned Superblock, illustrating the integration of vegetation and social spaces. Source: Leku studio webpage

The figure 24 illustrates the modular organization of planting and public space elements within the redesigned Superblock. Vegetated planters are combined with seating, pedestrian circulation, and small scale social spaces to create a flexible arrangement that can accommodate different activities. The distribution of vegetation provides localized shade and contributes to the diversification of the public space environment, while the modular configuration allows these elements to be positioned according to spatial and functional requirements. From a climate responsive perspective, this arrangement demonstrates how vegetation and shading can be introduced at a relatively small scale without occupying the entire public realm, allowing environmental improvements to coexist with pedestrian movement and social activities. The figure therefore reinforces the principle that urban greening can be implemented through targeted and adaptable interventions rather than through a continuous transformation of the existing urban fabric.

2.1.1.4 Microclimatic Assessment

The microclimatic effects of the Sant Antoni intervention were assessed through ENVI-met simulations reported by Kume et al. (2020). The study developed detailed three dimensional representations of the urban blocks surrounding the Sant Antoni Market and compared preintervention and post intervention conditions under hot and clear summer weather conditions. The simulations examined how modifications to pavement materials, vegetation, shading, and traffic circulation influenced pedestrian level environmental conditions.

The principal physical characteristics of the two scenarios are summarized in Table 2. The comparison shows that the intervention increased the average pavement albedo from 0.1710 to 0.1961, increased tree canopy cover from 11.43% to 12.83%, and increased grass cover from 0.60% to 1.05%. At the same time, the reported asphalt area decreased from 73,483 m^2 to 57,453 m^2. These changes indicate that the intervention modified the balance between impervious surfaces, vegetation, and surface radiative properties while maintaining the broader urban structure of the area.

Table 2 therefore provides an important link between the spatial design intervention and its subsequent microclimatic evaluation. By identifying measurable differences between the baseline and post intervention conditions, it establishes a physical basis for interpreting the ENVI-met results and demonstrates how changes in urban surfaces, vegetation, and spatial configuration can be translated into quantitative environmental analysis.

Urban characteristic	Before intervention	After intervention
Average pavement albedo	0.171	0.1961
Tree canopy cover	11.43%	12.83%
Grass cover	0.60%	1.05%
Asphalt area (m^2)	73,483	57,453
Average building height (m)	19	–
Building density	0.5	–
Vertical-to-horizontal ratio	0.95	–

Table 2. Comparison of selected urban characteristics in the Sant Antoni area before and after the Superblock intervention. Source: Author, based on Kume et al. (2020).

The comparison is particularly relevant to the present research because it demonstrates the importance of connecting physical design modifications with measurable microclimatic parameters. Rather than evaluating urban interventions only through their visual or spatial characteristics, the Sant Antoni case demonstrates how changes in surface albedo, vegetation coverage, and impervious surface extent can be incorporated into a simulation based assessment. This methodological relationship between urban design intervention, measurable physical parameters, and simulated microclimatic response provides a useful precedent for the analytical framework adopted in the present thesis.

2.1.1.5 Microclimatic Results

2.1.1.5.1 Air Temperature

The simulated air temperature results at approximately 1.5 m above ground level, corresponding to the pedestrian level, indicate an improvement in daytime thermal conditions following the intervention. The reported results show an average daytime reduction of approximately 0.6 K within the Superblock area.

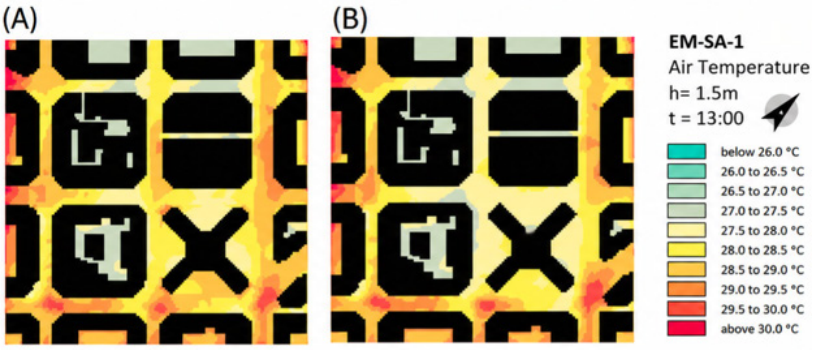


Figure 25. Comparison of simulated pedestrian-level air temperature in the Sant Antoni study area at 1.5 m height and 13:00: (A) before intervention and (B) after intervention. The maps show the spatial distribution of air temperature across the urban blocks and street network. Source: Kume et al. (2020).

The figure 25 presents the simulated air-temperature distribution at pedestrian level (1.5 m) at 13:00, allowing the spatial effects of the intervention to be examined across the street network and surrounding urban blocks. The results show that air temperature is spatially heterogeneous, with warmer and cooler areas occurring in relation to the configuration of streets, built surfaces, and open spaces. This demonstrates that the thermal response of an urban intervention cannot be understood from a single average temperature value, as local variations are strongly influenced by the spatial characteristics of the urban environment (Kleerekoper et al., 2012).

The comparison between the two scenarios further illustrates the relevance of ENVI-met as a tool for evaluating the microclimatic consequences of urban design interventions. Changes in surface characteristics, vegetation, and the configuration of public space can modify the distribution of air temperature at pedestrian level, although the magnitude and spatial extent of these changes vary across the study area. The figure therefore provides a direct example of how modifications to the physical urban environment can be

translated into measurable microclimatic outcomes.

This approach is particularly relevant to the present thesis, where the proposed intervention is similarly evaluated through pedestrian level microclimatic indicators. Rather than assessing the design only through changes in land cover or spatial configuration, the comparison of simulated environmental conditions provides a quantitative basis for determining whether the proposed interventions contribute to improved thermal conditions.

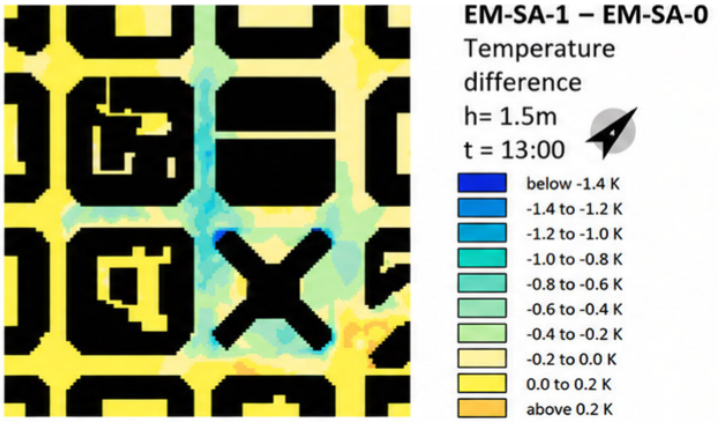


Figure 26. Simulated pedestrian-level air-temperature difference between the two Sant Antoni scenarios at 1.5 m height and 13:00 (EM-SA-1 – EM-SA-0). Blue areas indicate a decrease in air temperature following the intervention, while yellow and orange areas indicate little change or localized temperature increases. Source: Kume et al. (2020).

The figure 26 presents the spatial difference in simulated air temperature between the two Sant Antoni scenarios at pedestrian level (1.5 m) and 13:00. The temperature difference map provides a more direct assessment of the microclimatic effect of the intervention than the absolute temperature maps, as it identifies where cooling or warming occurs as a consequence of the proposed changes. The predominantly blue areas indicate reductions in air temperature, with the strongest cooling concentrated around the modified public

space and street areas, while areas shown in yellow and orange represent locations with limited change or localized increases.
The spatial distribution of the temperature differences shows that the effects of an urban intervention are not necessarily simulate across the study area. Cooling performance depends on the location and configuration of the intervention and its interaction with surrounding buildings, streets, vegetation, and surface conditions. This highlights the importance of evaluating both the magnitude and spatial distribution of microclimatic changes when assessing climate responsive urban design strategies.

The figure also provides a methodological precedent for the present research. Similar to the Sant Antoni study, the proposed intervention in this thesis is evaluated by comparing an existing condition with a design scenario through ENVI-met simulation. The use of difference maps allows the effect of the proposed interventions to be identified spatially and provides a clear basis for assessing whether modifications to vegetation, surface materials, shading, and open-space configuration contribute to improved pedestrian level thermal conditions.

2.1.1.5.2 Ground Surface Temperature

The strongest thermal changes were observed at the surface level. The combination of lighter pavement materials and newly shaded areas produced local reductions in ground surface temperature of up to approximately 20 K, while the reported average daytime reduction across the intervention area was approximately 10 K.

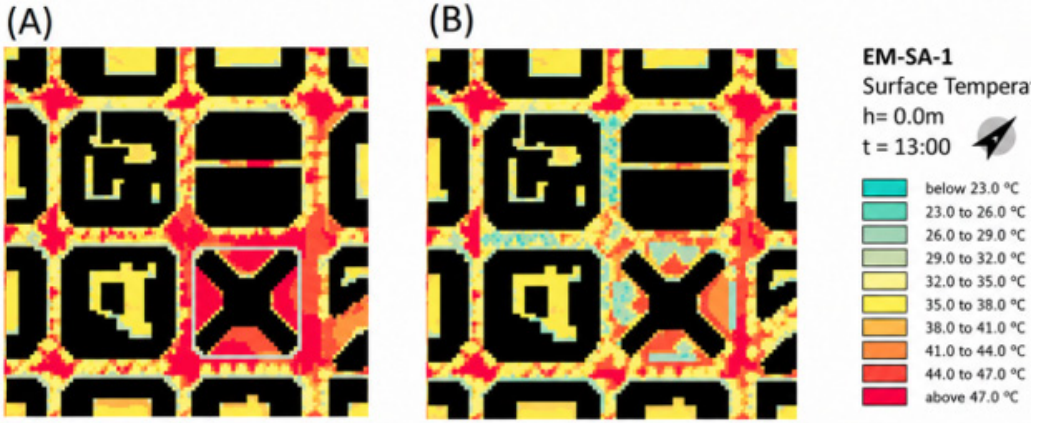


Figure 27. Comparison of simulated surface temperature in the Sant Antoni study area at 0 m height and 13:00: (A) before intervention and (B) after intervention. The maps illustrate the spatial distribution of surface temperature across streets, open spaces, and urban blocks at 1:00 p.m . Source: Kume et al. (2020).

The figure 27 presents the simulated surface temperature distribution at 0 m height and 13:00, providing an assessment of the thermal conditions of the urban surfaces under the two scenarios. The results show substantial spatial variation in surface temperature across the study area, with higher values generally associated with exposed impervious surfaces and areas receiving greater solar radiation. In contrast, cooler areas occur where surface conditions, vegetation, or spatial configuration reduce solar heat absorption and surface heating.

The comparison demonstrates that modifications to the physical characteristics of the public realm can substantially alter the surface thermal environment. In particular, changes in pavement configuration, vegetation, and the distribution of open space influence the amount of solar radiation absorbed and stored by urban surfaces. The spatial pattern shown in the figure also reinforces the importance of evaluating surface temperature together with other microclimatic variables, since a reduction in surface temperature does not necessarily

correspond directly to an equivalent reduction in pedestrian-level air temperature or thermal stress.

The figure 28 is particularly relevant to the present research because the proposed intervention similarly includes modifications to urban surface materials and vegetation. The Sant Antoni case therefore provides a useful precedent for assessing how changes to the physical characteristics of an existing urban space can be evaluated through ENVI-met simulation. In the present thesis, surface temperature results are considered together with air temperature, mean radiant temperature, and thermal comfort indicators to provide a more comprehensive evaluation of the proposed design.

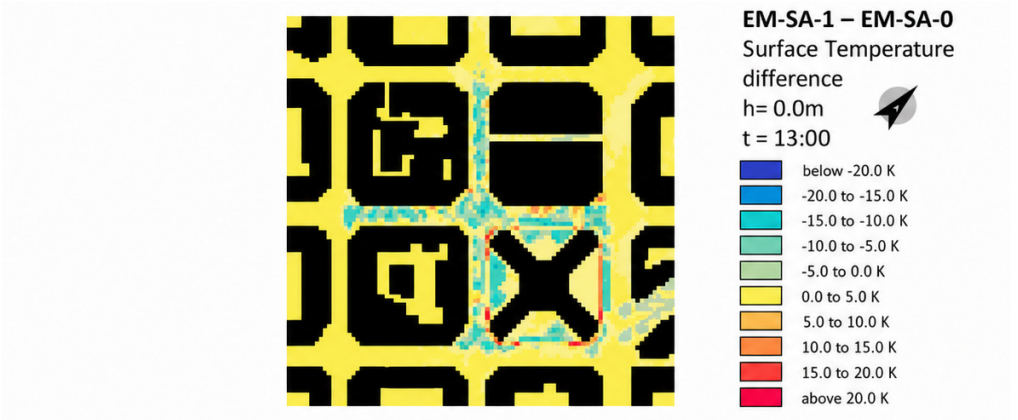


Figure 28. Simulated surface temperature difference between the two Sant Antoni scenarios at 0 m height and 13:00 (EM-SA-1 – EM-SA-0). Blue and cyan areas indicate reductions in surface temperature following the intervention, while yellow to red areas indicate little change or localized increases. Source: Kume et al. (2020).

The figure 28 presents the spatial difference in simulated surface temperature between the two Sant Antoni scenarios at 0 m height and 1:00 p.m. Compared with the absolute surface temperature distribution shown in Figure 27, the difference map more clearly identifies the locations where the intervention modified the thermal behaviour of urban surfaces.

The predominance of blue and cyan areas within the intervened public space and street areas indicates localized reductions in surface temperature, while yellow, orange, and red areas represent locations with limited change or localized increases. The results demonstrate that changes to surface materials and the configuration of the public realm can produce spatially heterogeneous thermal effects. The magnitude of the response varies according to solar exposure, surface characteristics, shading, vegetation, and the surrounding urban geometry. This reinforces the importance of evaluating material based interventions spatially rather than relying only on average surface temperature values.

The comparison between Figures 26 and 28 also highlights an important distinction between air temperature and surface temperature responses. A modification to the urban surface can produce a substantial change in surface temperature without generating an equivalent change in pedestrian level air temperature. Consequently, surface temperature should be considered as one component of the urban thermal environment rather than as a direct indicator of outdoor thermal comfort.

This distinction is particularly relevant to the present thesis, where changes in pavement materials constitute one of the principal design interventions. The Sant Antoni case demonstrates the value of using ENVI-met to identify not only whether an intervention produces cooling, but also where cooling occurs and which environmental variable is most strongly affected. In the present research, surface temperature results will therefore be interpreted together with

air temperature, mean radiant temperature, and thermal comfort indicators to assess the overall effectiveness of the proposed design.

2.1.1.5.3 Wind Speed and Relative Humidity

The intervention also modified wind and humidity conditions at pedestrian level. The reported results indicate a slight reduction in air speed in areas where tree density increased, with local values reaching approximately 0.9 m/s at 1:00 p.m, while the average change was approximately 0.18 m/s. Relative humidity increased by up to approximately 3.8% during peak daytime conditions.

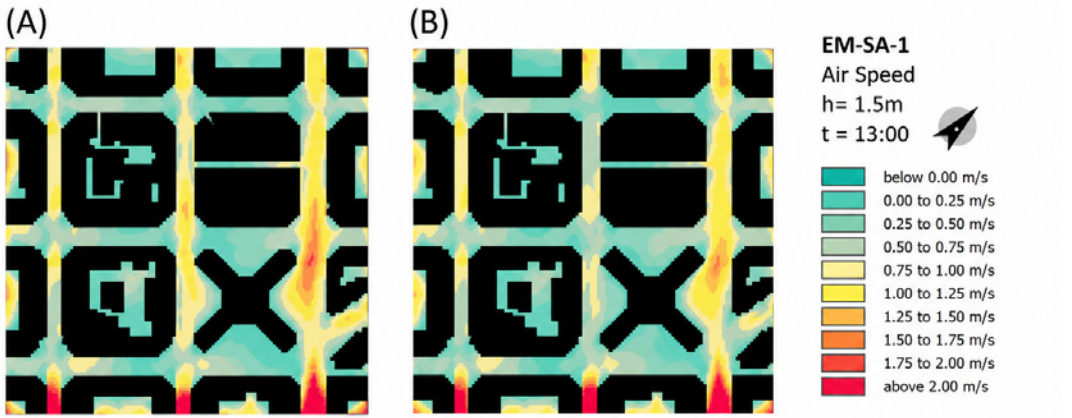


Figure 29. Comparison of simulated pedestrian level air speed in the Sant Antoni study area at 1.5 m height and 1:00 p.m : (A) before intervention and (B) after intervention. The maps illustrate the spatial distribution of air speed across the street network and open spaces. Source: Kume et al. (2020).

The figure 29 presents the simulated air-speed distribution at pedestrian level (1.5 m) at 1:00 p.m for the two Sant Antoni scenarios. The results show that air movement is spatially heterogeneous across the study area, with higher air speed values concentrated along particular street segments and intersections, while lower values occur within more enclosed urban spaces. This pattern reflects the influence of building configuration, street geometry, and the degree of openness of

the urban fabric on local airflow.

The comparison between the two scenarios indicates that changes to the public space configuration can modify local airflow conditions, although the response is spatially variable. Increased air movement can contribute to the removal of accumulated heat and improve convective heat exchange under appropriate thermal conditions. However, higher wind speed does not necessarily indicate improved thermal comfort in every situation, as its effect depends on air temperature, radiation, humidity, and the physiological conditions of pedestrians.

The inclusion of air speed alongside air temperature and surface temperature is therefore important for understanding the overall microclimatic response of the intervention. The figures 25–29 demonstrate that urban design measures can influence different components of the local thermal environment in different ways. This supports the use of a multi variable assessment rather than relying on a single environmental indicator.

This approach is directly relevant to the present thesis, where the effects of changes in urban morphology, vegetation, surface materials, and open space configuration are evaluated through ENVI-met. Air speed is considered together with air temperature, mean radiant temperature, and thermal comfort indicators to determine whether the proposed interventions improve the overall pedestrian level microclimate.



Figure 30. Simulated difference in pedestrian level air speed between the pre- and post-intervention scenarios at 1.5 m height and 13:00 (EM-SA-1 – EM-SA-0). Blue and cyan areas indicate reductions in air speed, while yellow to red areas indicate little change or localized increases. Source: Kume et al. (2020).

The figure 30 presents the spatial difference in simulated air speed between the two Sant Antoni scenarios at pedestrian level (1.5 m) and 1:00 p.m. The map shows that the intervention produced a spatially heterogeneous response, with both reductions and localized increases in air speed across the study area. The strongest changes are concentrated around the modified streets and public space areas, where changes in vegetation, surface configuration, and circulation influence the local airflow pattern.

The predominance of blue and cyan areas in several parts of the intervention indicates a reduction in air speed, while the yellow, orange, and red areas represent locations where air speed changed only slightly or increased following the intervention. These variations demonstrate that the introduction of vegetation and the reconfiguration of the public realm can modify airflow at pedestrian level, but that the effect depends strongly on the surrounding building geometry, street orientation, vegetation density, and degree of spatial openness.

A reduction in air speed should not necessarily be interpreted as a negative microclimatic outcome. Although higher wind speeds can enhance convective heat exchange, vegetation can simultaneously provide shading and evapotranspirative cooling. The thermal effect of a change in air speed therefore depends on its interaction with air temperature, mean radiant temperature, humidity, and solar exposure. Consequently, airflow should be evaluated together with the other environmental variables rather than considered independently.

The spatial variability shown in the Figure 30 reinforces the importance of the configuration and density of vegetation, rather than simply the total amount of greenery introduced. This is particularly relevant to the present research, where vegetation is strategically positioned within an active public space environment. The Sant Antoni case demonstrates that tree placement and density should be considered in relation to existing urban morphology and ventilation pathways to balance shading and cooling benefits with the potential modification of airflow.

The results emphasize the importance of evaluating vegetation together with airflow conditions. While trees can provide valuable shade and evaporative cooling, their aerodynamic effect may locally reduce wind speed. Consequently, vegetation density and configuration should be considered in relation to the existing urban morphology and ventilation potential.

2.1.1.5.4 Thermal Comfort – PET

The most significant improvement from the perspective of human thermal exposure was observed in the Physiological Equivalent Temperature (PET). The reported results indicate reductions of up to approximately 12 K at 1:00 p.m in shaded areas, with an average daytime reduction of approximately 5 K across the intervention area.

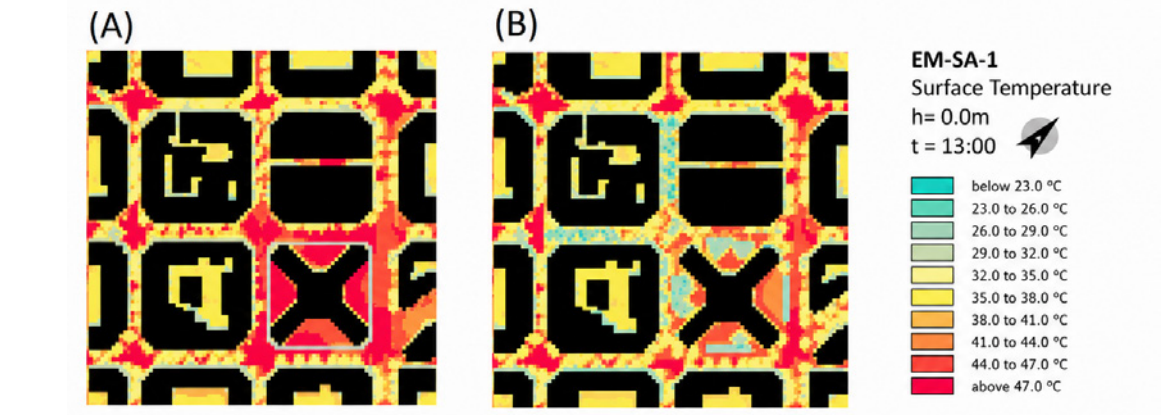


Figure 31. Comparison of simulated Physiological Equivalent Temperature (PET) at pedestrian level (1.5 m) at 1:00 p.m : (A) before intervention and (B) after intervention. The maps show the spatial distribution of outdoor thermal comfort conditions across the Sant Antoni study area. Source: Kume et al. (2020).

The figure 31 presents the simulated Physiological Equivalent Temperature (PET) at pedestrian level (1.5 m) and 1:00 p.m for the two Sant Antoni scenarios. Unlike the previous figures, which describe individual environmental variables such as air temperature, surface temperature, and air speed, PET integrates the combined influence of the surrounding thermal environment on the human body. The spatial distribution shown in the figure therefore provides a more direct indication of the thermal conditions experienced by pedestrians.

The results demonstrate that thermal comfort conditions vary considerably across the study area. Higher PET values are concentrated in highly exposed and strongly irradiated

urban spaces, while comparatively lower values occur in areas benefiting from shading, vegetation, and modified surface conditions. The comparison between the two scenarios indicates that changes to the urban environment can alter the spatial distribution of thermal stress, although the response is not uniform throughout the site (Höppe, 1999; Matzarakis et al., 1999).

The PET results also demonstrate why individual environmental variables should not be interpreted independently when evaluating urban heat interventions. A reduction in surface or air temperature does not necessarily produce an equivalent improvement in human thermal comfort because PET is also strongly influenced by mean radiant temperature, wind speed, humidity, and physiological parameters. Consequently, an intervention should ultimately be evaluated according to its combined effect on the thermal environment experienced by pedestrians rather than through a single environmental variable.

This is particularly relevant to the present research, where ENVI-met is used to evaluate the existing and proposed design conditions. The Sant Antoni case demonstrates clear methodological progression from physical urban characteristics and design interventions to simulated microclimatic variables and, ultimately, pedestrian thermal comfort. This approach provides a direct precedent for evaluating the effectiveness of the proposed interventions in the present study.

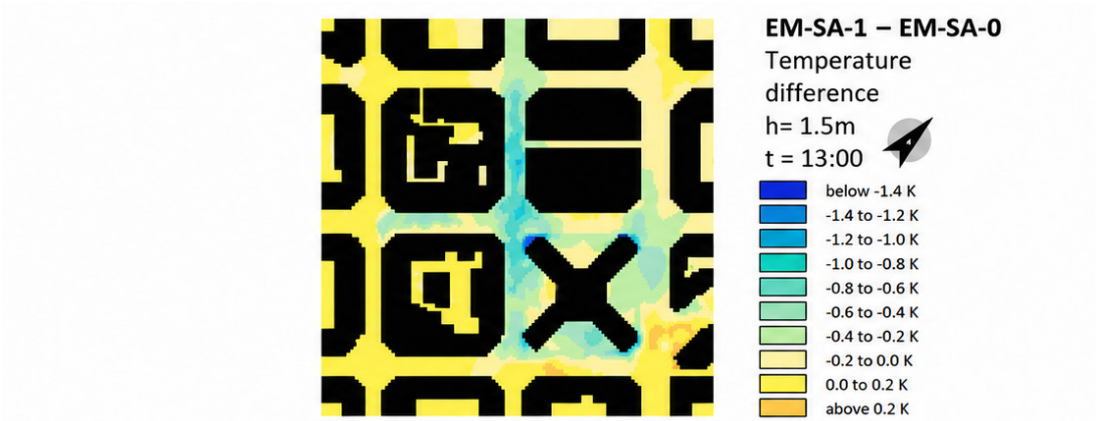


Figure 32. Simulated difference in Physiological Equivalent Temperature (PET) between the two Sant Antoni scenarios at pedestrian level (1.5 m) and 1:00 p.m (EM-SA-1 – EM-SA-0). Blue and cyan areas indicate reductions in PET and therefore improved thermal conditions, while yellow to red areas indicate little change or localized increases in thermal stress. Source: Kume et al. (2020).

The figure 32 presents the spatial difference in Physiological Equivalent Temperature (PET) between the two Sant Antoni scenarios at 1.5 m height and 1:00 p.m. Unlike the previous difference maps, which describe changes in individual environmental variables, this figure represents the combined thermal response experienced by pedestrians. The spatial distribution of PET differences therefore provides a direct indication of where the intervention produces improvements or deterioration in outdoor thermal conditions.

The predominantly blue and cyan areas indicate reductions in PET and consequently improved thermal conditions following the intervention, particularly around the modified public space and street areas. Areas shown in yellow represent relatively limited changes, while orange and red areas indicate localized increases in PET. This spatial variability demonstrates that the thermal benefit of urban intervention is dependent on its location and interaction with surrounding morphology, vegetation, surface characteristics, solar exposure, and airflow.

The comparison between Figures 31 and 32 is particularly important because the absolute PET map shows the thermal conditions under each scenario, whereas the PET difference map directly isolates the effect of the intervention. This makes it possible to identify not only whether the redesigned space performs better overall, but also where the greatest thermal benefits occur.

The results reinforce the importance of evaluating urban heat interventions through integrated thermal comfort indicators rather than relying exclusively on air temperature or surface temperature. Since PET incorporates the combined effects of air temperature, mean radiant temperature, humidity, and wind conditions, it provides a more comprehensive representation of pedestrian thermal exposure. This methodological approach is directly relevant to the present thesis, where the effectiveness of the proposed interventions is evaluated through changes in pedestrian level microclimate and thermal comfort.

2.1.1.5.5 Overall Results and Design Implications

The Sant Antoni Superblock demonstrates that a combination of street reconfiguration, high albedo surfaces, vegetation, shading, and traffic reduction can produce measurable improvements in the urban thermal environment.

The reported results indicate that the strongest changes occurred in surface temperature and pedestrian thermal comfort, while the reduction in air temperature was comparatively smaller. This difference is important because it demonstrates that climate responsive urban design should not be evaluated solely according to air temperature reduction. Changes in solar exposure, mean radiant temperature,

shading, surface heating, wind, and humidity can collectively produce substantial improvements in the thermal conditions experienced by pedestrians.

The intervention also demonstrates the importance of combining strategies. High albedo pavement reduced surface heat absorption, vegetation and shading reduced direct solar exposure and contributed to localized cooling, and traffic reorganization reduced the dominance of vehicular activity within the public realm. The resulting improvement was therefore produced through the interaction of several interventions rather than through a single measure.



Figure 33. Sant Antoni Market before and after the urban intervention: (A) existing condition and (B) post intervention condition. The transformation illustrates the shift from a predominantly vehicle oriented space toward a more pedestrian oriented public realm with increased vegetation, seating, and redesigned open space. Source: Kume et al. (2020).

The figure 33 illustrates the physical transformation of the Sant Antoni Market and its surrounding public space following the intervention. The existing condition is characterized by a predominantly vehicle oriented environment, with extensive paved surfaces, on street parking, traffic circulation, and limited pedestrian oriented public space functions. Following the intervention, the area is reorganized as a more pedestrian oriented urban space, incorporating expanded public areas,

vegetation, seating, and improved conditions for walking and everyday activities.

The transformation demonstrates how relatively targeted changes to the organization and design of an existing urban environment can alter both its functional character and its environmental performance. The intervention does not require the complete reconstruction of the surrounding urban fabric; instead, it modifies the relationship between traffic, pedestrian space, vegetation, and public activities. This approach is particularly relevant to climate responsive urban design, where interventions must often improve environmental conditions while maintaining the existing identity, morphology, and functional requirements of a neighborhood.

The physical transformation shown in Figure 33 provides the spatial context for the ENVI-met results presented in Figures 25–32. The changes in pavement, vegetation, public space configuration, and circulation represent the physical inputs through which modifications in air temperature, surface temperature, air speed, relative humidity, and PET can occur. The Sant Antoni case therefore demonstrates the complete relationship between urban design intervention, physical environmental modification, microclimatic response, and pedestrian thermal comfort.

This case provides an important precedent for the present research. Similar to Sant Antoni, the proposed intervention in the study area seeks to improve the environmental performance of an existing public space without fundamentally altering its urban morphology or primary function. The case therefore

supports an approach based on targeted, context sensitive modifications to surfaces, vegetation, shading, circulation, and public space configuration, whose effects can subsequently be evaluated through microclimatic simulation.

2.1.1.5.6 Relevance to the Present Research

The Sant Antoni case provides several principles that are directly relevant to the present thesis. First, it demonstrates the potential of surface material modification to substantially reduce ground surface temperatures in areas dominated by impervious pavement. Second, it shows the importance of shading and strategically positioned vegetation for reducing pedestrian radiant exposure and improving thermal comfort. Third, it demonstrates that environmental interventions can be integrated with flexible public space functions, rather than requiring permanent occupation of the entire intervention area.

This last aspect is particularly relevant to the present case study, where the existing market is an active public space with functional requirements that must be maintained. The Sant Antoni example suggests that climate responsive interventions can be introduced through a combination of light colored or high albedo surfaces, strategically located vegetation, shading elements, and flexible public space components while preserving the primary function of the market.

At the same time, the case highlights the importance of evaluating potential trade offs. The reported changes in wind speed and humidity demonstrate that increasing vegetation can modify more than temperature alone, while the small

night time PET increase illustrates that a strategy producing daytime benefits may have different effects under night time conditions (Kume et al., 2020). Consequently, the Sant Antoni case supports the methodological approach adopted in this thesis: climate responsive interventions should be evaluated through multiple microclimatic variables and thermal comfort indicators rather than through a single performance parameter.

2.1.2 Viale Carlo Felice Gardens

Location: Rome, Italy **Year:** 2024

Architect: Ahmed et al. **Area:** 48800 m^2

Viale Carlo Felice Gardens represents a second relevant precedent for investigating climate responsive urban design through the integration of spatial interventions and microclimatic simulation by Sapienza University team. Located in Rome, the case study examines the potential of combining vegetation, shading structures, cool paving materials, and water based interventions to reduce urban overheating and improve outdoor thermal comfort under summer conditions. The study is particularly relevant to the present research because it establishes a direct relationship between physical design modifications, ENVI-met simulation, and measurable thermal comfort outcomes (Ahmed et al., 2024).

The study investigates the existing gardens and surrounding public spaces through two principal scenarios: a baseline scenario, representing the existing condition, and a renovation scenario, representing the proposed redesign. This scenario based approach allows the effects of individual and combined design strategies to be evaluated through simulated environmental and thermal comfort parameters. The case is particularly relevant within the Italian context because it demonstrates how climate responsive interventions can be introduced into an existing urban environment without relying exclusively on large scale reconstruction. Instead, the proposed approach combines relatively targeted modifications to vegetation, paving, shading, water, and pedestrian space configuration. The methodology therefore provides a useful precedent for evaluating how similar interventions can be adapted to other Italian urban contexts, including Turin (Ahmed et al., 2024)

Existing Condition and Baseline Scenario

The baseline scenario represents the existing configuration of Viale Carlo Felice Gardens, including the existing vegetation, paving materials, furnishings, and spatial organization. The ENVI-met model was developed based on the existing site configuration, including the existing vegetation, paving materials, and spatial organization., providing the basis for comparison with the subsequent renovation scenario.

The existing condition is characterized by extensive impervious surfaces, open pedestrian areas, and exposure to solar radiation. Although vegetation is already present within the gardens, the configuration of open paths and plazas results in substantial areas with limited shade during periods of strong solar exposure. The baseline model therefore provides a reference condition against which the potential effects of the proposed climate responsive interventions can be assessed.



Figure 34. Aerial view of Viale Carlo Felice Gardens and its surrounding urban context in Rome, showing the linear garden structure, adjacent urban blocks, major road corridors, and existing vegetation. Source: Google Maps.

adapted to other Italian urban contexts, including Turin.

2.1.2.1 Existing Condition and Baseline Scenario

The baseline scenario represents the existing configuration of Viale Carlo Felice Gardens, including the existing vegetation, paving materials, furnishings, and spatial organization. The ENVI-met model was developed using environmental data and a digitized representation of the existing site, providing the basis for comparison with the subsequent renovation scenario.

The existing condition is characterized by extensive impervious surfaces, open pedestrian areas, and exposure to solar radiation. Although vegetation is already present within the gardens, the configuration of open paths and plazas results in substantial areas with limited shade during periods of strong solar exposure. The baseline model therefore provides a reference condition against which the potential effects of the proposed climate responsive interventions can be assessed.

The figure 34 illustrates the spatial context of Viale Carlo Felice Gardens within the surrounding urban fabric of Rome. The garden forms a prominent linear open space structure enclosed by dense urban blocks and major road corridors. The aerial view highlights the contrast between the vegetated central open space and the highly developed surrounding urban environment, as well as the presence of extensive paved surfaces and transportation infrastructure. These characteristics are relevant to the microclimatic performance of the site because building density, vegetation distribution, open space configuration, and exposure to surrounding

paved areas influence solar exposure, shading, airflow, and thermal conditions. The spatial configuration shown in Figure 34 therefore provides the contextual basis for understanding the existing condition and the subsequent climate responsive interventions evaluated through ENVI-met.

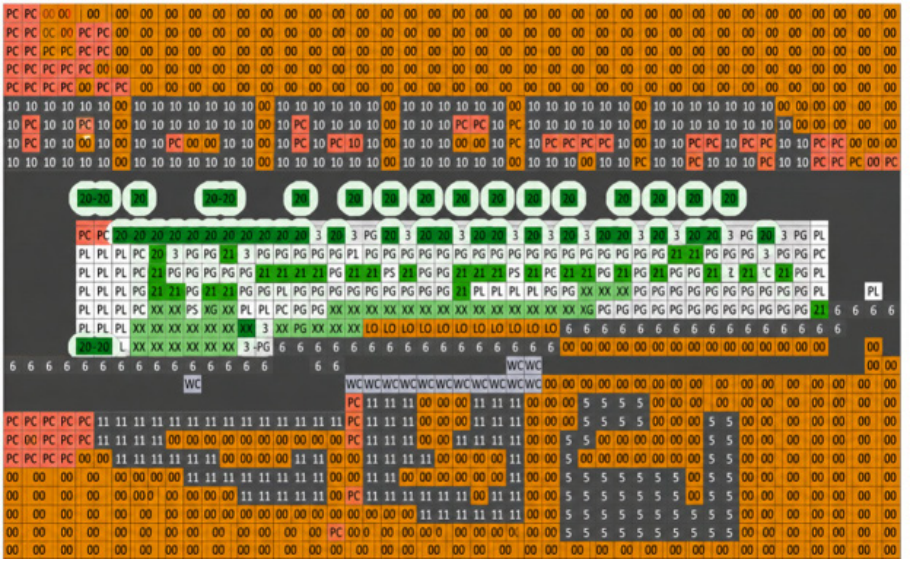


Figure 35. Digitized ENVI-met model of the existing condition of Viale Carlo Felice Gardens, showing the spatial configuration of buildings, paved surfaces, vegetation, and other elements represented in the baseline simulation. Source: Ahmed et al. (2024), ENVI-met v5.1.5.

The existing condition of Viale Carlo Felice Gardens was digitally reconstructed in ENVI-met to establish the baseline scenario for the microclimatic assessment. The figure 35 presents the spatially digitized model used to represent the existing urban configuration, including the distribution of buildings, paved surfaces, vegetation, and other elements incorporated into the simulation. This model provides the physical basis for calculating the microclimatic conditions of the site under the selected summer weather scenario.

Establishing the existing condition as a reference scenario is essential for evaluating the effects of the proposed interventions. The baseline model allows the simulated thermal environment to be compared with the redesigned condition

while maintaining the same general climatic and simulation assumptions. Differences between the two scenarios can therefore be interpreted in relation to the changes introduced through vegetation, surface materials, shading structures, water-related interventions, and spatial reconfiguration.

In this case study, the ENVI-met model serves as a link between the physical characteristics of the existing site and the quantitative assessment of outdoor thermal conditions. The resulting simulations provide a basis for evaluating how specific design interventions influence variables such as air temperature, surface temperature, and thermal comfort indicators.

2.1.2.2 Design / Intervention Scenario

The proposed redesign introduces a combination of passive and nature based interventions intended to modify the thermal environment of the gardens. These include increased vegetation using native and low-water plants species, optimized tree placement to improve the distribution of shade, replacement of conventional paving with cooler and higher albedo materials, water features for localized evaporative cooling, and shading structures such as pergolas and canopies above gathering areas and pedestrian routes.

Rather than relying on a single mitigation strategy, the intervention combines several mechanisms that influence different components of the urban thermal environment. Vegetation contributes through shading and evapotranspiration, reflective paving modifies solar heat absorption, water features provide evaporative cooling, and

shading structures reduce direct solar exposure in areas of pedestrian activity. The combined approach therefore provides a useful example of how multiple climate responsive strategies can be integrated within a single public space design.



Figure 36. Proposed masterplan for the redesigned Viale Carlo Felice Gardens, showing the integration of increased vegetation, shaded structures, cool and higher-albedo paving, water features, and reconfigured pedestrian spaces as climate-responsive interventions. Source: Ahmed et al. (2024).

The intervention scenario proposes a climate responsive redesign of Viale Carlo Felice Gardens through the coordinated integration of vegetation, shading, surface modification, water sensitive elements, and pedestrian space improvements. As illustrated in Figure 36, the redesign introduces additional planted areas and trees, strategically distributed shading structures, water features, and modified paving surfaces within the existing linear park structure. The interventions are intended to increase shaded areas, reduce the exposure of pedestrians and urban surfaces to direct solar radiation, support evaporative cooling, and modify the thermal properties of the existing paved environment.

The spatial arrangement of these interventions is particularly important because the objective is not simply to increase

the amount of vegetation or introduce isolated cooling technologies, but to modify the relationship between vegetation, pedestrian movement, open space, and solar exposure. Trees and planted areas provide shade and evapotranspirative cooling, while water elements introduce additional opportunities for evaporative heat dissipation. The use of cooler paving materials further modifies the surface energy balance by reducing solar heat absorption, while shaded structures provide additional protection in areas intended for pedestrian use and gathering.

The redesigned configuration was subsequently introduced into ENVI-met as a renovation scenario. The baseline and renovation models were then compared using thermal comfort indicators, particularly Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), and Physiological Equivalent Temperature (PET). These indicators provide complementary information on the thermal conditions experienced by pedestrians and allow the effects of the proposed interventions to be assessed quantitatively.

2.1.2.3 Microclimatic and Thermal-Comfort Assessment

The ENVI-met simulations provide a comparison between the existing and redesigned conditions at different times during summer conditions. Figure 37 presents the simulated thermal comfort conditions at 09:00 and 15:00, allowing the influence of the intervention to be considered under different stages of daytime solar exposure.

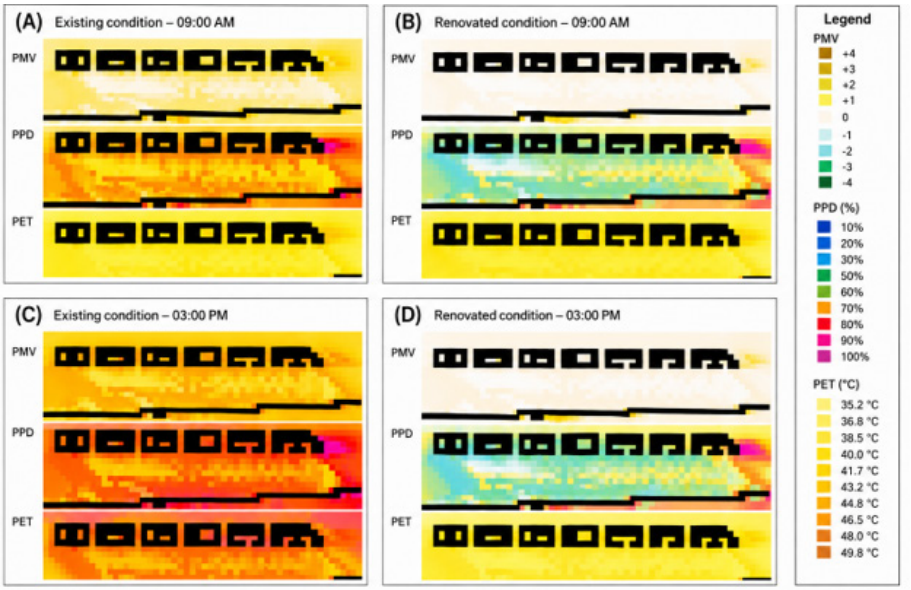


Figure 37. Comparison of simulated PMV, PPD, and PET under existing and renovated conditions at 09:00 and 15:00 during a peak summer day in July. (A) Existing condition at 09:00; (B) renovated condition at 09:00; (C) existing condition at 15:00; and (D) renovated condition at 15:00. The comparison illustrates the spatial distribution of pedestrian thermal comfort under the two scenarios. Source: Ahmed et al. (2024).

Figure 37 compares the simulated pedestrian thermal comfort conditions of Viale Carlo Felice Gardens under existing and renovated scenarios at two representative times of day: 09:00 and 15:00 during a peak summer day in July. The comparison is based on three complementary indicators, Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), and Physiological Equivalent Temperature (PET), which together describe the thermal conditions experienced by pedestrians.

At 09:00, Figure 37(A) shows the existing condition, where PMV values remain predominantly positive and the PPD distribution indicates a considerable level of thermal dissatisfaction. PET values are generally within the warm range, reflecting the influence of solar exposure and the existing distribution of vegetation and paved surfaces. In contrast, Figure 37(B) presents the renovated condition at the same time. The spatial distribution of PMV and PPD shifts toward more favourable conditions, while PET also shows a reduction in thermally

stressful areas. This indicates that the proposed interventions begin to improve outdoor thermal comfort during the morning period.

The difference becomes more pronounced at 15:00, when solar exposure and accumulated surface heating intensify thermal stress. Figure 37(C) shows the existing afternoon condition, with higher positive PMV values, extensive areas of elevated PPD, and higher PET values compared with the morning scenario. These patterns indicate predominantly hot thermal conditions and limited opportunities for thermal relief across the open space. Figure 37(D), however, shows a clear improvement under the renovated scenario. The areas associated with higher PMV and PPD values are reduced, while the PET distribution shifts toward lower thermal stress categories. The renovated condition therefore provides more favourable pedestrian-level thermal conditions, particularly during the critical afternoon period.

The comparison between the four panels demonstrates that the effectiveness of the intervention is not limited to a single moment of the day. Vegetation and tree shading reduce direct solar exposure and radiant heat load, while cooler paving materials can reduce surface heat accumulation. Water related elements and shaded structures further contribute to localized cooling and improved thermal conditions. The results also demonstrate the importance of evaluating both morning and afternoon conditions, since the magnitude and spatial distribution of thermal stress change considerably throughout the day.

Overall, Figure 37 provides a useful methodological precedent for the present thesis. It demonstrates how a combination of PMV, PPD, and PET can be used to compare existing and proposed urban conditions and to assess whether climate responsive interventions produce measurable improvements in pedestrian thermal comfort. This approach is particularly relevant to the present study, where the effects of changes in vegetation, surface materials, shading, and open space configuration are similarly evaluated through microclimatic simulation.

2.1.2.4 Comparison of Thermal-Comfort Performance

The overall comparison between the existing and renovated conditions is summarized in Figure 38.

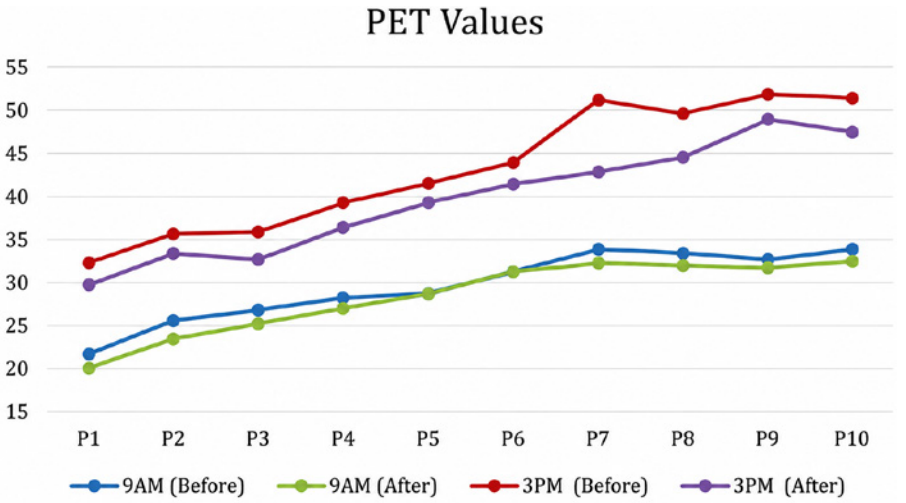


Figure 38. Comparison of simulated Physiological Equivalent Temperature (PET) values at ten representative points (P1–P10) under existing and renovated conditions at 09:00 and 15:00 during a peak summer day in July. The graph compares morning and afternoon PET values before and after the proposed intervention, illustrating the spatial and temporal variation in pedestrian thermal exposure. Source: Ahmed et al. (2024).

Figure 38 presents the PET values extracted at ten representative points (P1–P10) to provide a direct quantitative comparison between the existing and renovated conditions. The results show a consistent reduction in PET following the intervention, although the magnitude of improvement varies according to the time of day and the spatial location of each point.

At 09:00 during a peak summer day in July, the existing condition shows PET values ranging approximately from 21.5 to 34.0 °C, while the renovated condition ranges from approximately 20.0 to 32.5 °C. The reduction is relatively moderate during the morning, with the largest differences occurring at several of the points where the intervention provides greater shading or modifies the surface conditions. This indicates that the proposed measures begin to improve thermal exposure even before the period of maximum daytime heat.

The differences become more pronounced at 15:00, when the existing condition reaches PET values of approximately 32.5–51.5 °C across the sampled points. Under the renovated condition, the corresponding values decrease to approximately 29.5–49.0 °C. The magnitude of reduction varies between points, with several of the locations experiencing substantial improvements under the renovated condition. This spatial variation suggests that the effectiveness of the intervention depends on local exposure conditions and the distribution of shading, vegetation, and surface modifications.

The graph also highlights an important spatial characteristic of urban thermal comfort: the effectiveness of the intervention is not uniform across the study area. Some points show only limited changes, while others experience a more substantial reduction in PET. This variation can be related to differences in shading, vegetation distribution, surface materials, and local exposure conditions. Therefore, the results suggest that the spatial arrangement of climate responsive interventions is as important as their overall quantity Overall, Figure 38 supports the findings presented in Figure 37 by converting the spatial

simulation results into a point-based quantitative comparison. The consistent reduction in PET, particularly during the afternoon, demonstrates the potential of combining vegetation, shading, cooler surface materials, and other passive cooling measures to reduce pedestrian thermal stress. This provides a useful precedent for the present thesis, where PET is similarly used to evaluate the effectiveness of targeted interventions between existing and proposed urban conditions.

2.1.2.5 Design Implications

The Viale Carlo Felice Gardens case study demonstrates several principles that are directly relevant to climate-responsive urban design. First, vegetation and shading are particularly important for reducing pedestrian exposure to direct solar radiation. Their effectiveness, however, depends on their spatial arrangement and relationship with pedestrian movement and gathering areas.

Second, surface modification provides an additional mechanism for reducing thermal loading. The use of higher albedo paving can reduce solar heat absorption, while its effectiveness should be considered together with shading and the surrounding radiation environment. The case therefore supports the use of material interventions as part of a broader combination of strategies rather than as a standalone solution. Third, the incorporation of water based interventions demonstrates the potential for localized evaporative cooling in public spaces. However, such measures are inherently dependent on water availability and operational requirements and should therefore be considered according to the environmental and functional conditions of the site.

Finally, the case demonstrates the importance of spatial integration. The proposed interventions are distributed according to pedestrian movement, gathering areas, shade requirements, and existing spatial conditions rather than being applied uniformly across the entire site. This reinforces the principle established in Chapter 1 that climate responsive urban design should be understood as a context dependent process in which the configuration of interventions is as important as their individual performance.

2.1.2.6 Relevance to the Present Research

The Viale Carlo Felice Gardens case provides a useful methodological precedent for the present research because it demonstrates how a public space redesign can be translated into a measurable microclimatic assessment. The study moves from the identification of thermal problems in the existing condition, through the definition of specific design interventions, to their representation in ENVI-met and evaluation using integrated thermal-comfort indicators.

The case is particularly relevant to the present thesis because the principal strategies investigated vegetation, shading, surface modification, and changes to the configuration of public space correspond closely to the types of interventions considered in the study area. At the same time, the case demonstrates that these strategies should be adapted to the functional and morphological constraints of the site rather than applied as universal solutions.

For the present research, this precedent supports an approach in which the existing urban condition is first established through

physical and environmental analysis, followed by a targeted design intervention and comparative ENVI-met simulation. The effectiveness of the proposed design can then be evaluated through changes in pedestrian level environmental conditions and thermal comfort indicators, particularly air temperature, surface temperature, mean radiant temperature, wind conditions, and PET.

The Viale Carlo Felice Gardens case therefore strengthens the methodological framework of this thesis by demonstrating a complete sequence of existing condition assessment → climate responsive design intervention → ENVI-met simulation → thermal-comfort evaluation.This sequence provides a clear basis for the subsequent case studies and for the evaluation of the proposed climate responsive design in the Barrier di Milano district.

2.1.3 Mitigation Effects of UHI in a Historical Center in Teramo

Location: Teramo, Italy **Year:** 2014

Architect: Amborsini et el. **Area:** 110000 m^2

The academic study by Ambrosini et al. (2014) investigates the formation of the Urban Heat Island (UHI) effect within the historical center of Teramo, a medium sized city in the Abruzzo region of central Italy. The case is particularly relevant to climate responsive urban design because it examines the relationship between compact historical urban morphology, building and roof characteristics, and microclimatic performance within a relatively small Italian urban context.

Teramo is characterized by a compact historical fabric, narrow streets, mid rise masonry buildings, and limited vegetation. These characteristics can contribute to heat accumulation by increasing the proportion of enclosed urban spaces and limiting opportunities for shading and ventilation. The study therefore used ENVI-met simulations to investigate the existing microclimatic conditions and to evaluate the potential effectiveness of two mitigation strategies: high albedo reflective roofs (Cool Case) and green roofs (Green Case).

The study area covers approximately 110,000 m^2, corresponding to a modelled area of approximately 385 × 285 m. The simulations focused on pedestrian level environmental conditions and examined changes in air temperature, mean radiant temperature, relative humidity, and wind conditions. Three scenarios were compared: the Base Case, representing the existing condition; the Cool Case, in which roof albedo was substantially increased; and the Green Case, in which vegetated roof surfaces were introduced.

The case is particularly useful for the present thesis because it demonstrates how material properties and vegetation can be tested as independent climate mitigation strategies within an existing historical urban fabric. It also provides a useful comparison between interventions that primarily modify the surface energy balance and those that additionally introduce evapotranspiration and vegetation related cooling.

2.1.3.1 Base Case: Existing Condition

The Base Case represents the existing configuration of the historical center of Teramo. The model includes narrow urban canyons, mid rise masonry buildings ranging approximately from 3 to 15 m in height, and limited vegetation concentrated mainly around the principal open spaces.

The existing buildings were represented using standard radiative properties, with a roof albedo of approximately 0.30 and a wall albedo of approximately 0.20. These parameters establish the reference surface conditions against which the mitigation scenarios were subsequently evaluated.

The modelled urban morphology is particularly relevant because the compact building arrangement creates relatively enclosed street canyons. Such conditions can influence solar exposure, radiant heat exchange, wind flow, and the accumulation of heat within the urban fabric. The Base Case therefore provides the reference condition for assessing how changes to roof materials and vegetation modify the simulated thermal environment.



Figure 39. Aerial view of the selected study area in the historical center of Teramo, Italy, showing the compact urban fabric, enclosed building blocks, narrow streets, and areas of existing vegetation considered in the ENVI-met study. The view is rotated approximately 32.5° relative to north. Source: Ambrosini et al. (2014).

The figure 39 presents the aerial context of the selected study area in the historical center of Teramo. The image illustrates the compact and relatively dense urban morphology, characterized by closely spaced building blocks, narrow streets, and limited but strategically distributed vegetated areas. The contrast between the densely built urban fabric and the larger vegetated spaces is particularly relevant to the study, as these spatial characteristics influence solar exposure, heat accumulation, and local airflow. The area shown in the figure forms the basis for the ENVI-met model used to evaluate the existing microclimatic conditions and the effects of the proposed mitigation scenarios.

2.1.3.2 Cool Case: High-Albedo Roofs

The Cool Case investigates the effect of increasing the reflectivity of building roofs while maintaining the existing urban geometry and other boundary conditions. In this scenario, the roof albedo was increased from approximately 0.30 to 0.90,

while the wall albedo remained unchanged at approximately 0.20. Maintaining the same building geometry and boundary conditions allows the effect of the roof material modification to be examined independently. The intervention therefore primarily affects the amount of solar radiation absorbed by the roof surfaces and consequently modifies the surface energy balance of the urban environment.

The hottest summer days under typical Italian summer heat wave conditions. at 14:00 indicated an overall reduction in average air temperature of approximately 0.5 K across the built up area compared with the Base Case. However, the cooling effect was spatially heterogeneous. Maximum temperatures reached approximately 40.2 °C within the main street canyon, while the vegetated area recorded approximately 31.7 °C. At 02:00, the difference between the Cool Case and the Base Case was considerably smaller, remaining within approximately 0.25 K. This limited nighttime effect is consistent with the fact that the principal mechanism of the intervention enhanced solar reflectance has a much stronger influence during periods of solar radiation.

The study also identifies a potential limitation of highly reflective surfaces. Although increasing roof albedo reduces solar heat absorption, reflected radiation can contribute to changes in the surrounding radiation environment and may potentially increase diffuse radiation or glare at pedestrian level. The Cool Case therefore demonstrates that material based mitigation can reduce daytime heat accumulation, but its effectiveness should be evaluated together with the broader radiation environment rather than through air temperature alone.

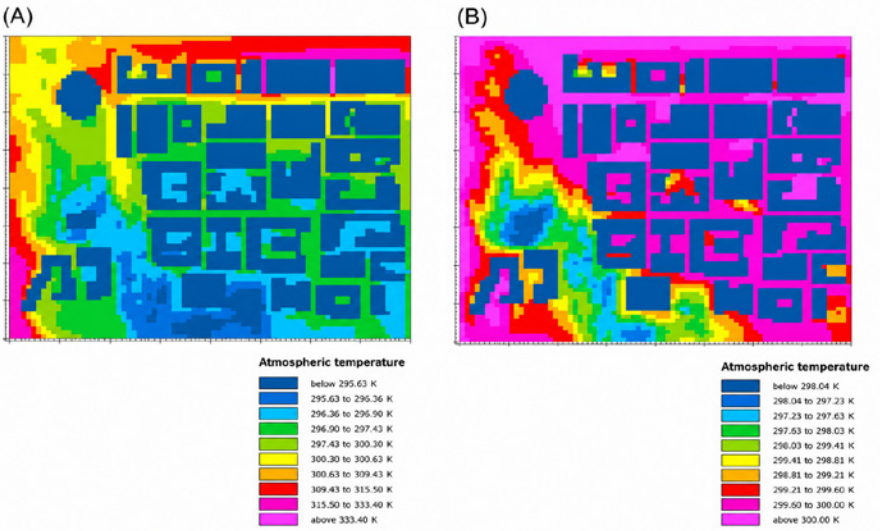


Figure 40. Atmospheric temperature distribution in the Base Case of the Teramo historical center study, shown at pedestrian level (z = 1.20 m) and along a vertical section (y = 220.5 m) at 2:00 p.m. on 22 July 2013 and 2:00 a.m. on 23 July 2013. The simulations represent the existing urban configuration prior to the implementation of heat mitigation strategies. Source: Ambrosini et al. (2014).

The figure 40 presents the simulated atmospheric temperature distribution for the Base Case, representing the existing configuration of the historical center before the introduction of mitigation measures. The results are shown both in plan at pedestrian level (z = 1.20 m) and through a vertical section, allowing the spatial distribution of temperature within the compact urban fabric to be examined during daytime and nighttime conditions. The daytime simulation corresponds to the warmest period considered in the study, at 2:00 p.m. on 22 July 2013, while the nighttime condition is represented at 2:00 a.m. on 23 July 2013.

The results illustrate the thermal behavior of the existing compact urban morphology, where closely spaced buildings and narrow street canyons contribute to the accumulation and spatial variation of heat. According to Ambrosini et al. (2014), the study area exhibits substantial temperature differences within the urban fabric, demonstrating the presence of localized heat accumulation under summer conditions. The comparison between the daytime and nighttime maps also

provides a baseline against which the Cool Case and Green Case can subsequently be evaluated.

This baseline is particularly important for the present thesis because it establishes the reference microclimatic condition before any mitigation strategy is introduced. By maintaining the same urban geometry and simulation conditions when comparing the alternative scenarios, the study isolates the influence of roof albedo and vegetation related interventions on the local thermal environment.

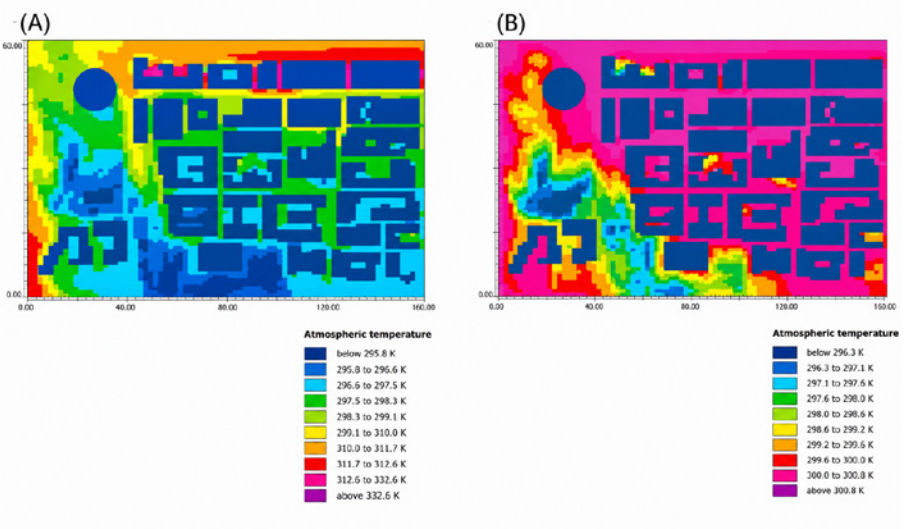


Figure 40. Atmospheric temperature distribution in the Base Case of the Teramo historical center study, shown at pedestrian level (z = 1.20 m) and along a vertical section (y = 220.5 m) at 2:00 p.m. on 22 July 2013 and 2:00 a.m. on 23 July 2013. The simulations represent the existing urban configuration prior to the implementation of heat mitigation strategies. Source: Ambrosini et al. (2014).

The figure 41 presents the atmospheric temperature distribution obtained for the Cool Case, in which the roof albedo was increased from 0.30 to 0.90, while the wall albedo and the existing urban geometry were maintained unchanged. This scenario was designed to isolate the influence of highly reflective roof surfaces on the thermal environment of the historical center. The results are presented for both daytime and nighttime conditions, allowing the effect of the intervention to be assessed under and after direct solar exposure.

At 2:00 p.m., the simulation indicates a general reduction in atmospheric temperature compared with the Base Case. According to Ambrosini et al. (2014), the average air temperature across the built-up area decreased by approximately 0.5 K, although the cooling effect was spatially heterogeneous. The highest temperatures remained concentrated within the more exposed and enclosed urban spaces, while areas with existing vegetation showed comparatively lower temperatures. This indicates that increasing roof reflectance can reduce the amount of solar energy absorbed by buildings and consequently limit heat transfer to the surrounding urban environment.

The nighttime results shown in Figure 41(B) indicate that the difference from the Base Case becomes considerably smaller after solar radiation is no longer present. The study reports a temperature difference of ≤ 0.25 K during the nighttime period, demonstrating that the cooling benefit of reflective roofs is primarily associated with daytime solar exposure rather than nocturnal conditions. The authors also note that highly reflective surfaces may increase diffuse radiation, potentially creating additional radiant exposure or glare at pedestrian level.

The comparison between Figure 40 (Base Case) and Figure 41 (Cool Case) therefore demonstrates that increasing roof albedo can provide a measurable but relatively moderate reduction in daytime atmospheric temperature, while its influence on nighttime conditions remains limited. The result is particularly relevant to climate responsive urban design The result is particularly relevant to climate responsive urban

design because it shows that material-based interventions alone may not be sufficient to address the full range of urban heat effects and should be considered within the historical context of the urban area. Their effectiveness depends on solar exposure, urban morphology, surface configuration, and interaction with other mitigation measures This finding provides an important basis for comparison with the Green Case, where vegetation and evapotranspiration are introduced as an alternative mitigation strategy.

2.1.3.3 Green Case: Vegetation and Green Roofs

The Green Case investigates the contribution of vegetation to microclimatic mitigation. The scenario introduces vegetated surfaces to the buildings and incorporates vegetation within the urban environment to evaluate the combined effects of shading, evapotranspiration, and modified surface properties. The building roofs were modelled with a vegetated layer approximately 50 cm in height, with an albedo of approximately 0.26, while the wall properties remained consistent with the Base Case. The vegetated layer was incorporated into the ENVI-met Area Input File to represent the thermal and evapotranspirative characteristics of the green roof system.

In addition to modifying the roof surfaces, the scenario considers vegetation along streets and open spaces, with broad canopy vegetation intended to increase shading of pedestrian areas and building façades. The resulting configuration therefore differs from the Cool Case not only through surface reflectance but also through the introduction of vegetation related cooling processes effect than the Cool Case. Air temperatures within the built up area were reduced

The daytime simulations at 14:00 indicate a stronger cooling

by up to approximately 1.2 K compared with the Base Case, with simulated temperatures ranging approximately from 31.8 to 39.1 °C.

The cooling effect was also observed during the nighttime period. Although the UHI remained present at 02:00, temperature reductions of several tenths of a degree were observed in parts of the study area, particularly toward the southern portion of the model.

The Green Case therefore produced a broader microclimatic response than the Cool Case. The combination of vegetation, evapotranspiration, shading, and modified roof properties provides cooling mechanisms that remain relevant beyond periods of direct solar exposure. This makes the Green Case particularly relevant to climate responsive design strategies that seek to address both surface heating and pedestrian level thermal conditions.

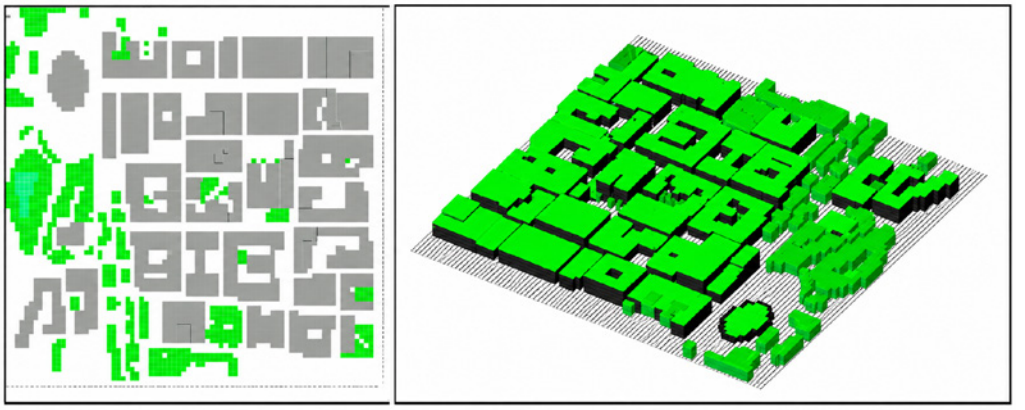


Figure 42. ENVI-met model adopted for the Green Case in the historical center of Teramo: (a) Area Input File showing the spatial distribution of the introduced vegetation and (b) three dimensional representation of the simulated urban environment with vegetated roof surfaces. The Green Case introduces a 50 cm vegetated layer on the building roofs to simulate the cooling effects of vegetation and evapotranspiration. Source: Ambrosini et al. (2014).

The figure 42 illustrates the ENVI-met model configuration adopted for the Green Case. In this scenario, vegetation was introduced into the model to evaluate its potential contribution to the mitigation of urban heat within the compact historical fabric of Teramo. The Area Input File shown in Figure 42(a) defines the spatial distribution of the vegetated elements within the simulation domain, while the three-dimensional model in Figure 42(b) illustrates how the vegetation was represented in relation to the existing building morphology.

For the Green Case, the study introduced a 50 cm vegetated layer on the building roofs, using a grass layer with an albedo of approximately 0.26. The existing wall properties and urban geometry were maintained, allowing the effect of the vegetated roof treatment to be assessed while limiting changes to the other model parameters. The vegetation was implemented through the ENVI-met Area Input File to represent the additional evapotranspiration and thermal effects of the green roof system.

The configuration shown in Figure 42 is particularly relevant because it demonstrates how a design intervention can be translated into a quantifiable ENVI-met simulation scenario. Rather than modifying the urban morphology itself, the intervention changes the environmental properties of the roof surfaces. This allows the subsequent Green Case results to be compared directly with the Base Case and Cool Case, providing a controlled assessment of the relative contribution of vegetation to urban heat mitigation.

The following Figure 43 should then present the atmospheric

temperature results of this Green Case, allowing the simulated thermal effects of the intervention to be evaluated.

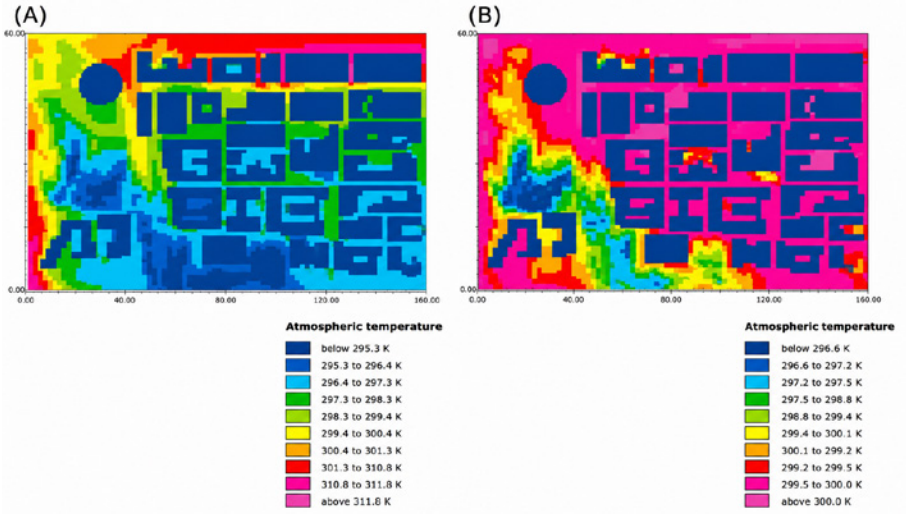


Figure 43. Atmospheric temperature distribution in the Green Case of the Teramo historical center study at pedestrian level (z = 1.20 m), showing the simulated conditions at 2:00 p.m. on 22 July 2013 (A) and 2:00 a.m. on 23 July 2013 (B). The scenario represents the introduction of vegetated roof surfaces within the existing urban configuration. Source: Ambrosini et al. (2014).

The figure 43 presents the atmospheric temperature distribution obtained for the Green Case, in which vegetated roof surfaces were introduced throughout the modeled urban area. The comparison between Figure 43(A), representing the daytime condition at 2:00 p.m., and Figure 43(B), representing the nighttime condition at 2:00 a.m., illustrates the temporal variation in the thermal response of the historical urban fabric following the introduction of vegetation.

During the daytime period, the Green Case produces a more evident cooling effect compared with the Base Case. According to Ambrosini et al. (2014), temperatures within the built up area were reduced by up to approximately 1.2 K, with simulated atmospheric temperatures ranging from approximately 31.8°C to 39.1°C. The cooling effect is particularly relevant in the densely built portions of the study area, where the vegetated roof treatment contributes to reducing heat accumulation through evapotranspiration and the thermal properties of the vegetated layer.

The nighttime simulation in Figure 43(B) shows that the cooling effect becomes less pronounced after the removal of direct solar radiation. Nevertheless, the study reports temperature reductions of several tenths of a degree compared with the Base Case, particularly in the southern part of the modeled area. This indicates that the Green Case does not only influence daytime surface and atmospheric temperatures but can also contribute to a modest reduction in nighttime thermal conditions.

The comparison with the Base Case (Figure 40) and Cool Case (Figure 41) demonstrates the different responses associated with the two mitigation approaches. While the Cool Case primarily modifies the radiative properties of roof surfaces, the Green Case introduces additional evapotranspirative processes and thermal insulation. The latter therefore produces a broader daytime cooling response within the simulated urban environment.

Overall, the Green Case demonstrates the potential of vegetation-based interventions to mitigate urban heat even within a compact historical urban morphology. However, the results also indicate that the effectiveness of such measures is spatially and temporally dependent. This is relevant to the present thesis, where vegetation is similarly considered as one component of a broader climate responsive strategy rather than as an isolated solution.

2.1.3.4 Results and Comparison of Mitigation Scenarios

The ENVI-met simulations demonstrate that the compact morphology of the historical center of Teramo can generate

The comparison between the three scenarios demonstrates different levels of mitigation performance. The Cool Case produced a moderate reduction in daytime air temperature, with an average improvement of approximately 0.5 K, but its influence during nighttime conditions was limited. This indicates that increasing roof reflectivity can reduce solar heat absorption but does not necessarily provide substantial nocturnal cooling.

The Green Case, in contrast, produced a stronger and more spatially distributed cooling effect. Daytime air temperatures were reduced by up to approximately 1.2 K relative to the Base Case, while smaller reductions were also observed during nighttime conditions. The greater effectiveness of the Green Case can be associated with the combined effects of evapotranspiration, shading, and modified surface thermal behaviour.

The comparison therefore demonstrates that the thermal performance of an intervention depends on the physical mechanism through which it modifies the urban energy balance. Reflective roofs primarily reduce solar absorption, whereas vegetated surfaces introduce additional processes, including evapotranspiration and shading. Consequently, vegetation based interventions can provide a broader range of microclimatic effects than surface reflectance modifications alone.

2.1.3.5 Design Implications

The Teramo case provides several important implications for climate responsive urban design.

First, the study demonstrates that urban morphology is a fundamental component of microclimatic performance. The compact historical fabric and narrow street canyons influence solar exposure, heat accumulation, and airflow. Therefore, mitigation strategies cannot be evaluated independently from the spatial structure in which they are implemented.

Second, the Cool Case demonstrates the potential of high albedo materials to reduce daytime heat accumulation. However, the relatively modest temperature reduction and limited nighttime effect indicate that reflective materials should not be considered a universal solution. Their interaction with the surrounding radiation environment must also be considered.

Third, the Green Case demonstrates the broader potential of vegetation based interventions. Through evapotranspiration, shading, and modification of surface conditions, vegetation can address several components of the urban thermal environment simultaneously. This finding supports the integration of green infrastructure as part of a combined climate responsive strategy.

Finally, the case demonstrates the importance of evaluating mitigation strategies through quantitative microclimatic simulation. Rather than assuming that an intervention will automatically improve thermal conditions, the study tests different scenarios under comparable simulation conditions and identifies the magnitude and spatial distribution of their effects. Nevertheless, the feasibility of the proposed green strategy needs to be demonstrated through quantitative evaluation.

2.1.3.6 Relevance to the Present Research

The Teramo case is relevant to the present thesis because it examines climate mitigation within an Italian historical urban context characterized by compact morphology, limited vegetation, and significant heat accumulation. Although the scale and specific interventions differ from the present study, the methodological approach provides a direct precedent for evaluating how targeted modifications to urban surfaces and vegetation can influence pedestrian level microclimatic conditions.

The study also reinforces an important principle established in the previous case studies: no single mitigation strategy should be considered independently from the wider urban system. The Cool Case demonstrates the potential and limitations of modifying material properties, while the Green Case demonstrates the additional cooling mechanisms provided by vegetation. Together, the scenarios suggest that the most effective climate responsive design approach should consider the interaction between surface materials, vegetation, shading, urban morphology, and solar exposure.

This principle is directly applicable to the present thesis. The proposed intervention similarly combines modifications to surface materials and vegetation while maintaining the existing urban morphology and functional characteristics of the site. The Teramo case therefore supports the methodological decision to compare existing and proposed conditions through ENVI-met and to evaluate the resulting changes using measurable microclimatic parameters.

In particular, the case strengthens the rationale for examining air temperature, surface temperature, wind conditions, mean radiant temperature, and PET rather than relying on a single environmental indicator. It demonstrates that an intervention may improve one component of the thermal environment while having a more limited effect on another. A comprehensive assessment is therefore necessary to understand the overall effect on pedestrian thermal comfort. However, the feasibility of the proposed green strategies should not be assumed and needs to be demonstrated through the analysis and evaluation of the proposed intervention.

Overall, the Teramo study contributes to the methodological framework of the present thesis by demonstrating how urban morphology and targeted mitigation strategies can be translated into ENVI-met scenarios and subsequently evaluated through measurable microclimatic responses. Together with the Sant Antoni and Viale Carlo Felice Gardens case studies, it provides a progressively broader basis for selecting and evaluating climate responsive interventions in the Aurora study area.

2.1.4 Virgen del Carmen Neighborhood

Location: Valencia, Spain **Year:** 2024
Architect: Caraballo et el. **Area:** 215700 m^2

The case study of the Virgen del Carmen neighborhood in Valencia, Spain, examines the evolution of a low income residential district originally designed and constructed during the 1960s according to the principles of the Modern Movement. The neighborhood represents a type of post war residential development characterized by relatively open spaces, isolated building blocks, and a strong separation between buildings and public space. Similar Modern Movement (MoMo) neighborhoods are widely distributed across Europe and constitute an important part of the existing residential fabric.

The study is particularly relevant in the context of climate change because these neighborhoods are increasingly exposed to heat stress, while their residents may have limited capacity to adapt through mechanical cooling. The original housing stock was developed according to principles of healthy, efficient, and affordable housing; however, many dwellings are now outdated and may lack effective HVAC systems. Consequently, increasing outdoor and indoor heat exposure can become particularly significant in areas affected by energy or fuel poverty.

The study investigates how changes in urban morphology, surface materials, vegetation, shading, and public space configuration influence outdoor thermal conditions. Rather than considering a single intervention, the research compares a sequence of historical, existing, future, and mitigation scenarios to evaluate the neighborhood's resilience under

both current and projected climatic conditions.
The case study therefore provides an important example of how climate responsive interventions can be evaluated not only in relation to present day conditions but also against future extreme climate scenarios.

2.1.4.1 Existing Urban Context

The public space of Virgen del Carmen has undergone substantial transformation since its original construction. Changes in the surrounding urban structure have modified the relationship between buildings, roads, pedestrian areas, vegetation, and open space. These transformations also influence the neighborhood's microclimatic performance.

The original configuration consisted of large open areas of sandy soil surrounding relatively isolated residential buildings. Vegetation was limited, and the pedestrian connections between buildings were narrow. As a result, the open public spaces provided little solar protection and limited opportunities for thermal refuge during hot weather. The evolution of the neighborhood is represented through a series of scenarios, allowing the researchers to assess how changes in urban configuration have affected thermal conditions over time.



Figure 44. Virgen del Carmen neighborhood in Valencia, showing the original Modern Movement residential configuration and its open public spaces. (a) Residential buildings surrounded by extensive open and predominantly unshaded ground; (b) spatial relationship between the residential blocks, pedestrian paths, and open areas. Source: Grupo de viviendas Virgen del Carmen, Valencia, as reproduced in Caraballo et al. (2024)..

The figure 44 illustrates the spatial characteristics of the Virgen del Carmen neighborhood during its original development. The residential buildings are arranged as relatively isolated blocks within extensive open areas, reflecting the principles of the Modern Movement. The spaces between the buildings are predominantly open and have limited vegetation, with narrow pedestrian paths providing connections between the residential blocks. The absence of substantial tree canopy or other shading structures results in considerable exposure to direct solar radiation.

The images also demonstrate the relationship between the built form and the surrounding open space. Rather than being defined by a continuous street wall, the residential buildings are separated from one another by large areas of public and semi public space. This configuration provides spatial openness but, in its original form, offers limited climatic protection during hot periods. These characteristics form an important basis for understanding the subsequent transformation of the neighborhood and the different microclimatic responses evaluated through the SC-1 to SC-5 scenarios of the simulation.

2.1.4.2 Scenario Development

The study considers five scenarios representing different stages of urban development and potential future interventions:

SC-1: Original Configuration – 1960s

SC-1 represents the neighborhood as originally constructed during the 1960s according to Modern Movement principles. Two large groups of isolated residential buildings were positioned within extensive open areas of sandy terrain. Vegetation was scarce, and narrow transversal walkways provided

connections between the buildings.

The public spaces were largely unshaded and exposed to solar radiation. The limited presence of trees and other vegetation provided little thermal protection, resulting in poor outdoor microclimatic conditions during hot periods.

SC-2: Existing Configuration – 2020s

SC-2 represents the contemporary configuration of the neighborhood following several decades of urban transformation and renovation. The original large blocks were subdivided into smaller urban units, separated by asphalt roads and new cobblestone sidewalks. These changes increased the proportion of impervious surfaces, including asphalt and cement based paving. At the same time, a large scale greening campaign introduced additional trees and shrubs, resulting in a considerably greater vegetation canopy than in the original configuration.

The introduction of glazed balconies also represents an architectural transformation of the residential buildings. These balconies extend the window plane outward without substantially changing the overall glazed surface ratio.

SC-2 therefore represents a more complex environmental condition in which increased imperviousness and urban vegetation coexist, producing both positive and negative effects on outdoor thermal performance.

SC-3: Future Climate Scenario – 2080s

SC-3 evaluates the performance of the existing SC-2

configuration under a future extreme climate scenario based on IPCC RCP8.5. The purpose is to examine the resilience of the existing neighborhood under projected increases in temperature.

This scenario is particularly relevant because it tests whether the current urban configuration and existing vegetation are sufficient to maintain acceptable thermal conditions under intensified climate stress. The scenario therefore functions as a baseline for evaluating the future mitigation strategies proposed in SC-4 and SC-5.

SC-4: Material-Based Mitigation Strategy

SC-4 proposes a return to some of the spatial principles of the original Modern Movement configuration while adapting the public spaces to future climatic conditions.

One of the main strategies is the substantial reduction of vehicular infrastructure between the residential blocks. Roads are removed almost completely from the central public areas, allowing these spaces to be recovered primarily for pedestrian use.

The intervention also replaces conventional paving and asphalt with materials intended to improve thermal performance. Remaining asphalt surfaces are replaced with light colored permeable asphalt, while existing cement based walkways are replaced with light stone paving characterized by medium albedo and lower thermal inertia.

A further intervention is the introduction of paved grass, combining porous cement surfaces with small, vegetated openings. According to Caraballo et al. (2024), this material

provides a rigid walkable surface while allowing evapotranspiration and maintaining a relatively high albedo.

Existing natural-soil areas are complemented by additional wild grass zones, increasing the proportion of green and semi natural surfaces. The original sandy soil is also retained in the new configuration. As a result, SC-4 restores approximately 71% pervious surface of the SC-1, with approximately 45% of the total area consisting of natural or semi natural soil.

SC-5: Material and Shading Strategy

SC-5 builds upon the material and spatial interventions introduced in SC-4 and adds a further layer of temporary textile shading structures.

The proposed shading elements take the form of freestanding awnings positioned at different heights throughout the public space. Their configuration is intended to provide additional solar protection without creating a continuous barrier to ventilation. The structures can also be removed during the colder season, allowing seasonal adaptation of the public space.

The combination of vegetation and awnings increases the total shaded area of the public space to approximately 20%, representing an increase of approximately 7 percentage points compared with the existing SC-2/SC-3 configuration.

This scenario therefore combines two major passive cooling mechanisms: modification of surface thermal properties and reduction of direct solar exposure through shading.

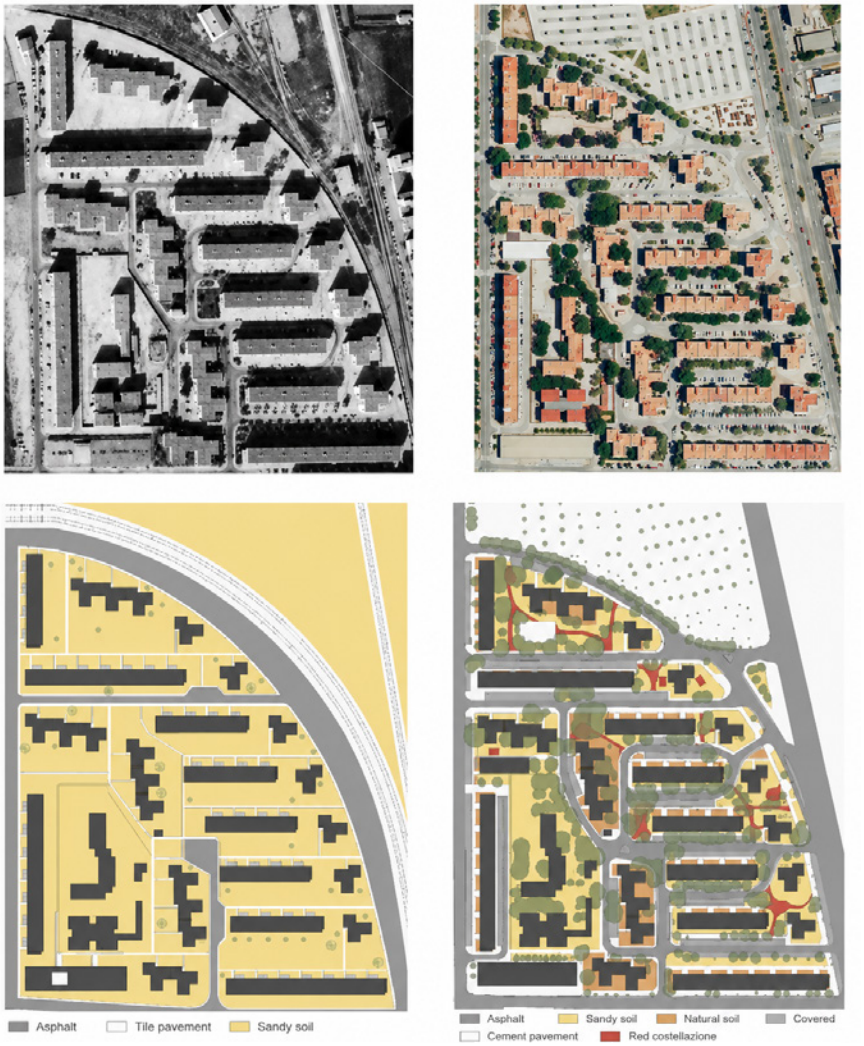


Figure 45. Transformation of the Virgen del Carmen neighborhood through changes in urban layout, vegetation, and ground-surface conditions. (a) Historical aerial view of the residential complex; (b) contemporary aerial view showing the increased presence of vegetation and landscape elements; (c) representation of the earlier spatial and surface configuration, characterized by extensive sandy ground and limited vegetation; (d) contemporary configuration showing increased vegetation, landscaped areas, pedestrian connections, and changes in surface materials. Source: Caraballo et al. (2024).

The figure 45 illustrates the transformation of the Virgen del Carmen neighborhood through a comparison of its historical and contemporary spatial conditions. The historical aerial image in Figure 45(a) shows a relatively open residential layout, with the buildings organized in linear and fragmented configurations and large areas of exposed ground between them. In comparison, the contemporary aerial image in Figure 45(b) indicates a stronger presence of mature vegetation and landscaped spaces within and around the residential blocks.

The lower diagrams further clarify this transformation. Figure 45(c) represents the earlier configuration, where large areas are identified as sandy soil, and the amount of vegetation is relatively limited. The spatial structure is dominated by buildings, asphalt, tile paving, and exposed ground. Figure 45(d) illustrates the contemporary condition, in which vegetation has become more prominent, and the open spaces have been reorganized through additional planting, landscaped areas, pedestrian connections, and changes in surface treatment. The comparison therefore demonstrates that the environmental character of the neighborhood has evolved substantially, particularly through the increased incorporation of vegetation and differentiated ground surfaces.

From a microclimatic perspective, this transformation is relevant because the proportion and spatial distribution of vegetation and surface materials influence solar exposure, shading, surface heating, and the thermal conditions of outdoor spaces. The figure therefore provides an important visual basis for understanding how changes in the landscape structure of the neighborhood can contribute to its environmental performance and supports the subsequent assessment of the different mitigation scenarios investigated in the study.

The material composition and surface cover distribution of the five scenarios are summarized in Table 4. The comparison illustrates how the intervention scenarios progressively modify the proportion of impervious, permeable, vegetated, and shaded surfaces within the study area.

Materials % presence per each scenario

Pavement material	Scenario 1	Scenario 2/3	Scenario 4/5
Asphalt	17%	30%	--
Tile Pavement	5%	--	--
Sandy Soil	78%	20%	19%
Natural Soil	0%	6%	--
Concrete	0%	6%	--
Cement Pavement	0%	35%	--
Red Cobble	0%	2%	--
Clear permeable Asphalt	--	--	26%
Clear walkway Pavement	--	--	29%
Grass	--	--	7%
Paved Grass	--	--	19%

	Surface Covering		Shadow covering summary		
	Impervious	previous	Green cover	Shade sail cover	Total shadowed Area
Sc. 1	22%	78%	1%	--	1%
Sc. 2/3	74%	26%	13%	--	13%
Sc. 4	29%	71%	13%	--	13%
Sc. 5	29%	71%	13%	6%	20%

Table 4 Materials % presence per each scenario. Source: Caraballo et al., (2024)

The comparison shows a substantial shift in surface composition between the baseline and mitigation scenarios. Scenario 1 is dominated by sandy soil (78%), whereas Scenarios 2 and 3 contain a considerably higher proportion of impervious surfaces (74%). Scenarios 4 and 5 introduce permeable asphalt, clear walkway pavement, grass, and paved grass, reducing the proportion of impervious surfaces to 29%. Green cover reaches 13% in Scenarios 2–5, while Scenario 5 additionally introduces shade sails, increasing the total shaded area to 20%, compared with 13% in Scenario 4. These changes provide the physical basis for evaluating the subsequent differences in simulated microclimatic conditions.

Microclimatic Performance of SC-1, SC-2 and SC-3

The comparison between SC-1, SC-2, and SC-3 demonstrates how changes in urban configuration influence thermal performance under both present and future climatic conditions. The study evaluates passive cooling strategies including cooling pavements, additional vegetation and shading, reduction of vehicular areas, and replacement of hard surfaces with more permeable and heat mitigating materials.

According to the reported microclimatic simulations, these interventions can reduce urban heat stress by up to approximately 6.3 °C UTCI under the worst case future climate scenario.

The comparison between SC-1 and SC-2 also demonstrates that the effect of vegetation is dependent on the time of day. At 12:00 and 16:00, SC-2 performs better than SC-1, primarily because the increased vegetation and modified urban configuration provide additional shade and reduce mean

radiant temperature.

However, at 06:00 and 22:00, SC-1 can show slightly better thermal conditions. The study attributes this to the role of vegetation in limiting long wave radiation exchange with the sky and potentially restricting ventilation during nighttime periods.

The comparison between SC-2 and SC-3 further demonstrates the vulnerability of the existing neighborhood under future climatic conditions. Under the projected future climate, SC-3 presents higher UTCI values, with differences of approximately 2–7 °C compared with the existing configuration at certain locations and times.

The results also emphasize the importance of surface materials. Asphalt is associated with substantially higher heat stress than materials such as soil or concrete, particularly during periods of peak solar exposure.

SC-4 and SC-5: Proposed Mitigation Strategies

The proposed interventions in SC-4 and SC-5 respond directly to the thermal weaknesses identified in SC-3.

SC-4 focuses primarily on surface and spatial modifications, while SC-5 extends the strategy by introducing additional shading structures. The two scenarios therefore allow the researchers to distinguish the contribution of material changes from the additional effect of solar protection.

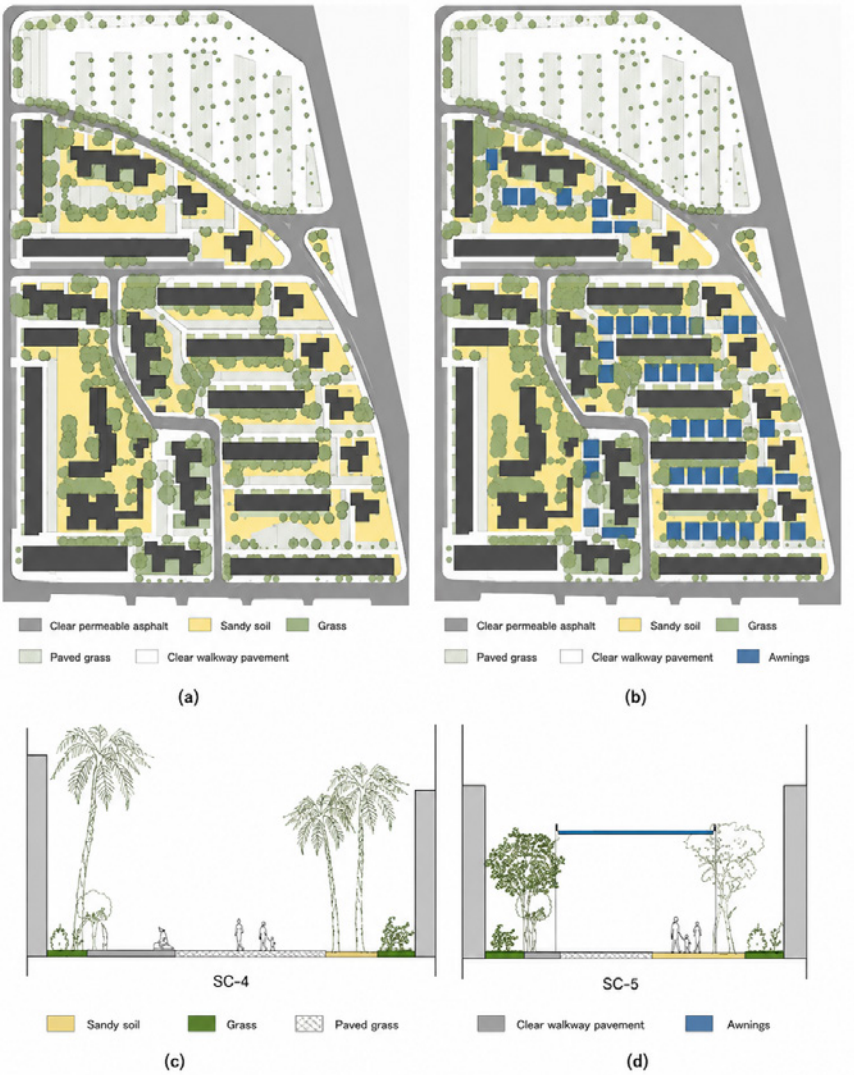


Figure 46. Comparison of the spatial configuration and shading strategies adopted in Scenarios 4 and 5. (a) Plan view of SC-4 showing the modified surface materials and vegetation; (b) plan view of SC-5 showing the same material and vegetation strategy with the addition of awnings; (c) section illustrating the spatial and vegetative configuration of SC-4; and (d) section illustrating the addition of overhead shading structures in SC-5. Source: Caraballo et al. (2024).

Scenarios 4 and 5 introduce progressively more comprehensive mitigation strategies through changes in surface materials, vegetation, and shading. As shown in Figure 46(a) and Figure 46(c), SC-4 incorporates clear permeable asphalt, clear walkway pavement, sandy soil, grass, and paved grass, together with vegetation distributed throughout the residential and pedestrian areas. The spatial arrangement maintains the existing urban structure while increasing the proportion of permeable and vegetated surfaces. The section in Figure 46(c)

illustrates the resulting relationship between buildings, pedestrian areas, vegetation, and the modified ground surfaces.

SC-5 builds upon the material and vegetation interventions of SC-4 by introducing additional overhead shading structures. The figure 46(b) shows the distribution of the awnings within the site, while Figure 46(d) illustrates their position above pedestrian activity areas. These structures provide direct solar protection at pedestrian level and complement the cooling effects associated with vegetation and modified surface materials. The comparison therefore demonstrates that SC-5 does not replace the strategies introduced in SC-4, but rather adds a further layer of solar-shading intervention.

The two scenarios consequently represent different levels of climate responsive intervention. SC-4 primarily relies on surface modification and vegetation, whereas SC-5 combines these measures with artificial shading. This distinction is particularly relevant for the subsequent ENVI-met simulations, as it allows the effects of increased shading to be assessed in addition to those produced by changes in surface materials and vegetation. The comparison also demonstrates how the mitigation strategies are integrated spatially rather than applied uniformly across the entire site.

SC-5 retains these interventions and introduces additional textile awnings distributed at different heights. The arrangement provides additional shade while avoiding a continuous overhead surface that could restrict ventilation. The seasonal removability of the awnings also provides

flexibility, allowing the intervention to respond to different climatic conditions throughout the year.
The two scenarios therefore represent a progressive approach to climate adaptation: SC-4 modifies the surface and spatial structure, while SC-5 adds direct solar protection.

Results of SC-4 and SC-5

The comparison of SC-3, SC-4, and SC-5 provides the clearest indication of the effectiveness of the proposed mitigation strategies.

SC-3 versus SC-4

The results show that SC-4 improves thermal conditions throughout the areas where conventional materials are replaced. The most significant improvement occurs at noon, when the replacement of asphalt surfaces with natural materials and paved grass produces a reduction in UTCI of up to approximately 4.3 °C in the streets between the longitudinal building blocks.

An additional improvement is observed in the northern area outside the building blocks. Because this area is not substantially shaded, the reduction in UTCI is attributed primarily to the modification of surface materials rather than to shading.

During nighttime conditions, the reduction is smaller, at approximately 1 °C, but remains measurable. These results demonstrate that changing surface materials can produce a significant reduction in daytime thermal stress even in areas where additional shading is not available.

SC-3 versus SC-5

SC-5 produces an additional improvement by combining the material interventions of SC-4 with textile shading structures. At noon, the reduction in UTCI reaches approximately 6.4 °C in areas where the shading structures are installed. This represents a greater improvement than the material based strategy alone and demonstrates the importance of reducing direct solar exposure in addition to modifying surface properties.

However, the results also identify an important nighttime trade off. At 06:00 and 22:00, areas located beneath the shading structures can exhibit UTCI values approximately 2.4 °C higher than the corresponding areas in SC-3.

The study attributes this effect to the obstruction of nighttime radiative exchange between the pavement and the sky. By reducing the amount of long-wave radiation emitted toward the sky, the shading structures can limit nighttime surface cooling. This result demonstrates that shading should not be evaluated only according to its daytime performance. The temporal behavior of the intervention and its interaction with nighttime radiative cooling and ventilation must also be considered.

The figure 47 presents the spatial distribution of the UTCI difference between the future extreme climate scenario (SC-3) and the combined material and shading mitigation scenario (SC-5) at four representative times of day: 06:00, 12:00, 16:00, and 22:00. The comparison isolates the additional effect of combining material based mitigation measures with textile shading.

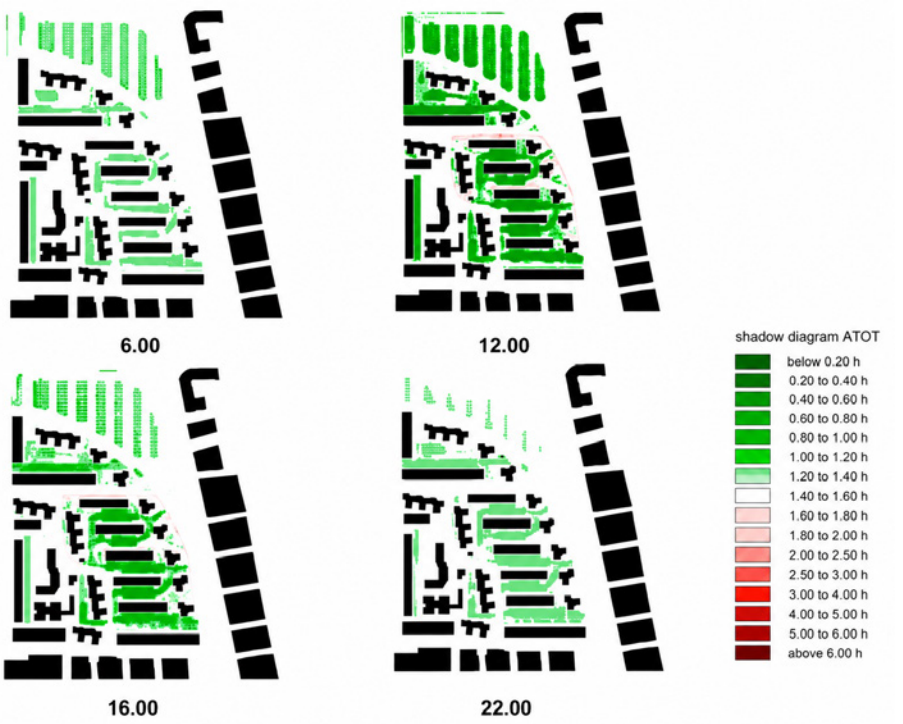


Figure 47. UTCI difference between the future extreme climate scenario SC-3 and the combined material and shading mitigation scenario SC-5 at different times of day (06:00, 12:00, 16:00, and 22:00). The results illustrate the additional daytime cooling achieved through textile shading and the localized increase in nighttime UTCI associated with reduced radiative cooling. Source: Caraballo et al. (2024).

During the daytime, particularly at 12:00 and 16:00, the maps show more pronounced differences in UTCI across the intervention area. These differences indicate that the introduction of textile shading in SC-5 provides additional protection from direct solar radiation and consequently improves outdoor thermal conditions compared with the unshaded future extreme climate scenario. The effect is spatially heterogeneous, with the strongest changes occurring in areas directly influenced by the shading structures and their surrounding pedestrian spaces.

The 06:00 condition shows a comparatively different pattern because solar exposure is still limited at the beginning of the day. At 22:00, the daytime shading effect is no longer the dominant mechanism. Instead, localized increases in UTCI can occur in the mitigation scenario because shading structures

can reduce exposure of surfaces to the sky and consequently modify nighttime radiative cooling. This demonstrates that a mitigation strategy that is highly beneficial during daytime heat conditions may produce different thermal responses after sunset.

Overall, Figure 47 demonstrates that the effectiveness of the combined mitigation strategy is time dependent and spatially heterogeneous. Textile shading provides an additional daytime cooling benefit under extreme climate conditions, while its nighttime influence is more complex. The results therefore emphasize the importance of evaluating mitigation strategies across the full daily cycle rather than assessing their performance at a single time of day.

The stronger performance compared with SC-4 highlights the role of direct solar protection in reducing mean radiant temperature and consequently pedestrian thermal stress. The intervention is therefore particularly effective during periods of high solar exposure, when shading and surface cooling act together.

At night, however, the shaded areas can perform less favorably than the unshaded condition. The reported increase of approximately 2.4 °C in UTCI is attributed to the reduction of nighttime radiative exchange with the sky. This finding is particularly important because it demonstrates that an intervention optimized for daytime thermal comfort may produce a different response after sunset.

The results therefore support a time dependent approach

to climate-responsive design, in which the effectiveness of shading, vegetation, and surface materials is assessed across the complete daily cycle rather than only during peak daytime heat.

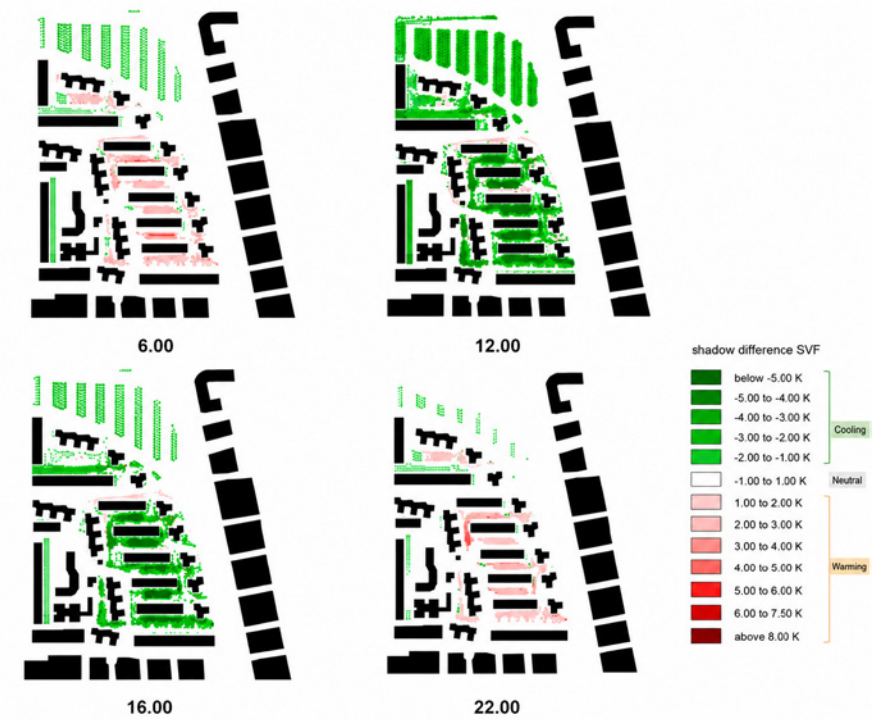


Figure 48. Difference in Sky View Factor (SVF) between the SC-3 and SC-5 scenarios at different times of day (06:00, 12:00, 16:00, and 22:00). The maps illustrate the spatial changes in sky exposure resulting from the introduction of shading elements in SC-5 compared with the future extreme climate scenario SC-3. Green areas indicate a reduction in SVF, while red areas indicate an increase in SVF. Source: Caraballo et al. (2024).

The figure 48 illustrates the difference in Sky View Factor (SVF) between SC-3 and SC-5 at four representative times of day: 06:00, 12:00, 16:00, and 22:00. The comparison demonstrates how the introduction of shading elements in SC-5 modifies the degree of sky exposure within the urban environment. Areas shown in green represent a reduction in SVF, indicating that a smaller portion of the sky is visible from the corresponding locations, while red areas indicate an increase in SVF.

The strongest spatial changes are visible during the daytime, particularly at 12:00 and 16:00, when the position of the sun and the resulting shadow geometry produce more pronounced

differences between the two scenarios. The reduced SVF in areas affected by the shading intervention indicates greater obstruction of the sky hemisphere. This is relevant to thermal performance because SVF influences both the exposure of outdoor spaces to direct and diffuse radiation and their long wave radiative exchange with the sky.

At 06:00, the differences are more localized, reflecting the lower solar elevation and the early morning configuration of shadows. By 22:00, the spatial pattern changes again, when direct solar radiation is absent and the influence of the modified sky exposure becomes more relevant to nighttime radiative exchange. The results therefore demonstrate that the effect of the shading intervention is spatially and temporally dependent, rather than uniform throughout the day.

The comparison between SC-3 and SC-5 is particularly useful because it isolates the role of the additional shading strategy under the future extreme climate scenario. While SC-3 represents the future condition without the additional shading intervention, SC-5 incorporates both the material based mitigation measures and the added shading structures. The SVF comparison therefore helps explain the mechanism through which the shading intervention modifies the radiative environment and contributes to the subsequent differences in thermal comfort conditions.

2.1.4.3 Overall Assessment of the Case Study

The Virgen del Carmen case study demonstrates that urban heat mitigation in existing residential neighborhoods requires

Pavement material	Scenario 1	Scenario 2/3	Scenario 4/5
Asphalt	17%	30%	--
Tile Pavement	5%	--	--
Sandy Soil	78%	20%	19%
Natural Soil	0%	6%	--
Concrete	0%	6%	--
Cement Pavement	0%	35%	--
Red Cobble	0%	2%	--
Clear permeable Asphalt	--	--	26%
Clear walkway Pavement	--	--	29%
Grass	--	--	7%
Paved Grass	--	--	19%

	Surface Covering		Shadow covering summary		
	Impervious	pervious	Green cover	Shade sail cover	Total shadowed Area
Sc. 1	22%	78%	1%	--	1%
Sc. 2/3	74%	26%	13%	--	13%
Sc. 4	29%	71%	13%	--	13%
Sc. 5	29%	71%	13%	6%	20%

Table 5. Material and Surface Cover Distribution (%) Source: Author's elaboration.

consideration of urban morphology, surface materials, vegetation, shading, permeability, and future climate conditions simultaneously.

The comparison of SC-1, SC-2, and SC-3 demonstrates that the transformation of the neighborhood from its original Modern Movement configuration to the contemporary condition has produced both beneficial and unfavorable microclimatic effects. The increase in vegetation has improved daytime shading and reduced mean radiant temperature in some areas, while the expansion of impervious surfaces has increased heat accumulation.

The future SC-3 scenario further demonstrates that the current configuration may become increasingly vulnerable under extreme climate change conditions. This highlights the importance of testing adaptation strategies against future climatic conditions rather than evaluating them only under present day weather.

SC-4 demonstrates that material and permeability interventions alone can produce significant improvements, with UTCI reductions of up to approximately 4.3 °C at noon. SC-5 shows that adding shading can further increase the daytime benefit, reaching reductions of approximately 6.4 °C. At the same time, the nighttime results demonstrate that these interventions can generate trade offs. Shading structures may reduce nighttime radiative cooling, while vegetation can influence both radiation and ventilation. Therefore, the study reinforces the principle that urban heat mitigation should be evaluated as a dynamic and multidimensional process.

2.1.4.4 Relevance to the Present Research

The Virgen del Carmen case study is particularly relevant to the present thesis because it addresses climate adaptation within an existing residential neighborhood rather than a newly designed urban development. This is directly comparable to the approach adopted in the Aurora study area, where the existing urban morphology and functional characteristics are retained while targeted environmental interventions are introduced.

The case demonstrates the importance of working with the existing urban structure rather than replacing it entirely. In SC-4 and SC-5, the researchers modify paving, permeability, vegetation, shading, and pedestrian space while maintaining the fundamental residential structure of the neighborhood.
This principle is directly applicable to the present research, where the objective is similarly to improve outdoor thermal conditions without fundamentally altering the existing urban morphology.

The case also provides strong evidence for the role of surface materials in urban heat mitigation. The reduction of UTCI by up to approximately 4.3 °C through material changes alone demonstrates that the thermal properties of pedestrian surfaces can have a measurable influence on outdoor comfort. This supports the approach adopted in the present thesis, where the selection of paving materials and their thermal properties is considered an important component of the intervention.

The additional improvement achieved through shading in

SC-5 is also relevant. The increase in UTCI reduction from approximately 4.3 °C in SC-4 to approximately 6.4 °C in SC-5 demonstrates that material modification and shading can operate synergistically. However, the nighttime penalty associated with shading also highlights the need to avoid treating a single intervention as universally beneficial.

Finally, the case study reinforces the importance of evaluating vegetation spatially rather than simply increasing its quantity. The results demonstrate that vegetation can improve daytime thermal conditions through shading, but can also influence nighttime radiation and ventilation. This is particularly relevant to the present thesis, where vegetation is introduced selectively according to the spatial and functional requirements of the open market and surrounding public spaces.

Overall, the Virgen del Carmen study provides a strong methodological precedent for the present research by demonstrating how existing urban morphology, surface materials, vegetation, shading, and future climate conditions can be integrated into scenario based environmental analysis. Together with the Sant Antoni, Viale Carlo Felice Gardens, and Teramo case studies, it strengthens the basis for selecting a combination of material, vegetation, and shading strategies for the Aurora study area.

2.2 Overview

To identify the most effective microclimate mitigation strategies applicable to my project site, the four case studies presented in Section 2.1 were analyzed in Table 5.

Each project demonstrates different approaches to reduce urban heat stress ranging from material substitution and shading systems to vegetation based cooling and urban layout modifications. Table 5 provides a comparative summary of these case studies, outlining the strategies employed, the microclimatic indicators assessed, and the quantified improvements achieved.

Case Study	Main Strategies	Most Effective Strategy
Superblocks, Barcelona (Sant Antoni area)	Pedestrianization high-albedo pavements shading structures vegetation modular street furniture	Shading + vegetation + cool materials
Viale Carlo Felice Gardens, Rome	Increasing vegetation Cool pavements Shading structures Water features optimized tree placement	Combination of shading + vegetation
Historical Center of Teramo	Cool roofs Green roofs	Green roofs
Virgen del Carmen Neighborhood, Valencia	Cool pavements Vegetation shading devices permeable materials	SC-5: materials + shading

Microclimate Indicators Used	Key Results
Air Temp, Surface Temp, Wind, Humidity, PET	**Air temperature –0.6 K:** average air temperature decreased by 0.6°C **Surface temperature –10 to –20 K:** shaded/light pavements reduced ground temps up to 20°C **PET –12 K:** thermal comfort improved by up to 12°C **RH +3.8%:** vegetation increased humidity **Wind slightly reduced:** due to added trees
PET, PMV, PPD, Air Temp	**PET –4°C:** thermal comfort improved **PPD reduced by ~30%:** fewer people experiencing discomfort **PMV –2:** lower perceived heat **Hot-stress areas reduced:** qualitatively shown in maps
Air Temp, MRT, RH, Wind	**Cool roofs: Air temp –0.5K:** reflective roofs cooled air slightly **Green roofs: Air temp –1.2K:** evapotranspiration cooled air more effectively **Night cooling:** slight (few tenths of a degree)
UTCI	**SC-4: UTCI –4.3°C:** better comfort due to new pavements **SC-5: UTCI –6.4°C at noon:** shading + materials was most effective

Table 6. Comparison of Strategies and Climate Outcomes Across Case Studies
Source: Author's elaboration.

03

Turin Case Study

3.1 Turin Urban Condition

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3.1 Turin Urban Condition

Before examining the specific characteristics of the selected study area, it is necessary to establish the broader environmental and climatic context of Turin. As a dense urban centre located within the Po Valley, Turin is influenced by a combination of regional climatic conditions, urban morphology, land-cover characteristics, and increasing climate-related pressures. These factors affect the distribution of heat, solar radiation, precipitation, and air movement across the urban environment and consequently influence outdoor thermal conditions at the neighborhood scale.

Understanding these conditions provides the basis for identifying the main environmental vulnerabilities of the city and for interpreting the spatial distribution of the Urban Heat Island (UHI) effect. Therefore, this section examines Turin's climatic context, its principal urban vulnerabilities, and the spatial characteristics of UHI risk. This broader assessment establishes the environmental framework within which the subsequent analysis of the Barrier di Milano district is developed.

3.1.1 Climatic Context in Turin

Before examining how urban form influences local microclimatic conditions, it is necessary to establish the broader climatic context of Turin and identify the environmental pressures that influence its vulnerability to heat and other climate-related

hazards. Turin, the capital of the Piedmont region in northwestern Italy, is located within the Po Valley and at the foothills of the Alps. The city's elevation generally ranges from approximately 220 to 280 m above sea level, while the surrounding territory rises toward the Turin hills and reaches approximately 715 m at Colle della Maddalena (Geoportale Piemonte, 2024). Its geographical position within the Po Valley, combined with the surrounding mountainous topography, influences atmospheric circulation and can limit natural ventilation under certain meteorological conditions. This geographical configuration can favour the accumulation of heat and pollutants, particularly during periods of weak atmospheric circulation and thermal stability.

ARPA Piemonte, the regional environmental protection agency, monitors atmospheric, hydrological, and other environmental conditions throughout the region and provides data supporting environmental assessment and policy development. According to ARPA Piemonte, Turin has a humid subtropical climate (Cfa), characterized by relatively cold and foggy winters and hot, humid summers. At the Turin Centro–Giardini Reali monitoring station, average monthly temperatures are approximately 0.9 °C in January and 23.1 °C in July, while annual precipitation is approximately 804 mm distributed over around 79 rainy days (ARPA Piemonte, 2023).

These climatic characteristics are particularly relevant in relation to the urban environment. During summer, high air temperatures combined with solar radiation and extensive impervious surfaces can increase the accumulation of sensible heat within the urban fabric. During winter, the same

geographical conditions can contribute to atmospheric stagnation and the accumulation of pollutants, particularly during inversion periods.

Long-term climatic observations indicate a persistent warming trend in the Piedmont region. According to ARPA Piemonte's analysis for the period 1958–2022, maximum daily temperatures increased by approximately 0.4 °C per decade, while minimum temperatures increased by approximately 0.3 °C per decade. This corresponds to an overall increase of approximately 2 °C in maximum temperatures over the long-term observation period (ARPA Piemonte, 2023). Such changes are significant for urban environments because increasing background temperatures can intensify the thermal stress experienced during extreme heat events.

Recent climatic observations further demonstrate the continuing warming trend. According to the latest regional climate analysis, 2024 was among the warmest years recorded in Piedmont, with temperatures approximately 1.1 °C above the 1991–2020 reference average (ARPA Piemonte, 2025). Despite some seasonal variability, temperatures continued to exhibit an increasing trend, accompanied by changes in precipitation patterns, an increase in rainfall concentrated within particular periods, and a significant reduction in snowfall in the plains.

The recent climatic conditions therefore indicate that Turin is experiencing not only a gradual increase in average temperatures but also changes in the frequency and intensity of extreme climatic conditions. These changes are particularly relevant during the summer period, when prolonged heat

exposure can interact with the characteristics of the built environment and intensify outdoor thermal discomfort.

The analysis of recent climatic data also indicates significant seasonal variability. The hottest conditions in 2024 occurred during the second half of the summer, with August 11 identified as the hottest day of the year in the regional analysis. The highest temperature recorded in the Piedmont plains reached 37.8 °C on August 13 in Sezzadio (ARPA Piemonte, 2025). These observations demonstrate the intensity of recent summer heat events and highlight the increasing relevance of heat mitigation within urban areas.

At the same time, Turin continues to experience significant seasonal temperature variation, including occasional extreme cold events during winter. The climatic characteristics of Turin should therefore be understood as a combination of increasing long-term warming and substantial seasonal variability rather than as a uniform change throughout the year.

Table 5 presents the average monthly temperatures recorded in Turin in 2024 and compares them with the average temperatures observed during the 2014–2023 period (ARPA Piemonte, Uno Sguardo all'Aria, 2025). The comparison provides a more detailed understanding of the recent climatic conditions and illustrates the deviation of individual months from the preceding decade.

	Temprature (°C)		Rainy day (num)	
	2024	Average 2013-2024	2024	Average 2013-2024
Jan	4.7	3.7	4	4
Feb	8.7	6.3	9	6
Mar	10.8	10.1	14	5
Apr	13.8	14.0	9	7
May	16.5	17.7	16	12
Jun	21.2	22.8	10	9
Jul	25.6	25.2	5	7
Aug	25.8	24.2	6	6
Sep	18.6	19.7	9	5
Oct	15.3	14.3	15	5
Nov	8.0	8.5	1	8
Dec	4.4	4.3	1	5
Year	14.4	14.2	99	78

3.1.2 Urban Vulnerabilities

The climatic changes affecting Turin are accompanied by a range of interconnected urban vulnerabilities. Among the most relevant are extreme heat, heat waves, intense precipitation, flooding, and hydrological instability. These phenomena are not independent of the urban environment; their impacts are influenced by the physical characteristics of the city as well as by the distribution and vulnerability of its population.

Turin i s located within a complex hydrological system and includes both relatively flat urban areas and hilly territories characterized by additional hydrological and geomorphological constraints. The city's river system and its tributaries expose several parts of the urban area to flooding risks. Historical events in 1994, 2000, and 2016 resulted in considerable damage associated with flooding, demonstrating the city's exposure to extreme hydrological events (Città di Torino, 2020).

The figure 49 illustrates the broader territorial and hydrological context of Turin and highlights the city's position within a complex network of rivers, waterways, and surrounding natural areas. The urbanized territory is embedded within a landscape characterized by extensive green areas and a dense network of watercourses, with the major hydrological corridors extending through and around the metropolitan area. This spatial relationship is particularly relevant to Turin's environmental vulnerability, as the interaction between urban development, water systems, and natural land cover influences both flood exposure and the city's capacity to regulate environmental conditions. The figure therefore provides a territorial-scale context for understanding the environmental

pressures affecting Turin, before focusing on more localized vulnerabilities such as extreme heat and the Urban Heat Island (UHI) effect. In the context of this thesis, it also emphasizes the importance of considering the relationship between the built environment and surrounding ecological systems when developing climate-responsive urban strategies.

At the same time, extreme heat has become an increasingly important urban vulnerability. Turin experienced a major heat related emergency during the summer of 2003, while subsequent climatic assessments have identified a significant increase in extreme temperatures and heat related discomfort.

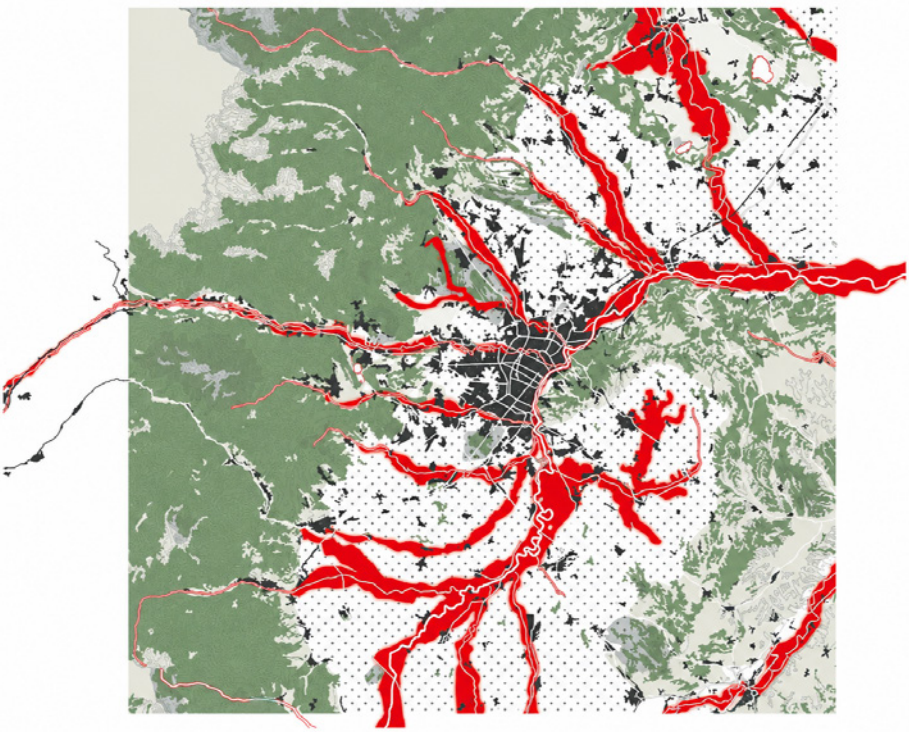


Figure 49. The municipality of Turin within its surrounding hydrological context, illustrating the relationship between the urbanized area, river and drainage networks, and the surrounding natural landscape.
Source: Turin – Towards the Metropolitan Regional Strategy, G. Pasqui (Politecnico di Milano) and C. Calvaresi (IRS: Institute for Social Research), Torino Strategica (Strategic Turin).

According to the analysis conducted by ARPA Piemonte and the City of Turin, temperatures in the city have increased by up to approximately 5 °C above the 1971–2000 average during the last two decades considered in the assessment. These conditions approach the extreme values observed during particularly hot summers, including those of 2003, 2015, and 2017 (ARPA Piemonte Dipartimento Rischi Naturali e Ambientali & Città di Torino, 2020).

An important indicator of this changing thermal environment is the increasing frequency of tropical days and tropical nights. Tropical days are defined as days during which the maximum air temperature exceeds 30 °C, while tropical nights occur when the minimum temperature remains above 20 °C (ARPA Piemonte Dipartimento Rischi Naturali e Ambientali & Città di Torino, 2020; European Commission & European Environment Agency, n.d.). These indicators are particularly relevant to urban thermal comfort because persistent high temperatures can increase the duration of human exposure to heat and reduce opportunities for nocturnal cooling.

The relationship between these climatic indicators and physiological thermal discomfort was also examined in the municipal climate vulnerability assessment. The analysis compared two periods, 1989–2016 and 2001–2016, in order to evaluate whether a significant change had occurred in the frequency of days characterized by thermal discomfort. When these results were considered together with the trends in tropical days and tropical nights, the analysis indicated a marked increase in the number of days associated with physiological thermal discomfort during the more recent

period (ARPA Piemonte Dipartimento Rischi Naturali e Ambientali & Città di Torino, 2020). Tropical nights, however, showed a comparatively more stable trend.

These findings demonstrate that climate vulnerability in Turin is not limited to the occurrence of extreme climatic events themselves. The persistence of elevated temperatures and the increasing frequency of thermal discomfort can create longer periods of exposure, particularly in densely built neighborhoods where limited vegetation, extensive impervious surfaces, and insufficient shading reduce the potential for natural cooling.
Furthermore, climatic vulnerability is not distributed uniformly throughout the city. The consequences of heat exposure depend not only on the intensity of the climatic hazard but also on the characteristics of the urban environment and the population exposed to it. Age, housing conditions, socioeconomic characteristics, and adaptive capacity can therefore influence the severity of the impacts experienced by different neighborhoods.

This relationship between environmental exposure and social vulnerability is particularly important when evaluating UHI risk. Areas with high temperatures do not necessarily represent the areas with the highest overall risk. Instead, the most critical locations are those where high climatic exposure overlaps with vulnerable populations and limited adaptive capacity.

3.1.3 UHI in Turin

In addition to the broader climatic pressures affecting Turin, the physical structure of the city plays an important role in determining local thermal conditions. The relationship between urban morphology, land cover, vegetation, and atmospheric conditions contributes to the formation and intensity of the Urban Heat Island (UHI) effect.

A large proportion of Turin's municipal territory is urbanized and characterized by extensive impervious surfaces and relatively limited vegetation coverage, particularly within dense residential and former industrial areas (Cimbaro et al., 2024).. Impervious materials such as asphalt, concrete, and masonry absorb and store solar radiation during the day and release accumulated heat after sunset. This process can increase both daytime surface temperatures and nighttime air temperatures, particularly in areas characterized by dense building configurations and limited vegetation.

Turin's geographical setting further contributes to these conditions. The city is located within the Po Valley and is surrounded by the Alps and Turin hills. Under certain meteorological conditions, this geographical enclosure can limit atmospheric circulation and favour the accumulation of heat and humidity during summer. During winter, the same conditions can contribute to cold-air stagnation and the accumulation of pollutants.

The UHI effect should therefore be understood as the result of an interaction between regional climate, urban morphology, surface properties, vegetation, radiation, and atmospheric

circulation. The intensity of the phenomenon varies spatially according to the characteristics of individual urban areas. Dense urban districts with extensive impervious surfaces and limited vegetation can experience greater heat accumulation than more open and vegetated areas.

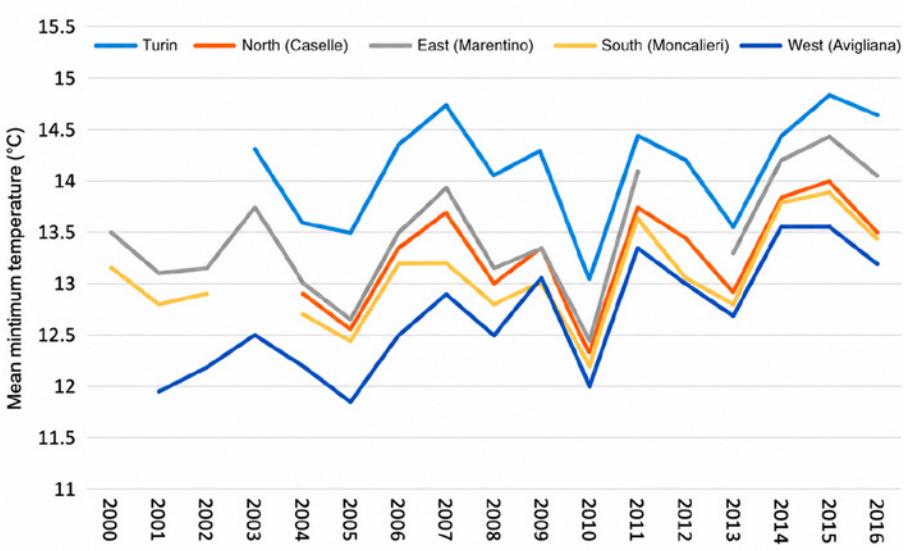


Figure 50. Annual mean temperature in Turin and four nearby rural stations from 2000 to 2016, showing the persistent temperature difference between the urban area and its surrounding rural context. Source: Garzena et al. (2018).

The figure 50 compares the annual mean temperature recorded in Turin with four nearby rural stations—North (Caselle), East (Marentino), South (Moncalieri), and West (Avigliana)—between 2000 and 2016. Turin consistently records higher annual mean temperatures than the surrounding rural stations, although all locations exhibit similar year-to-year fluctuations. The persistent temperature difference between the urban and rural stations provides evidence of the influence of urbanization on Turin's local thermal environment and supports the relevance of the Urban Heat Island (UHI) effect. The comparison also indicates that the urban influence extends beyond the most densely built areas, as increasing temperatures observed at surrounding stations may partly reflect the expansion and spatial influence of urbanization (Heino, 1999; Soux et al., 2004; Sovrano Pangallo, 1998).

The analysis also highlights an important characteristic of the Turin UHI: the spatial extent of the urban influence can extend beyond the most densely built areas. The increasing temperatures observed at rural monitoring stations may partly reflect the expansion of urbanized areas and the increasing spatial influence of the Turin UHI. Consequently, the distinction between urban and rural climatic conditions is not completely static, and the area affected by the city's thermal influence can change as urbanization expands (Heino, 1999; Soux et al., 2004; Sovrano Pangallo, 1998).

While city-wide temperature measurements are useful for understanding the general evolution of the UHI, they do not fully describe how thermal risk is distributed among different neighborhoods. For this reason, recent research has increasingly focused on micro-scale assessments that combine climatic information with demographic and socioeconomic characteristics.

Ellena et al. (2023) developed a micro-scale UHI risk assessment model for Turin by integrating three principal dimensions: climatic hazard, demographic exposure, and social vulnerability. The analysis was conducted at the census-tract scale, allowing the spatial distribution of UHI risk to be examined at a finer level than city-wide temperature measurements.

The results demonstrate that areas characterized by high thermal exposure do not necessarily correspond to the areas with the highest overall risk. Instead, risk increases where elevated climatic hazard overlaps with vulnerable populations and limited adaptive capacity. The study identified factors

such as a high proportion of elderly residents, poor housing conditions, and lower educational levels as relevant indicators of social vulnerability (Ellena et al., 2023). Industrial areas, despite exhibiting high thermal intensity, may show lower overall risk when population exposure is limited.

This relationship demonstrates that UHI risk in Turin is strongly influenced by the city's socio-spatial structure and by inequalities inherited from its industrial development. The physical distribution of heat therefore needs to be considered together with the characteristics of the population exposed to it.

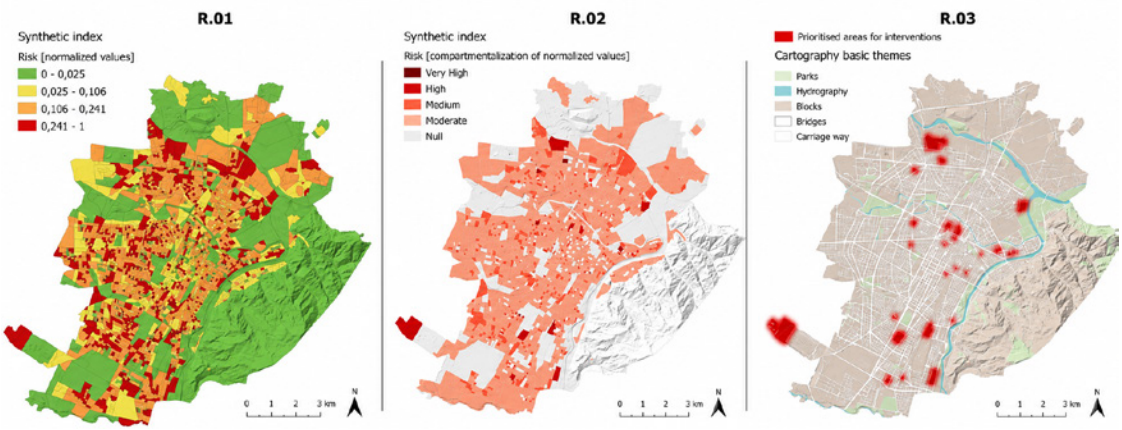


Figure 51. Spatial assessment of climate-related risk across Turin, showing the synthetic risk index (R.01), the classification of normalized risk values (R.02), and the identification of priority areas for intervention (R.03). The maps highlight the spatial concentration of higher-risk areas within the urban fabric and their relationship with parks, hydrographic systems, blocks, bridges, and the main road network. Source: Turin metropolitan/regional strategy documentation.

The figure 51 presents a three-stage spatial assessment of environmental risk across the Municipality of Turin. Map R.01 illustrates the synthetic risk index using normalized values, revealing a heterogeneous distribution of risk across the metropolitan territory. Higher-risk values are concentrated primarily within the densely urbanized areas, while the

surrounding green and less-developed areas generally exhibit lower values.

Map R.02 reorganizes these normalized values into five risk categories, ranging from null and moderate to medium, high, and very high risk, making the spatial concentration of vulnerable areas more apparent. Finally, R.03 identifies the areas prioritized for intervention and overlays them with the main territorial components, including parks, hydrographic systems, urban blocks, bridges, and the carriageway network. The resulting pattern indicates that priority areas are not distributed uniformly but are concentrated at specific locations within the urban fabric and along important environmental and infrastructural corridors. This assessment provides an important territorial-scale basis for identifying areas where climate adaptation and mitigation measures may have greater relevance. For the present thesis, the map is particularly useful in establishing the broader environmental context of Turin before moving toward the more detailed analysis of the Aurora district and the identification of site-specific microclimatic vulnerabilities and intervention strategies.

The spatial distribution of the resulting risk values indicates that several densely populated areas in Turin experience comparatively high levels of UHI risk. These include Barriera di Milano, Mirafiori Nord, Mirafiori Sud, Parella, Pozzo Strada, and Vanchiglietta. These areas combine relatively high thermal exposure with significant demographic and socioeconomic vulnerability, resulting in higher composite risk values.
In contrast, the southeastern hilly areas of Turin generally show lower UHI risk.

The findings of Ellena et al. (2023) therefore indicate that Turin's UHI should not be interpreted solely as a physical climatic phenomenon. Rather, it represents a socio-spatial risk, in which the intensity of the climatic hazard interacts with the characteristics of the urban environment and the vulnerability of the population exposed to it.

This distinction is particularly relevant to the present research. The Barrier di Milano district is characterized by relatively dense urban fabric, extensive paved surfaces, limited continuous vegetation, and intensively used public spaces. These characteristics make the analysis of thermal conditions at the neighborhood and pedestrian scales particularly important. City wide temperature averages alone cannot adequately describe the thermal conditions experienced by users of individual public spaces.

The city scale assessment therefore provides the broader justification for examining microclimatic conditions within Barrier di Milano. It establishes that UHI risk in Turin is influenced by the interaction between urban morphology, surface materials, vegetation, shading, and social exposure. Understanding these relationships provides the basis for evaluating targeted urban interventions capable of improving pedestrian-level thermal conditions while maintaining the existing urban structure and functional characteristics of the district.

3.2 Mapping the zone

3.2.1 The study area

This research focuses on a defined urban area within the Aurora district in northern Turin, a neighborhood that represents one of the city's most historically significant industrial areas while currently undergoing an extensive process of urban regeneration. Its strategic location immediately north of Turin's historic center, together with its industrial heritage and evolving urban character, makes it an appropriate case study for investigating the relationship between urban morphology, microclimate, and climate responsive design (Figure 1).

Barrier di Milano developed rapidly during the Industrial Revolution as a working class district characterized by dense residential blocks, industrial facilities, and manufacturing activities concentrated along the Dora River. Following the decline of industrial production in the late twentieth century, many factories were abandoned or repurposed, leaving behind a distinctive urban fabric composed of compact perimeter blocks, narrow street canyons, and large industrial buildings (Figure 2). Although the economic function of the district has changed considerably, its historic morphology remains largely intact and continues to influence the local urban environment.

Today, Barrier di Milano represents the intersection of industrial heritage and contemporary urban development. Former industrial



Figure 52 .The case study area. Source: GIS Map

areas have gradually been transformed into cultural, commercial, and mixed use spaces while preserving much of their historical identity. Landmarks such as the Museo Lavazza and the historic Porta Palazzo Open Market contribute to the district's cultural significance and reinforce its role as one of the most vibrant and diverse neighborhoods in Turin (Figure 3).

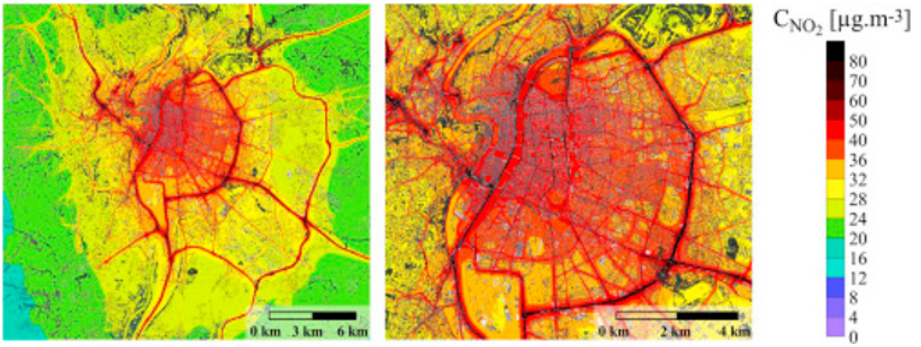


Figure 53 Urban identity and landmarks

From an environmental perspective, the study area exhibits several characteristics that make it particularly relevant for microclimate research. The dense urban fabric, high percentage of impervious surfaces, limited vegetation, and extensive use of heat-retaining materials contribute toelevated surface temperatures and increased susceptibility to the Urban Heat Island (UHI) effect.

In addition, the compact street network reduces sky visibility and natural ventilation, creating conditions that intensify outdoor thermal stress, particularly during summer. As illustrated in the city scale UHI analysis presented in Figure 54, the selected area falls within a medium to high UHI risk zone, further supporting its suitability as the focus of this research.

The district is also the subject of ongoing urban regeneration initiatives aimed at improving environmental quality, public spaces, and urban resilience through the introduction of greener infrastructure and more sustainable urban design strategies. This combination of historical industrial morphology, current redevelopment processes, and significant microclimatic challenges provides an ideal setting for evaluating how climate responsive urban interventions can enhance outdoor thermal comfort while preserving the district's cultural and historical identity.



3.2.2 Analysing the zone

The selected study area is characterized by a compact urban structure composed of dense perimeter blocks, a well-defined street network, and limited open spaces. The morphology reflects the historical development of the district, where residential, commercial, and former industrial functions are closely integrated. This compact configuration creates a continuous built fabric that strongly influences local ventilation patterns, solar exposure, and the spatial distribution of outdoor thermal conditions.



Source for base map: Geoportale Comune di Torino

3.2.2.1 Land use

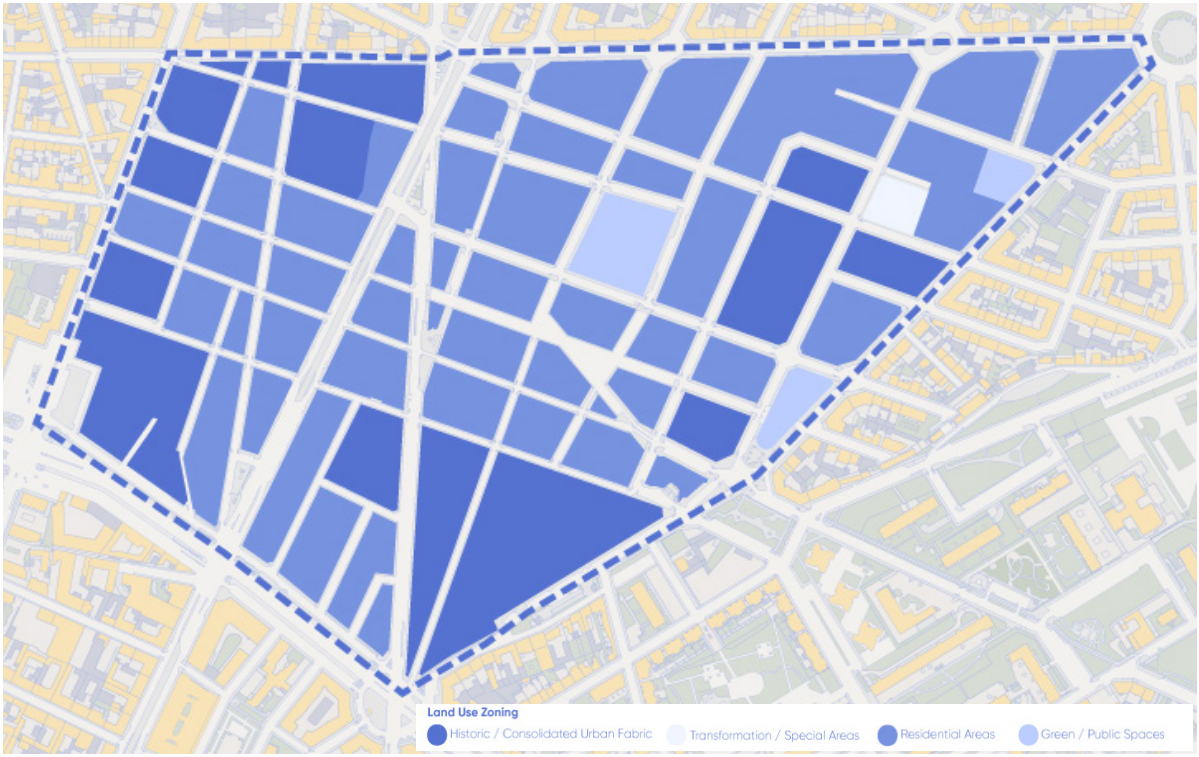
The study area covers approximately 958.32 m^2 and is predominantly occupied by residential land use, complemented by commercial activities, historic urban fabric, and a limited number of public green spaces. The high proportion of built-up surfaces and the relatively low vegetation coverage indicate a highly sealed urban environment, where land-use composition is expected to influence local microclimatic conditions through increased heat storage and reduced evaporative cooling.

Historic / Consolidated Urban Fabric: 15% **Total Area:** 141,204

Transformation / Special Areas: 0.003% **Total Area:** 3016

Residential Areas: 83% **Total Area:** 798,951

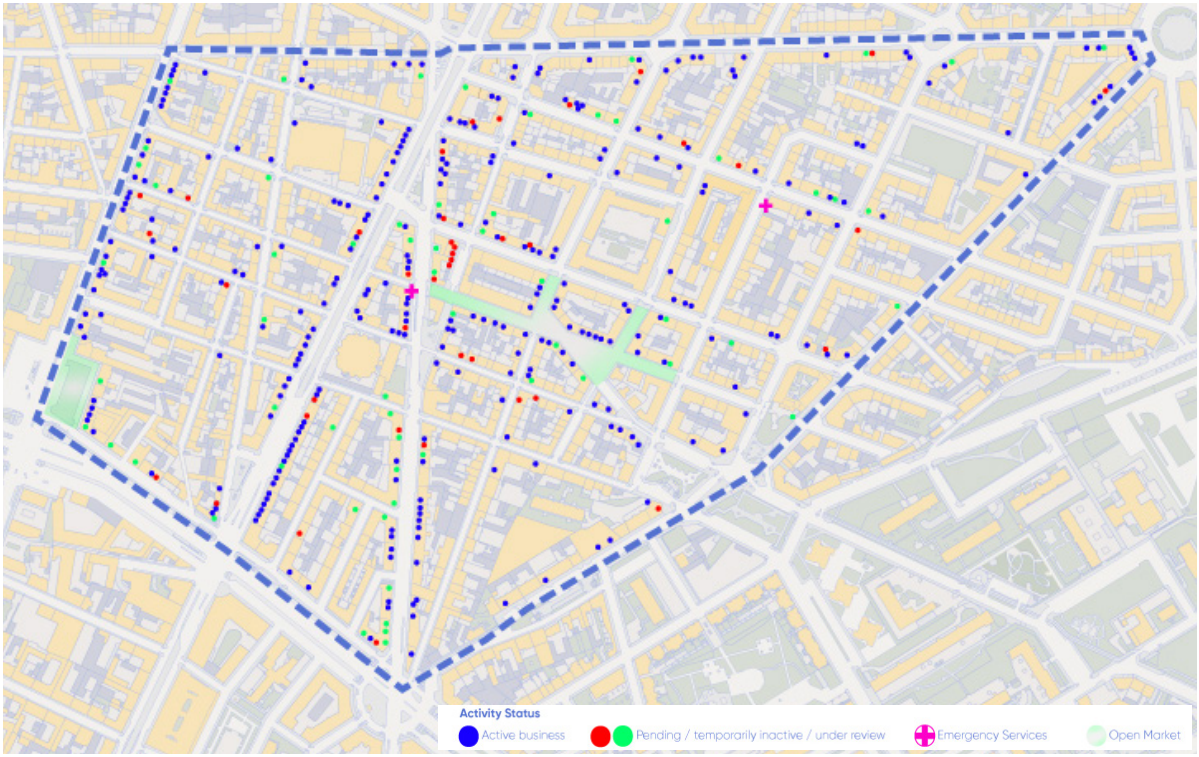
Green / Public Spaces: 2% **Total Area:** 15,149



Source for base map: Geoportale Comune di Torino

3.2.2.2 Activity Distribution

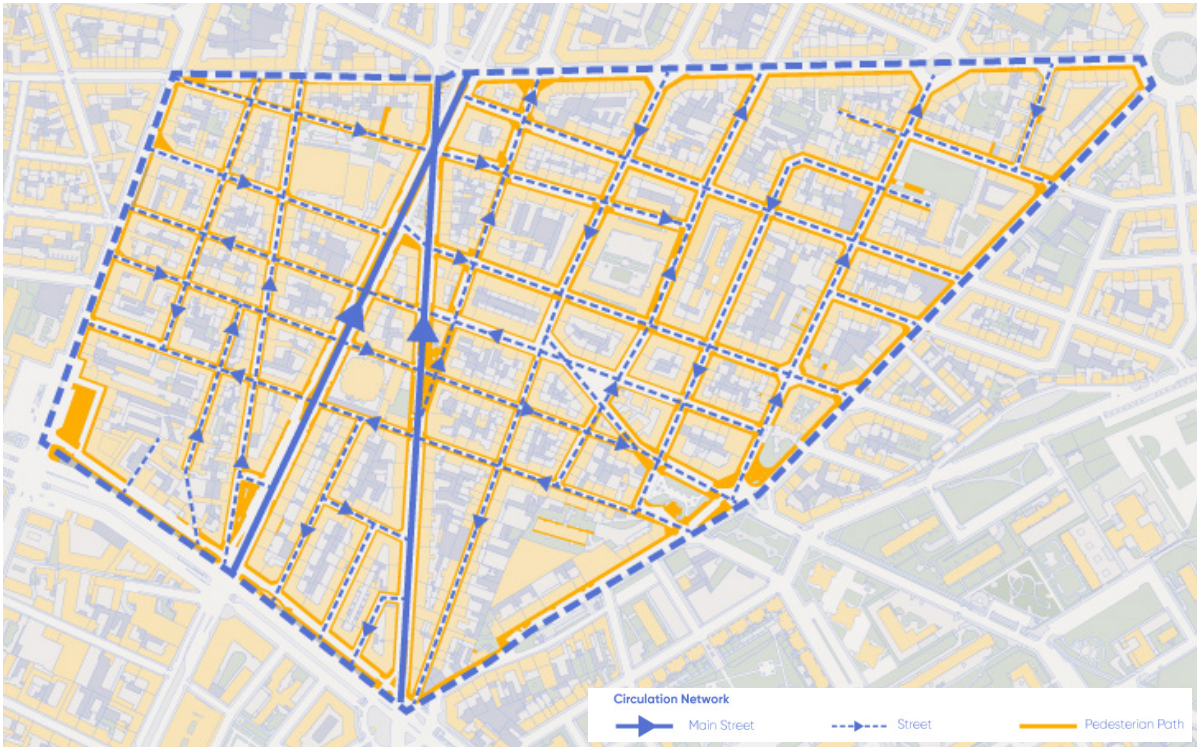
The study area supports a diverse mix of urban activities, with active commercial and service functions concentrated primarily along the main streets and major intersections. Residential areas occupy the interior blocks, while local markets, public services, and small businesses contribute to the district's daily vitality. Although a limited number of temporarily inactive or under-review properties are present, the overall distribution of activities indicates a vibrant mixed-use environment that generates continuous pedestrian movement throughout the day.



Source for base map: Geoportale Comune di Torino

3.2.2.3 Circulation Network

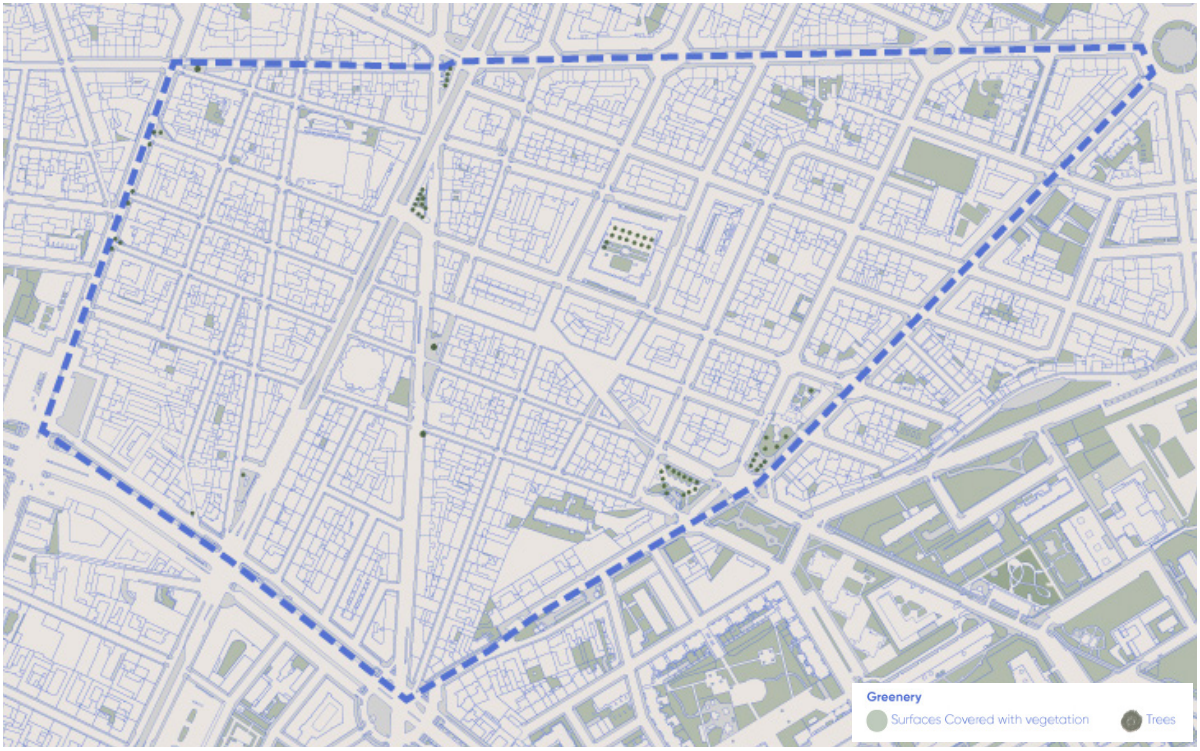
The circulation network is structured around a hierarchy of primary roads, secondary streets, and pedestrian routes that provide high connectivity throughout the study area. The compact street grid ensures efficient accessibility while supporting active mobility between residential, commercial, and public destinations. The presence of multiple interconnected pedestrian paths reinforces walkability; however, the dense street configuration and limited street width may also influence airflow and outdoor thermal conditions within the urban canyon environment.



Source for base map: Geoportale Comune di Torino

3.2.2.4 Vegetation

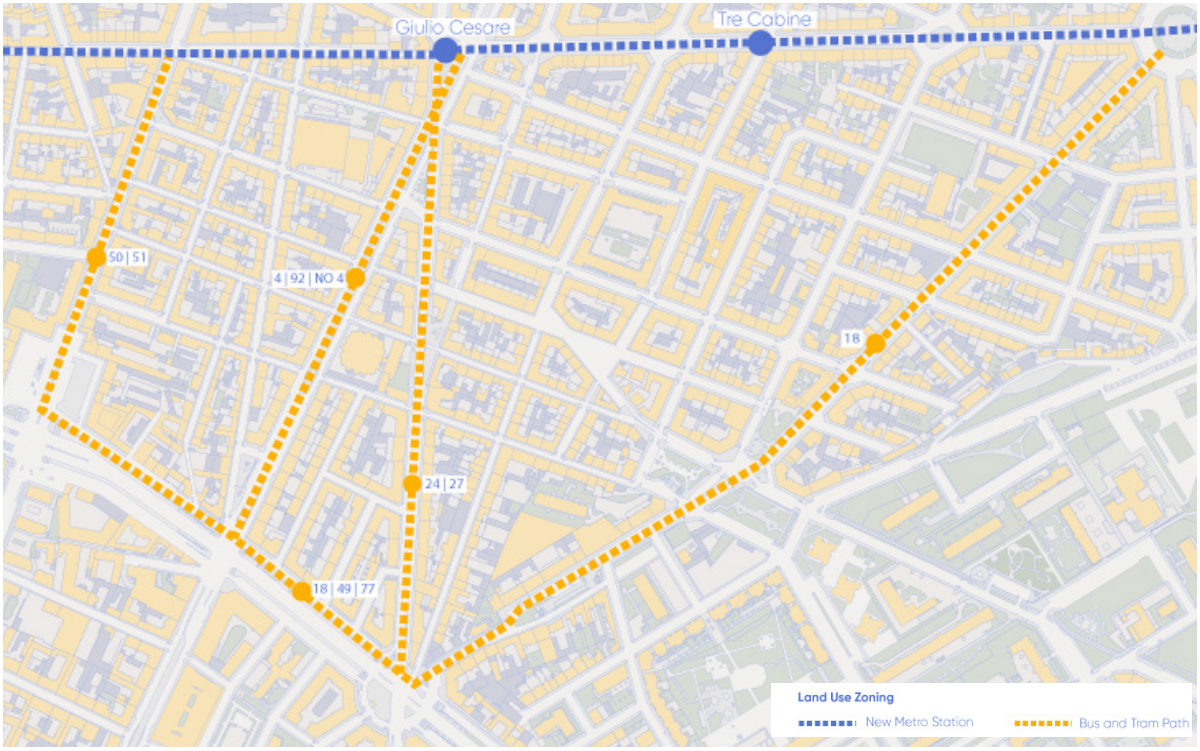
Vegetation plays a fundamental role in regulating urban microclimatic conditions by providing shading, reducing surface temperatures, and mitigating the Urban Heat Island (UHI) effect. Within the study area, green spaces cover approximately 15,149 m^2, representing 2.26% of the total area, indicating a relatively limited vegetation cover. Based on data obtained from the Geoportale del Comune di Torino, 66 trees were identified, with Acer campestre as the dominant species, followed by Ulmus minor. Coniferous trees are less common and are represented mainly by Pinus nigra var. austriaca. Most trees are mature, ranging from 10 to 18 m in height and exceeding 40 years of age, forming continuous tree canopies along several of the area's primary streets.



Source for base map: Geoportale Comune di Torino

3.2.2.5 Public Transportation

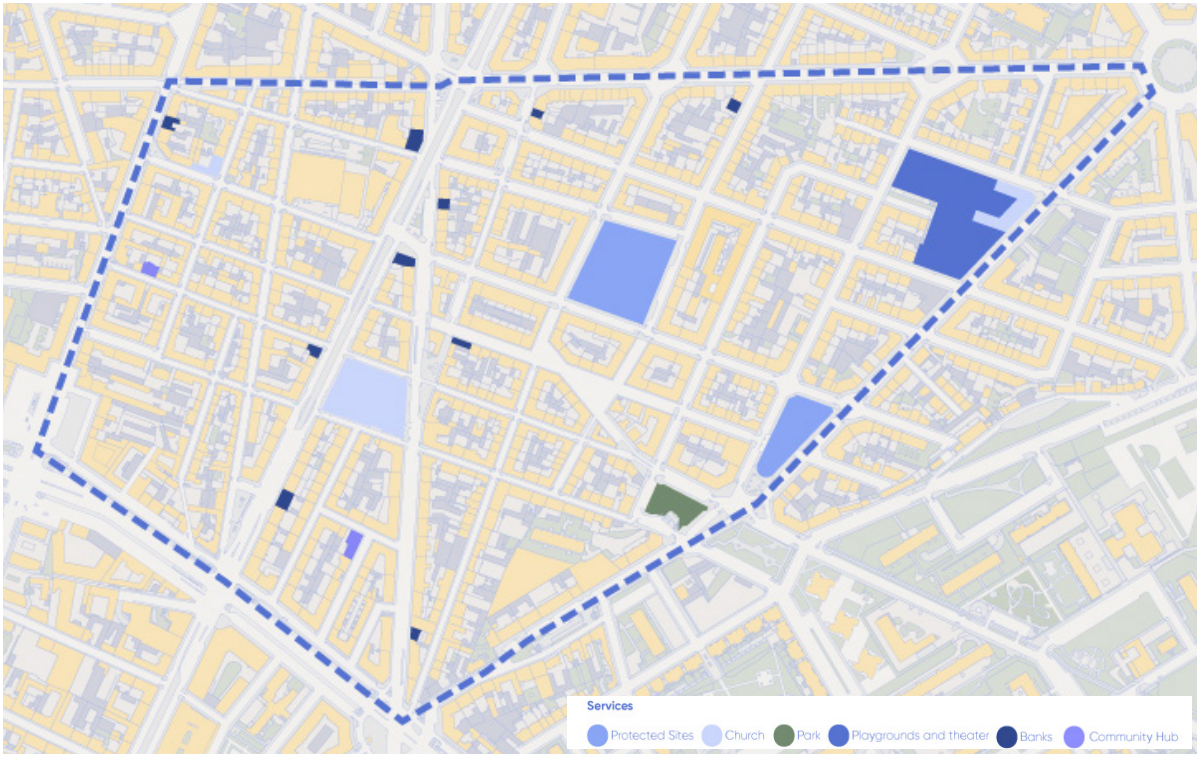
The study area is well served by public transportation, with several bus and tram routes providing connections across the district. In addition, the planned extension of Turin's metro network, including a new station adjacent to the study area, is expected to significantly enhance accessibility and connectivity. This future infrastructure investment has the potential to strengthen the neighborhood's urban vitality, encourage sustainable mobility, and support the ongoing regeneration of the district by reducing dependence on private vehicles and improving access to surrounding areas.



Source for base map: Geoportale Comune di Torino

3.2.2.7 Urban Services and Public Facilities

The study area contains a range of public facilities and community services that support the daily needs of residents. These include educational and religious buildings, protected sites, neighborhood parks, playgrounds, cultural facilities, and financial services distributed throughout the district. Although these amenities are generally well dispersed, larger public and recreational spaces remain limited, highlighting the importance of preserving existing facilities while improving the accessibility and quality of public spaces as part of future urban regeneration initiatives.



Source for base map: Geoportale Comune di Torino

3.3 Microclimatic Simulation Using ENVI-met

3.3.1 Software Information

The microclimatic assessment presented in this thesis was carried out using ENVI-met (Version 5.9.0), a three-dimensional computational fluid dynamics (CFD)-based model specifically developed to simulate the complex interactions between the atmosphere, urban surfaces, vegetation, soil, and buildings at the neighbourhood scale. Unlike conventional energy balance models, ENVI-met integrates atmospheric physics, thermodynamics, plant physiology, radiation exchange, and soil processes into a coupled simulation environment, allowing a realistic representation of the urban microclimate under different environmental conditions.

ENVI-met has become one of the most widely adopted numerical tools for urban climate research because of its ability to reproduce microscale processes with high spatial and temporal resolution. The model has been extensively applied in studies investigating the Urban Heat Island (UHI) effect, outdoor thermal comfort, climate-sensitive urban design, green infrastructure, and nature-based solutions. Its capability to evaluate the climatic performance of alternative urban design scenarios makes it particularly suitable for assessing mitigation strategies before their physical implementation.

The model simultaneously simulates a wide range of physical

processes governing the urban environment. These include airflow around and between buildings, turbulent momentum exchange, shortwave and longwave radiation transfer, surface and façade energy balance, conductive heat transfer within construction materials, heat and moisture exchange between soil and atmosphere, evapotranspiration from vegetation, and pollutant dispersion. Through the coupling of these processes, ENVI-met provides a dynamic representation of the urban canopy layer and enables detailed analyses of environmental conditions at pedestrian level.

A significant advantage of ENVI-met is its explicit representation of vegetation. Unlike simplified urban climate models that treat vegetation as a surface parameter, ENVI-met models individual trees and shrubs according to their physiological characteristics, including species-specific height, crown geometry, Leaf Area Density (LAD), and transpiration behaviour. Consequently, the model can quantify the influence of urban greenery on shading, evapotranspiration, wind modification, and radiation exchange, making it particularly appropriate for evaluating green infrastructure interventions such as street trees, green corridors, green roofs, and vegetated public spaces.

Within this research, the Physiological Equivalent Temperature (PET) was selected as the principal biometeorological indicator for evaluating outdoor thermal comfort. PET combines meteorological variables including air temperature, relative humidity, wind speed, and mean radiant temperature (MRT) into a single index that reflects the thermal conditions perceived by pedestrians. Since PET incorporates both atmospheric conditions and human energy balance, it provides a

comprehensive measure for comparing existing and proposed urban design scenarios.

ENVI-met operates on a three-dimensional Cartesian computational grid in which the study area is discretized into horizontal and vertical cells. This grid-based approach enables detailed representation of buildings, pavements, vegetation, soil layers, and other urban elements. Depending on the complexity of the study area and the objectives of the simulation, calculations may extend over several consecutive hours or days, allowing both diurnal and short-term climatic variations to be investigated.

The modelling workflow adopted in this study follows the standard ENVI-met simulation procedure. Project initialization and computational settings were established within the Manage Projects module. Subsequently, the three-dimensional digital model of the study area was developed using Edit Model Area, where buildings, ground surfaces, pavement materials, vegetation, and soil properties were defined according to field observations, GIS data, and municipal databases. Meteorological forcing conditions, simulation duration, initial atmospheric parameters, and numerical boundary conditions were specified within Simulation Settings, after which the numerical calculations were performed using the Start Simulation module.

Following completion of the simulations, environmental variables were analysed through the Visualize Results module, which provides spatial and temporal distributions of air temperature, wind speed, relative humidity, mean radiant

temperature (MRT), surface temperature, and additional microclimatic variables. Outdoor thermal comfort was evaluated using the Simulate Thermal Comfort module, where PET values were calculated for the selected simulation periods.

To ensure realistic representation of the study area, the Materials and Objects Library was employed to assign the thermophysical properties of pavements, buildings, and construction materials, while the Tree Library was used to define vegetation species and their physiological characteristics. Furthermore, the TreePass module facilitated detailed vegetation parameterization, and the Projects/Workspaces environment supported efficient organization and management of the simulation workflow.

Overall, ENVI-met provides a robust framework for quantifying the impacts of urban morphology, surface materials, and green infrastructure on neighbourhood-scale microclimatic conditions. Its ability to simulate both existing and proposed urban configurations makes it an appropriate tool for evaluating climate-responsive design strategies and supporting evidence-based urban regeneration.

3.3.2 Model Domain and Boundary Conditions

The computational domain was georeferenced according to the geographical location of the study area in Turin, Italy, using a latitude of **45.07°** N and a longitude of **7.69°** E under the Central European Standard Time (CET) zone, with a reference longitude of 15.00° E. This configuration ensured that solar geometry, radiation exchange, and daylight conditions were accurately represented according to the local climatic context throughout the simulation period. Due to the large spatial extent of the study area and the computational limitations associated with high resolution ENVI-met simulations, the modelling domain was divided into two adjacent computational sections. This approach allowed the entire study area to be simulated while maintaining the selected spatial resolution and ensuring manageable computation times without compromising the representation of the existing urban morphology.

The first computational domain was discretised using a regular Cartesian grid consisting of **272 × 242 × 60** cells in the x, y, and z directions, respectively, whereas the second domain consisted of **168 × 242 × 60** cells. Both domains employed a uniform spatial resolution of **3.0 m × 3.0 m × 3.0 m**. This grid resolution was selected to provide sufficient geometric detail for representing the urban morphology while maintaining an acceptable computational cost for large scale simulations. To improve the accuracy of near-surface calculations, where the strongest exchanges of heat, momentum, and moisture occur between buildings, vegetation, ground surfaces, and the atmosphere, the lowest vertical grid cell was subdivided into five telescopic sublayers, allowing a more accurate

representation of atmospheric processes within the urban canopy layer. The resulting models provided a detailed representation of the existing urban environment, including building volumes, street canyons, courtyards, paved areas, open spaces, and vegetation. Such a configuration enables ENVI-met to simulate the complex interactions between urban geometry, surface materials, vegetation, and atmospheric processes, thereby providing a reliable basis for assessing local microclimatic conditions and outdoor thermal comfort. The adopted spatial resolution represents an appropriate compromise between geometric accuracy and computational efficiency, ensuring that the principal characteristics of the study area are adequately captured without excessive computational demand.

Meteorological boundary conditions were established using observational data obtained from a local ARPA Piemonte weather station in Turin. The input dataset included air temperature, relative humidity, wind speed and direction, together with the atmospheric parameters required to initialise the numerical model. Simulations were performed for a hot day of the reference year, representing the period of maximum thermal stress and the highest intensity of the Urban Heat Island (UHI) effect. This approach enabled the assessment of diurnal variations in air temperature, surface heating, and outdoor thermal comfort under extreme summer conditions, providing a robust basis for evaluating the effectiveness of the proposed climate-responsive design strategies.

3.3.3 Modeling Process and Simulation

The geometric model of the study area was developed using the Regional Technical Map (Carta Tecnica Regionale, CTR) obtained from the Geoportale del Comune di Torino. The original cartographic data were converted into a bitmap image and imported into the ENVI-met Spaces module, where they served as a geometric reference for the manual construction of the three-dimensional model.

Buildings, streets, paved surfaces, open spaces, and vegetation were subsequently digitised within the computational domain to accurately reproduce the existing urban morphology. Due to the extensive size of the study area and the computational demands associated with high-resolution ENVI-met simulations, the digital model was divided into two adjacent computational domains. This subdivision allowed the entire study area to be represented while preserving the selected spatial resolution and maintaining computational efficiency. Both domains were constructed following the same modelling methodology and using identical material properties, vegetation parameters, and simulation settings, ensuring the consistency and comparability of the simulation results.

The spatial resolution of the computational grid was determined according to the dimensions of the study area and the level of geometric detail required for the simulations. Based on the map scale and the physical dimensions of the selected site, a uniform grid resolution of 3.0 × 3.0 × 3.0 m was adopted for both computational domains.
This resolution represents an appropriate compromise between

modelling accuracy and computational efficiency, allowing the principal morphological characteristics of the urban environment to be represented while maintaining reasonable simulation times. The modelling process included the definition of building geometries, surface materials, vegetation characteristics, and terrain properties using the corresponding ENVI-met object and material libraries.

Once the digital models had been completed, the computational domains and simulation parameters were configured, after which the meteorological boundary conditions were assigned and the numerical simulations were executed independently for each domain. The principal model parameters adopted for the two computational domains are summarised in the following tables.

3.3.3.1 Model confguration parameters

Parameter	Description
Location	Turin, Italy
Geographic Coordinates	Latitude: 45.07° N, Longitude: 7.69° E
Reference Time Zone	Central European Standard Time (UTC +1)
Number of Grids	272 (x) × 242 (y) × 60 (z)
Nesting Grids	0
Resolution	3 × 3 × 3 m
Wall Material	Default wall – moderate insulation
Roof Material	Roofing tile
Real Dimensions	816m × 726 m
Area	592.416 m2



Figure 57. East computational domain. Three-dimensional ENVI-met model of the eastern section of the study area, showing the spatial distribution of buildings, streets, open spaces, and vegetation. This domain was generated using a 3 × 3 × 3 m grid resolution to preserve the geometric characteristics of the existing urban fabric while ensuring computational efficiency.

3.3.3.2 Soil Profiles

Following the definition of the building geometries and vegetation, appropriate ground materials were assigned to all surface elements to accurately represent the existing thermal characteristics of the study area. The majority of the materials were selected directly from the ENVI-met Materials Database, ensuring consistency with the software's validated thermophysical properties.

A default sandy loam soil profile was assigned as the base ground layer throughout the model. Surface materials, including asphalt pavements and vegetated areas, were then defined according to the existing land-use conditions. Since asphalt represents the dominant surface material within the study area and strongly influences the surface energy balance, a custom asphalt material was developed by modifying its surface emissivity to better reflect local pavement characteristics and improve the simulation of surface temperatures and heat exchange processes. The thermophysical properties of the principal materials implemented in the ENVI-met model are summarized in the following table:

Material	Albedo	Emissivity	Funcion
Default sandy loam	0.20	0.90	Base soil layer under the
Asphalt road	0.12	0.90	Car roads, Parking lane, Side walks
Grass 10 cm	0.20	0.97	Greenery

Table 7.. Material choices for ENVI-met models

3.3.3.3 Trees

Vegetation was modelled using the ENVI-met Tree Database, with tree species selected according to the existing urban vegetation identified through the municipal tree inventory. Acer platanoides was assigned to mature trees located within larger public green spaces, where their broad canopies provide substantial shading, while Ulmus campestris was used to represent the street trees distributed along residential streets and internal road corridors.

By incorporating the existing tree species, canopy dimensions, and spatial distribution into the numerical model, ENVI-met simulates the effects of vegetation on solar shading, evapotranspiration, airflow modification, and surface energy exchange. This enables a more realistic representation of the current microclimatic conditions and improves the reliability of the thermal comfort assessment. The characteristics of the tree species used in the model are summarized in the following table:

Scientific Name	Type	N° of Trees	Height (m)	Trunk Diam	ENVI-met Suggested Tree-Model
Acer platanoides (Norway Maple)	Broadleaf	14	10–15	40–50	Maple / Medium Broadleaf
Ulmus campestris (Field Elm)	Broadleaf	3	5	6	Elm / Small–Medium Broadleaf

Table 8. The species of trees in the case study area. Source for Info. Data: Geoportale Città di

3.3.4 Simulation Setup

After completing the digital model and assigning all material and vegetation properties, the simulation settings were configured using the ENVI-guide module. This module was used to define the numerical configuration of the model, including the simulation period, meteorological forcing, and boundary conditions required for the numerical calculations. The simulation was performed over a 48-hour period, starting at 00:00 on 28 May 2025. The first 24 hours were considered as a model spin-up period, allowing the coupled interactions between the atmosphere, urban surfaces, soil, and vegetation to reach a stable state before the analysis period. Consequently, the results presented in this study are primarily based on the second simulation day.

Meteorological boundary conditions were prescribed using the Simple Forcing option in ENVI-met. The meteorological data were obtained from a weather station located approximately 1.2 km from the project site. Due to this distance, the weather station data may not fully represent the local microclimatic conditions within the project area; however, they were used to provide the atmospheric forcing necessary to reproduce the prevailing weather conditions during the simulation period. These data ensured that the numerical model reflected the climatic conditions relevant to the study area. Following the definition of all simulation parameters, the numerical calculations were executed using the Simulation module of ENVI-met. Due to the large size of the computational domains and the high spatial resolution adopted in this study, each simulation required approximately 15 days to complete.

3.3.5 Output Processing and Analysis

Upon completion of the simulations, the generated output files were processed using the Leonardo module of ENVI-met. Leonardo provides advanced post-processing tools for visualising and analysing the spatial distribution of simulated environmental variables through horizontal plans, vertical sections, profiles, and thematic maps. Different output files were used according to the variable being analysed. Air temperature, wind speed, relative humidity, and other atmospheric variables were extracted from the Atmosphere output files, whereas land surface temperature and other surface related parameters were obtained from the Surface output files. Outdoor thermal comfort was evaluated using the BIO-met module, which calculates a range of biometeorological indices based on the simulated microclimatic conditions. In this research, the Physiological Equivalent Temperature (PET) was selected as the principal indicator for assessing outdoor thermal comfort, although the software is also capable of calculating other indices, including the Universal Thermal Climate Index (UTCI) and the Predicted Mean Vote (PMV).

For each analysis period, the desired simulation time and evaluation height were specified within the BIO-met module. The calculated PET values were automatically exported to a dedicated BIO-met output folder, which was subsequently imported into the Leonardo module. This workflow enabled the generation of high resolution spatial maps illustrating the distribution of thermal comfort across the study area and facilitated the comparison of existing and proposed design scenarios. The processed outputs were then used to evaluate the spatial

and temporal variations of key microclimatic variables, including air temperature, surface temperature, wind speed, relative humidity, mean radiant temperature (MRT), and Physiological Equivalent Temperature (PET). These parameters formed the basis for assessing the effectiveness of the proposed climate responsive design interventions in mitigating the Urban Heat Island (UHI) effect and improving outdoor thermal comfort.

Hour	T air °C	Humidity (%)	Wind speed (m/s)	Wind direction°
00:00:00	18.7	74	1	75
01:00:00	17.9	77	1	75
02:00:00	17.1	80	1	75
03:00:00	16.7	81	1	75
04:00:00	16.2	83	1	75
05:00:00	15.7	84	1	75
06:00:00	15.4	86	1	75
07:00:00	16.4	84	1	75
08:00:00	18.1	80	1	75
09:00:00	19.4	75	1	75
10:00:00	21.3	69	1	75
11:00:00	22.7	65	1	75
12:00:00	24.8	58	1	75
13: 00:00	25.5	54	1	75
14:00:00	26.4	52	1	75
15:00:00	26.8	52	1	75
16:00:00	26.9	54	1	75
17:00:00	26.8	56	1	75
18:00:00	26.8	56	1	75
19:00:00	26.2	58	1	75
20:00:00	25	62	1	75
21:00:00	22.8	70	1	75
22:00:00	21.8	63	1	75
23:00:00	21.3	63	1	75

Table 9. Input values for the simulation

3.3.6 Result (Existing Condition)

3.3.6.1 Air Temperature

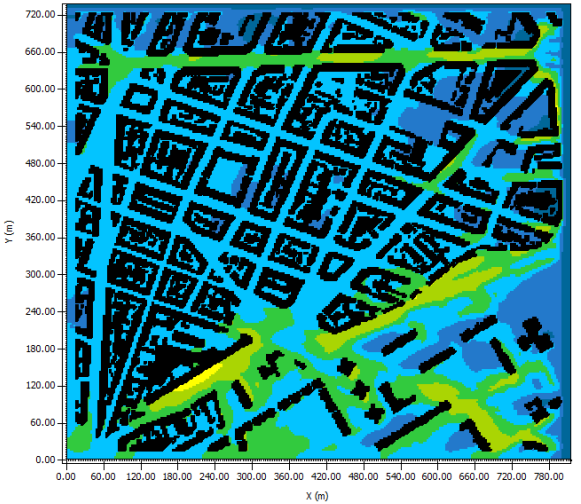
Figures 74–77 presents the spatial distribution of air temperature at 1.5 m under the existing urban conditions at 09:00, 12:00, 15:00, and 18:00. Air temperatures range from 19.70°C to 29.27°C, with clear spatial and temporal variations across the study area. The distribution is mainly influenced by solar exposure, urban morphology, building shading, and the presence of vegetation, resulting in cooler conditions within shaded and enclosed urban spaces and warmer conditions across exposed roads and open paved areas. The progressive increase in air temperature throughout the day indicates the strong influence of daytime solar radiation and the thermal response of the existing urban fabric.

At 09:00, air temperatures remain relatively low, ranging from 19.70°C to 24.02°C, with predominantly cooler conditions across the study area. Warmer areas are locally visible along exposed streets and open spaces, while the interiors of urban blocks remain comparatively cooler due to building shading. At 12:00, temperatures increase substantially to 24.06–27.46°C, with warmer conditions becoming more widespread, particularly along exposed roads and open areas. During 15:00, the highest temperatures are recorded, reaching 25.61–29.27°C, with most of the study area exhibiting warmer air-temperature conditions.

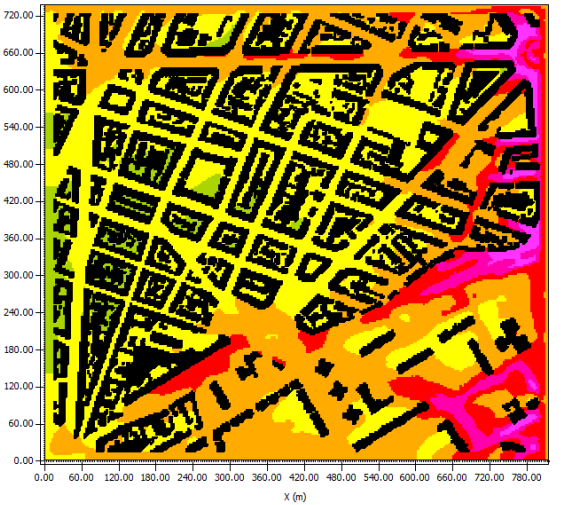
By 18:00, air temperatures range from 25.55°C to 27.80°C. Although the maximum temperature decreases compared with 15:00, relatively warm conditions remain across much of the study area. Cooler zones become more visible within shaded and enclosed urban spaces, while exposed areas continue to retain higher air temperatures. These results demonstrate that building morphology and shading provide localized thermal moderation, whereas exposed urban surfaces remain more susceptible to daytime warming and heat retention.

AIR TEMPERATURE

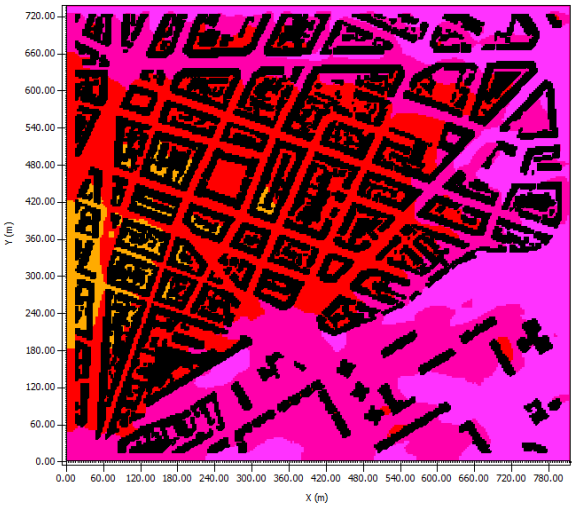
9:00 A.M



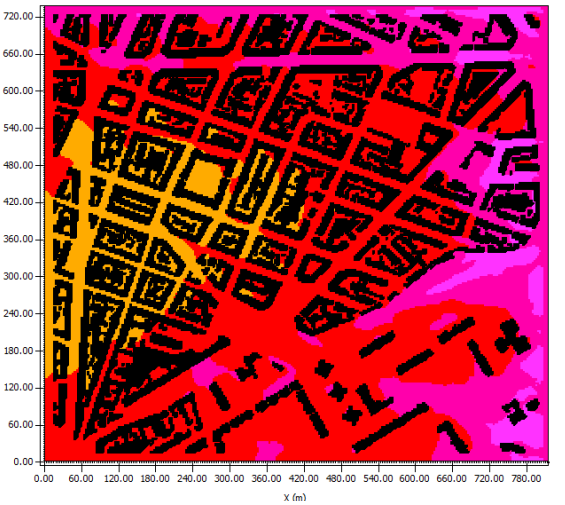
12:00 A.M



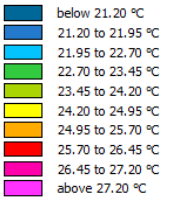
15:00 P.M



18:00 P.M



The figures 74-77, show Potential Air Temprature in the area with existing condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)





3.3.6.2 Surface Temperature (Tsurface)

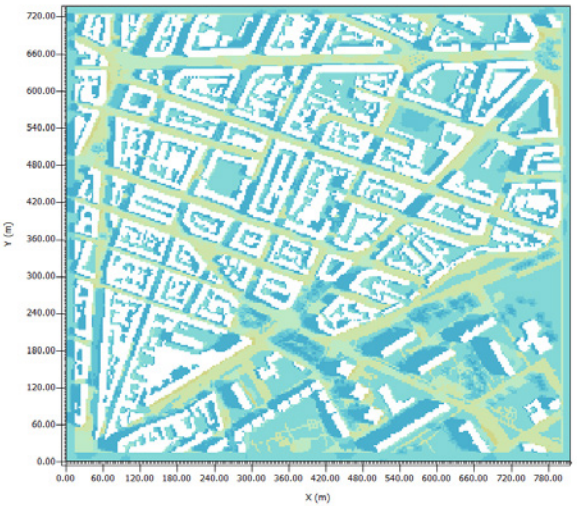
Figures 78–81 presents the spatial distribution of surface temperature under the existing urban conditions at 09:00, 12:00, 15:00, and 18:00. Surface temperatures range from 19.20°C to 50.06°C, showing substantially greater spatial variability than air temperature. The distribution is primarily influenced by surface materials, solar exposure, urban morphology, and the presence of vegetation and building shading. Warmer conditions are generally concentrated over exposed impervious surfaces, while shaded and vegetated areas remain comparatively cooler.

At 09:00, surface temperatures range from 19.20°C to 37.85°C, with relatively cooler conditions across shaded areas and urban spaces affected by building shadows. Higher temperatures are mainly observed on exposed roads and paved surfaces. During 12:00, surface heating becomes considerably stronger, with temperatures increasing to 22.49–49.39°C. The highest values are concentrated along major road corridors, intersections, and other highly exposed impervious surfaces, while shaded areas remain cooler.

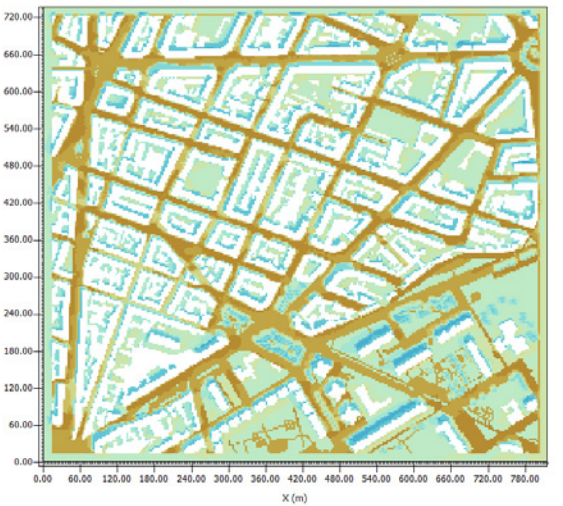
At 15:00, the strongest surface heating is observed, with temperatures reaching 25.11–50.06°C. Large paved areas and exposed roads exhibit the highest values, demonstrating the strong influence of solar radiation and surface characteristics. By 18:00, surface temperatures decline to 25.00–40.22°C, although several paved surfaces continue to retain considerable heat. Cooler conditions remain evident in shaded and vegetated areas. Overall, the results highlight the strong influence of land-cover and surface characteristics on thermal conditions and indicate that exposed impervious surfaces are the primary contributors to daytime surface heat accumulation.

T SURFACE

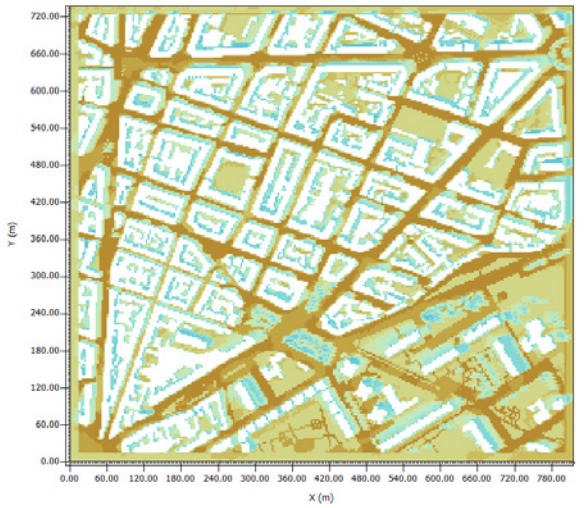
9:00 A.M



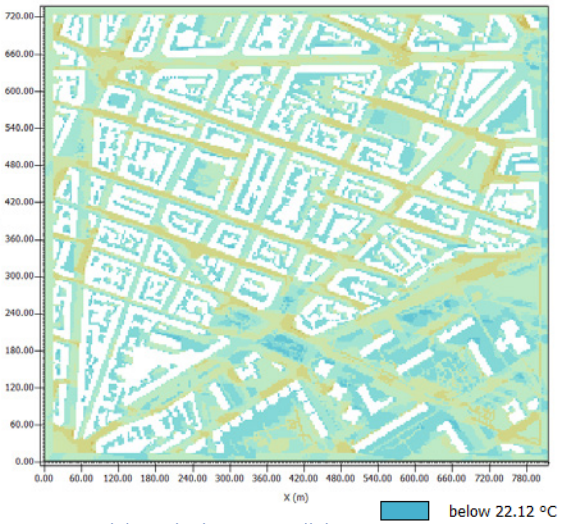
12:00 A.M



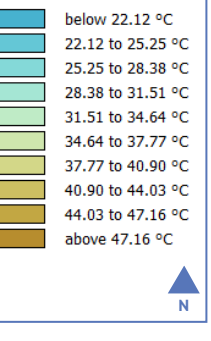
15:00 P.M



18:00 P.M



The figures 78-81, show Surface Temprature in the area with existing condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)



3.3.6.3 Wind Speed

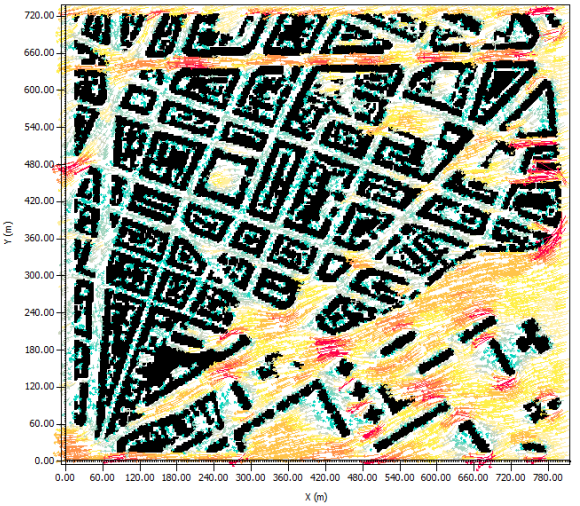
Figures 82–85 presents the spatial distribution of wind speed at 1.5 m under the existing urban conditions at 09:00, 12:00, 15:00, and 18:00. Simulated wind speeds range from 0.01 to 1.42 m/s, indicating generally low wind velocities across the study area, with localized areas of higher airflow. The spatial distribution is strongly influenced by urban morphology, building arrangement, street orientation, and the degree of openness of the urban fabric. Higher wind speeds are mainly concentrated along open areas and wider road corridors, while the compact urban blocks generally exhibit lower wind velocities.

At 09:00, wind speeds range from 0.01 to 1.18 m/s, with the highest velocities concentrated along the more open southern and eastern parts of the study area and selected wider streets. In contrast, the interiors of the dense urban blocks show predominantly low wind speeds, reflecting the obstruction and shielding effects of surrounding buildings. At 12:00, wind speeds range from 0.01 to 1.14 m/s, with a similar spatial pattern. The main road corridors and open spaces continue to function as localized ventilation paths, while airflow remains weaker within the compact urban fabric.

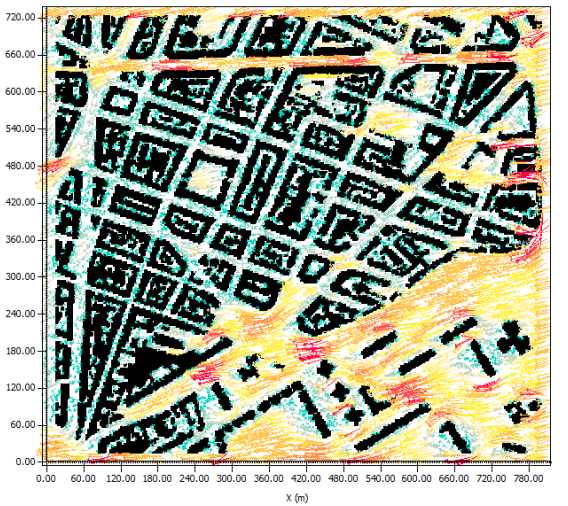
During 15:00, the maximum wind speed increases to 1.42 m/s, although low wind velocities continue to dominate most of the site. The highest values remain concentrated in open and exposed areas, particularly toward the southern and eastern portions of the study area. By 18:00, wind speeds remain within the same overall range of 0.01–1.42 m/s, with higher velocities persisting in open areas and along wider streets. Overall, the results indicate that the existing compact urban morphology restricts air movement within enclosed blocks, while wider streets and open spaces provide comparatively better ventilation and opportunities for heat dissipation.

Wind Speed

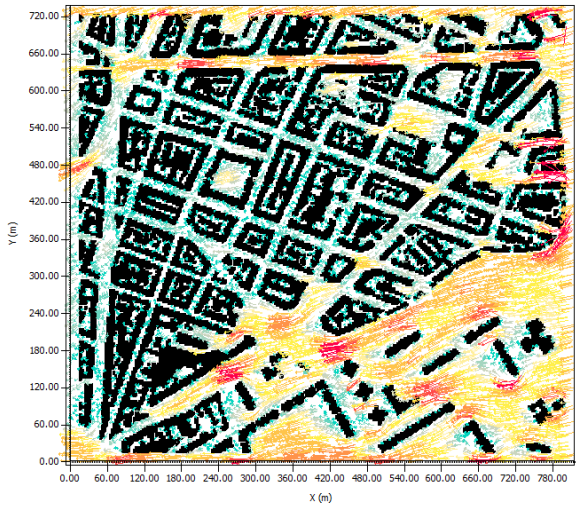
9:00 A.M



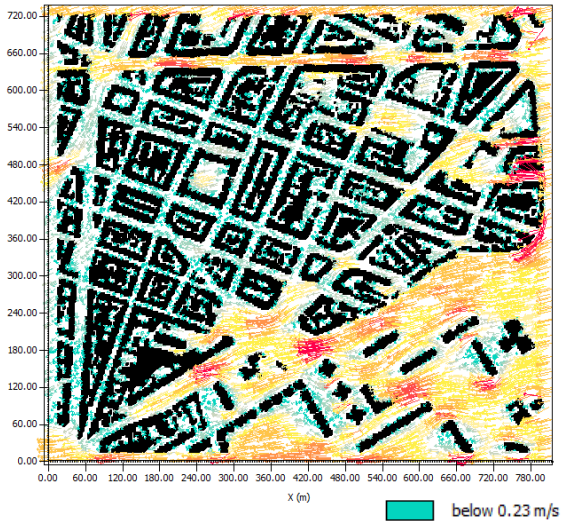
12:00 A.M

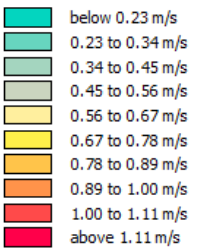


15:00 P.M



18:00 P.M





The figures 82-85, show Wind Speed in the area with existing condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)



3.3.6.4 Physiological Equivalent Temperature (PET)

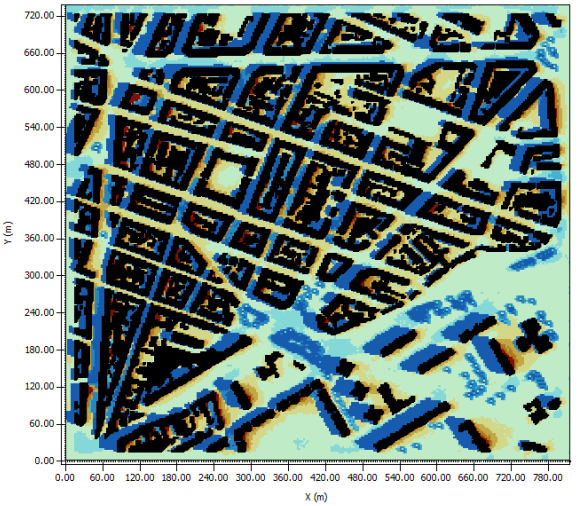
Figures 86–89 present the spatial distribution of Physiological Equivalent Temperature (PET) at 1.5 m under the existing urban conditions at 09:00, 12:00, 15:00, and 18:00. PET values range from 27.26°C to 58.11°C, indicating substantial spatial and temporal variation in outdoor thermal comfort across the study area. The distribution is strongly influenced by solar exposure, building shading, surface temperature, and local wind conditions. Higher PET values are generally concentrated in exposed areas with direct solar radiation and extensive impervious surfaces, while lower values occur mainly in shaded and enclosed urban spaces.

At 09:00, PET values range from 27.26°C to 56.96°C, with lower values concentrated in shaded areas and spaces protected from direct solar radiation. Higher PET values are locally visible across exposed paved surfaces and open areas. During 12:00, PET increases to 31.90–57.61°C, with warmer thermal conditions becoming more widespread as solar exposure intensifies. At 15:00, the highest PET values are recorded, ranging from 33.66°C to 58.11°C, with extensive areas experiencing elevated thermal stress, particularly across exposed roads, paved surfaces, and areas receiving direct solar radiation.

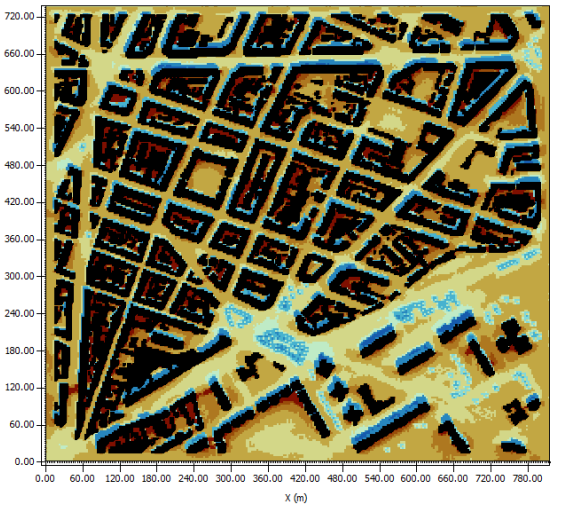
By 18:00, PET values decrease to 30.36–56.22°C as solar radiation weakens. Nevertheless, relatively high PET values persist across exposed impervious surfaces, indicating continued heat storage and thermal release from urban materials. Lower PET conditions remain concentrated in shaded and more enclosed spaces. Overall, the results demonstrate that outdoor thermal comfort in the existing condition is strongly controlled by solar exposure, building shading, surface characteristics, and local airflow, with exposed impervious areas remaining the most vulnerable locations to pedestrian thermal stress.

PET

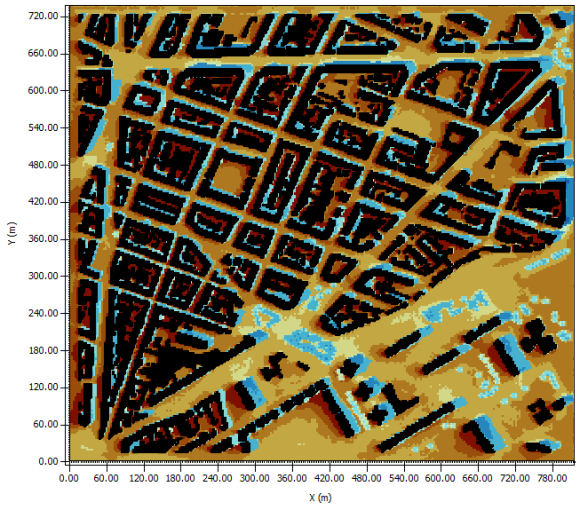
9:00 A.M



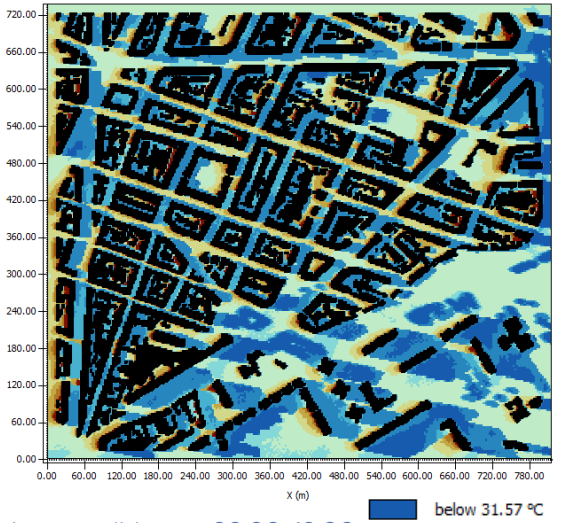
12:00 A.M

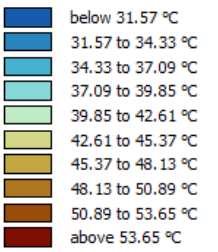


15:00 P.M



18:00 P.M







The figures 86-89, show PET in the area with existing condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)

The integrated analysis of air temperature, surface temperature, wind speed, and Physiological Equivalent Temperature (PET) demonstrates that the existing urban environment is characterized by significant spatial variations in thermal conditions and limited natural ventilation. Air temperature gradually increases from the morning toward the afternoon, reaching its highest values around 15:00, while surface temperature shows a substantially stronger response to solar radiation and surface characteristics. Impervious and exposed surfaces, particularly roads and large paved areas, experience the highest levels of daytime heating and continue to retain heat into the evening.

Wind speed remains generally low across the study area, with higher velocities mainly occurring along wider streets and open spaces. In contrast, the compact urban blocks and enclosed street canyons restrict airflow, reducing the potential for natural ventilation and heat dissipation. This limited airflow, combined with high surface temperatures and direct solar exposure, contributes to elevated PET values and increased pedestrian thermal stress, particularly during the afternoon period.

Overall, the existing condition reveals a strong relationship between urban morphology, surface characteristics, solar exposure, and outdoor thermal comfort. The most thermally vulnerable areas are generally associated with exposed impervious surfaces, limited shading, and weak airflow, whereas shaded and more enclosed spaces provide comparatively better thermal conditions. These findings indicate that improving surface properties, increasing strategically located vegetation and shading, and enhancing airflow through

appropriate spatial interventions could provide more effective strategies for reducing heat accumulation and improving outdoor thermal comfort in the study area.

3.3.7 The Role of Residential Courtyards in the Urban Block

Residential courtyards are an important intermediate space within the urban block, connecting the private realm of dwellings with the shared life of residents. As discussed by David Sim in Soft City (2019), the quality of dense urban environments depends not only on buildings themselves, but also on the spaces between them, where everyday social interaction and environmental comfort can take place. In this sense, courtyards can function as valuable shared spaces within compact urban neighbourhoods.

In the study area, the internal courtyards of the existing residential blocks are currently characterized by fragmented functions, scattered garages, extensive impervious surfaces, and limited vegetation. The microclimatic analysis also indicates that these enclosed spaces can experience high thermal stress, particularly during the midday and afternoon periods, with elevated PET and surface temperatures. At the same time, their existing spatial structure creates an opportunity to improve environmental conditions without altering the established urban morphology.

Therefore, the proposed intervention focuses on recovering and improving the environmental potential of these internal spaces. Rather than modifying the existing building blocks, the strategy works within their current structure to reorganize underused areas and introduce greener and more multifunctional conditions, with the aim of improving both the environmental quality and usability of the courtyards.

3.3.8 Selection of the Design Intervention Area

Based on the comprehensive analysis of the baseline ENVI-met simulations, a representative intervention area was identified within the eastern section of the computational domain. The selected site is centred around the existing open market, which serves as one of the most active public spaces within the study area. Owing to its mixed commercial and social functions, the market attracts a high volume of daily pedestrian activity while also accommodating temporary vehicle access. These characteristics make it a key component of the neighborhood's urban identity and an important location for evaluating the effectiveness of climate-responsive design strategies.

The selection of this intervention area was based on both its environmental performance and its urban significance. The baseline simulations consistently revealed elevated values of Potential Air Temperature (PAT), Surface Temperature (T_{surface}), and Physiological Equivalent Temperature (PET), particularly over the extensive impervious surfaces surrounding the market. In addition, the limited presence of vegetation and shading, together with restricted airflow in some sections of the site, contributed to increased heat accumulation and reduced outdoor thermal comfort. These characteristics identified the area as a priority location where targeted urban design interventions could generate the greatest environmental improvements.

A redesign proposal was therefore developed with the objective of improving the microclimatic performance of the site while preserving its existing urban structure and the functional role of the open market.

The proposed design incorporates climate-responsive landscape strategies, including the introduction of additional vegetation, enhanced shading elements, and thermally efficient surface materials, with the aim of reducing heat accumulation, mitigating thermal stress, and improving pedestrian comfort. To evaluate the effectiveness of these interventions, the redesigned scenario was reconstructed and simulated in ENVI-met using the same computational domain, modelling methodology, simulation settings, and meteorological boundary conditions adopted for the baseline model. The outputs of the redesigned scenario were subsequently compared with the existing condition simulations to quantitatively assess the environmental improvements achieved through the proposed design interventions.

3.4 Design Strategies

3.4.1 Selection of the Intervention Area

Based on the spatial analysis of the ENVI-met simulations and the temporal evaluation of the three monitoring points, the intervention area was selected within the eastern sector of the study area, focusing on the existing open market and the surrounding residential blocks. The simulation results consistently identified this area as one of the most thermally stressed parts of the neighbourhood, with the highest Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET) occurring during the afternoon, particularly between 15:00 and 16:00. The results further highlighted that extensive impervious surfaces, limited vegetation, and insufficient shading significantly reduce outdoor thermal comfort. The open market was identified as the primary intervention area due to its large paved surface, the absence of tree canopy, and its important social and economic role within the neighbourhood. Although the market functions as a vibrant public space, it currently offers little protection from solar radiation, leading to considerable heat accumulation during the hottest hours of the day. To improve thermal conditions while preserving its daily function, the proposed design introduces movable planting containers. This flexible solution increases vegetation cover and shading without interfering with market activities or restricting the temporary use of the space. A second design strategy focuses on the internal residential courtyards, where the simulations revealed persistent thermal stress caused by dense urban morphology and the lack of vegetation. Existing surface garages are proposed to be relocated underground, allowing these underutilised spaces to be transformed into shared green courtyards that incorporate vegetation, children's play areas, and communal gathering

spaces. This intervention not only improves the local microclimate but also encourages social interaction and strengthens the neighbourhood's sense of community.

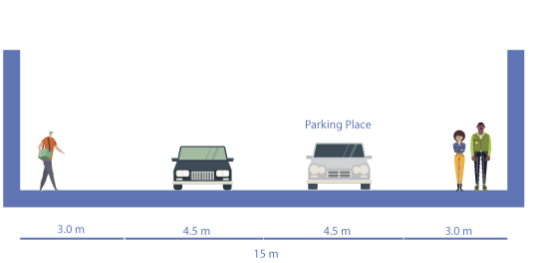
At the street level, additional green infrastructure is introduced through the implementation of rain gardens in locations with suitable spatial and drainage conditions. Besides increasing vegetation cover, these interventions contribute to stormwater management, enhance urban biodiversity, and reduce surface temperatures through evapotranspiration. The overall design approach is inspired by the principles presented in Soft City: Building Density for Everyday Life, promoting climate-responsive urban regeneration through targeted, small-scale interventions. Rather than altering the existing urban structure, the proposed strategies seek to improve environmental performance while preserving the neighbourhood's functional character and everyday urban life.

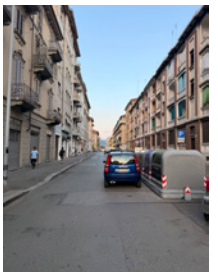


Figure 92. Proposed movable planters for the open market. The modular design allows vegetation to be introduced without interfering with the daily operation of the market. Source: Author

3.4.2 Diversity of Streets of Selected Area

The study area exhibits a diverse street network that supports different urban functions and mobility patterns. Rather than being exclusively pedestrian or vehicle-oriented, each street plays a distinct role within the neighborhood according to its width, traffic intensity, and surrounding land uses. While several streets primarily accommodate local traffic, others serve as key access routes to the open market, contributing to the area's social and commercial vitality. This diversity provides opportunities to implement context-specific climate-responsive design interventions that enhance both environmental performance and the quality of public space.





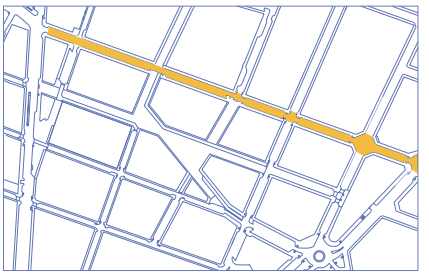
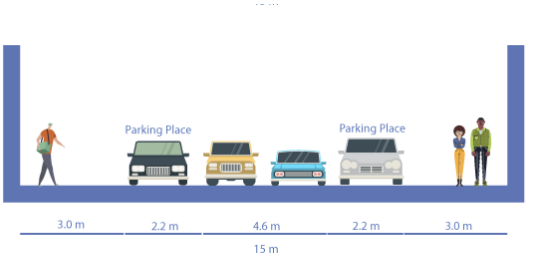


Fig. 93 Section view of via Alessandro Scarlatti

Via Alesaandro Scarlatti

This relatively wide street includes sidewalks on both sides. One side is dedicated to on-street parking, while the opposite lane accommodates moving vehicles. Due to its low traffic volume, the street maintains a calm atmosphere and provides a comfortable environment for everyday pedestrian activity despite the presence of vehicular traffic.

H/W = 1.00





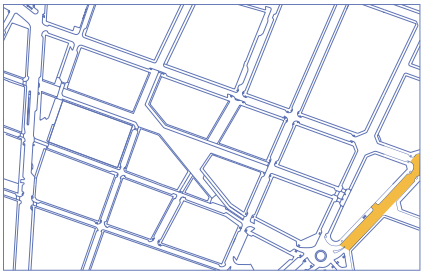
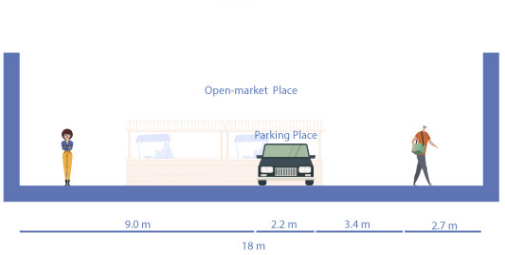


Fig. 94 Section view of via Giovanni Paisiello

Via Giovanni Paisiello

Via Giovanni Paisiello is one of the widest streets within the study area. It accommodates sidewalks on both sides, on-street parking along the edges, and two central traffic lanes. Bus Line 18 also passes through this corridor, making it one of the neighborhood's principal transportation routes.

H/W = 0.83





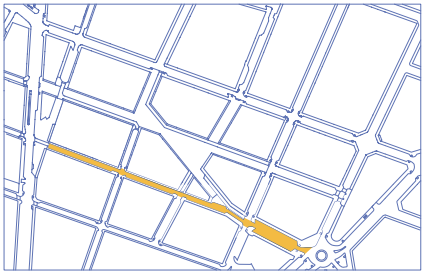
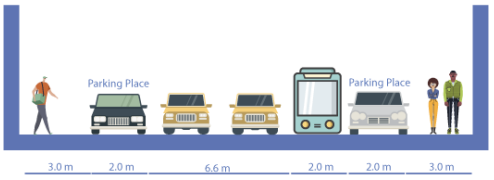


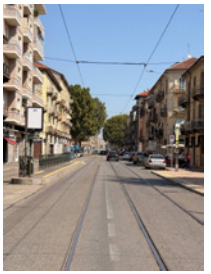
Fig. 95 Section view of via Sesia

Via Sesia

H/W = 0.64

Via Sesia functions as one of the primary access routes to the open market and is largely pedestrian-oriented. Most of the street is allocated to sidewalks and on-street parking, while through traffic remains limited and vehicle speeds are generally low, creating a safe and pedestrian-friendly environment.





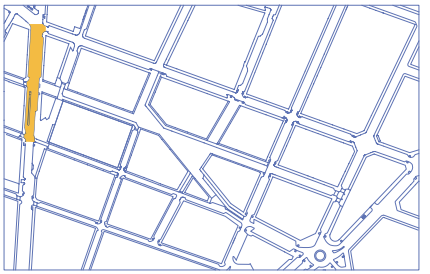
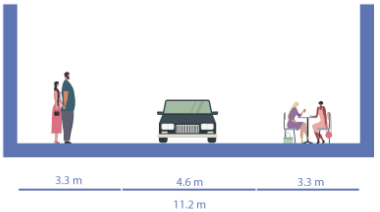


Fig. 96 Section view of Corso Giulio Cesare

Corso Giulio Cesare

H/W = 0.72

Corso Giulio Cesare is one of the main arterial streets within the study area. It accommodates sidewalks, on-street parking, and a tram line, providing an important public transport corridor. Owing to its strategic location and available street width, it has been identified as a suitable corridor for the introduction of additional green infrastructure in the proposed design.





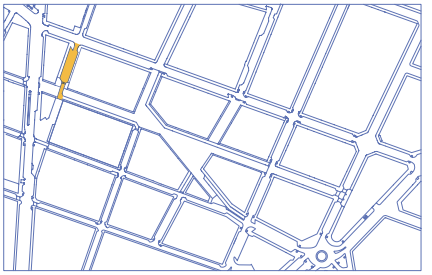
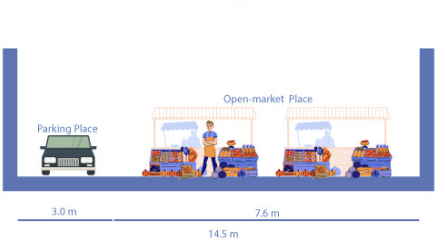


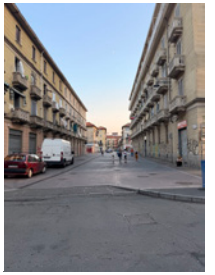
Fig. 97 Section view of via Montanaro

Via Montanaro

H/W = 0.87

Via Montanaro is a narrow local street that primarily functions as an access lane to the open market. It supports one-way vehicular movement and provides direct access to parking areas and nearby commercial activities, playing an important role in maintaining local accessibility while serving the daily operation of the market.





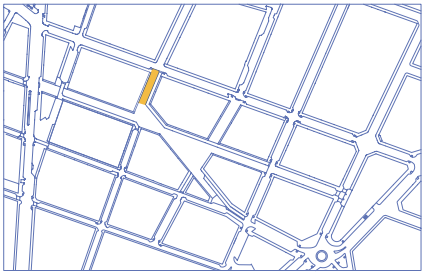
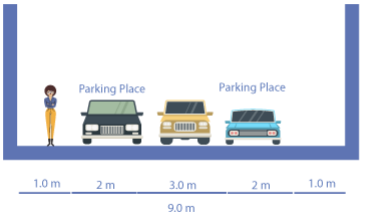


Fig. 98 Section view of via Monte Rosa

Via Monte Rosa

This dead-end street functions primarily as an extension of the open market rather than a conventional traffic route. Vehicular movement is limited, and during market hours the space is occupied by temporary market stalls and visitors. Once market activities end, the street becomes a quiet local space with very low pedestrian and vehicle activity.

H/W = 1.03





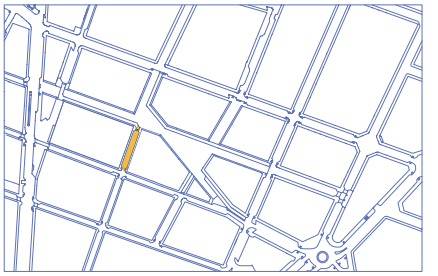
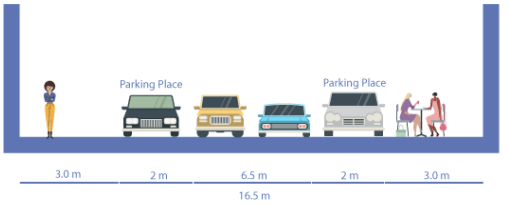


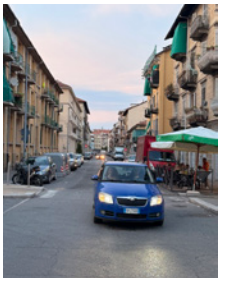
Fig. 99 Section view of via Monte Rosa

Via Monte Rosa

This narrow local street serves mainly as a low-traffic access route within the neighborhood. On-street parking occupies both sides, while the central carriageway accommodates local vehicular movement. Its compact cross-section and limited traffic create a calm environment that is primarily used by local residents.

H/W = 1.31





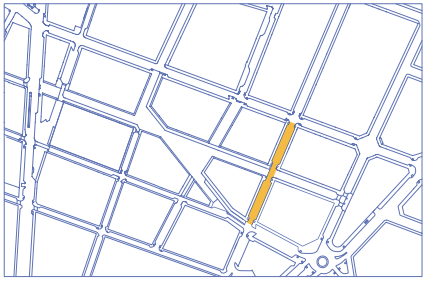
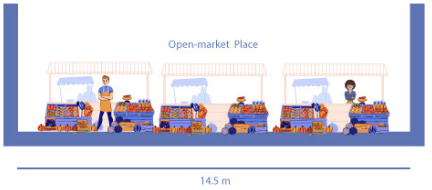


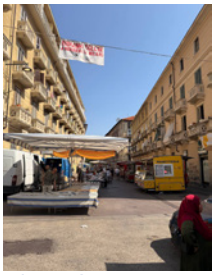
Fig. 100 Section view of via Crescentino

Via Crescentino

Via Crescentino accommodates two-way vehicular traffic with a single travel lane in each direction. On-street parking is provided along both sides, while continuous sidewalks ensure safe and convenient pedestrian circulation. The street functions as an important local connector between residential areas and the surrounding commercial streets.

H/W = 0.64





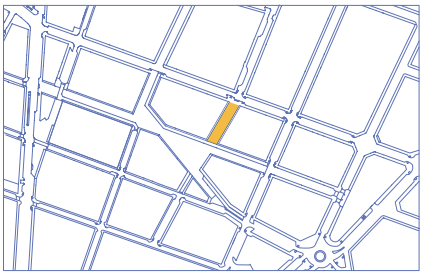
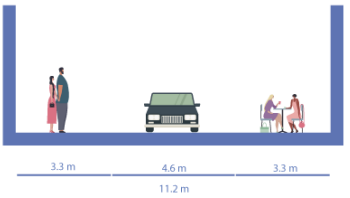


Fig. 101 Section view of via Santhia

Via Santhia

H/W = 0.93

This wide dead-end street provides direct access to the open market and serves as one of its principal activity spaces. Although through traffic is absent, the street becomes highly active during market hours, accommodating vendors, visitors, and market-related activities throughout the day.





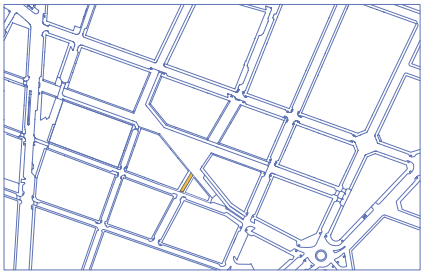
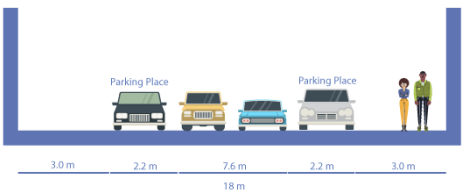


Fig. 102 Section view of via Santhia

Via Santhia

H/W = 1.09

This short dead-end street provides direct access to the open market and accommodates only limited vehicular traffic. A corner café with outdoor seating has transformed the space into an informal social gathering point, encouraging everyday interaction among residents and visitors.





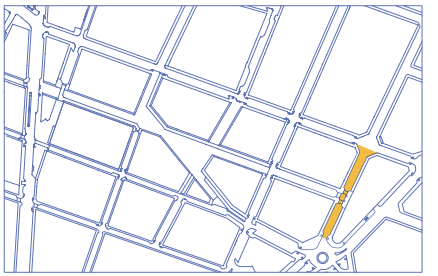


Fig. 103 Section view of via Saverio Mercadante

Via Saverio Mercadante

H/W = 0.40

Via Saverio Mercadante is a quiet local street characterized by low traffic volumes and direct access to a nearby green space. Its generous street width, limited vehicular activity, and pedestrian-friendly environment make it an important neighborhood connection and a suitable corridor for enhancing walkability.

3.4.3 Discussion

The baseline ENVI-met simulations demonstrate that the microclimatic conditions within the study area are governed more by the spatial configuration of the urban fabric than by regional meteorological conditions alone. Although the simulated air temperature exhibits relatively moderate spatial variation, the combined analysis of surface temperature, wind speed, and Physiological Equivalent Temperature (PET) reveals considerable differences in outdoor thermal comfort across the neighbourhood. This confirms that air temperature alone is insufficient to describe the thermal experience of pedestrians in dense urban environments.

The results indicate that extensive impervious surfaces, limited vegetation, and the morphology of the urban blocks collectively contribute to localized heat accumulation. Surface temperature maps identify paved areas, particularly the open market and major traffic corridors, as the primary hotspots due to their high solar exposure and thermal storage capacity. In contrast, shaded streets and areas beneath mature tree canopies consistently exhibit lower surface temperatures, highlighting the importance of vegetation and shading in regulating the urban surface energy balance.

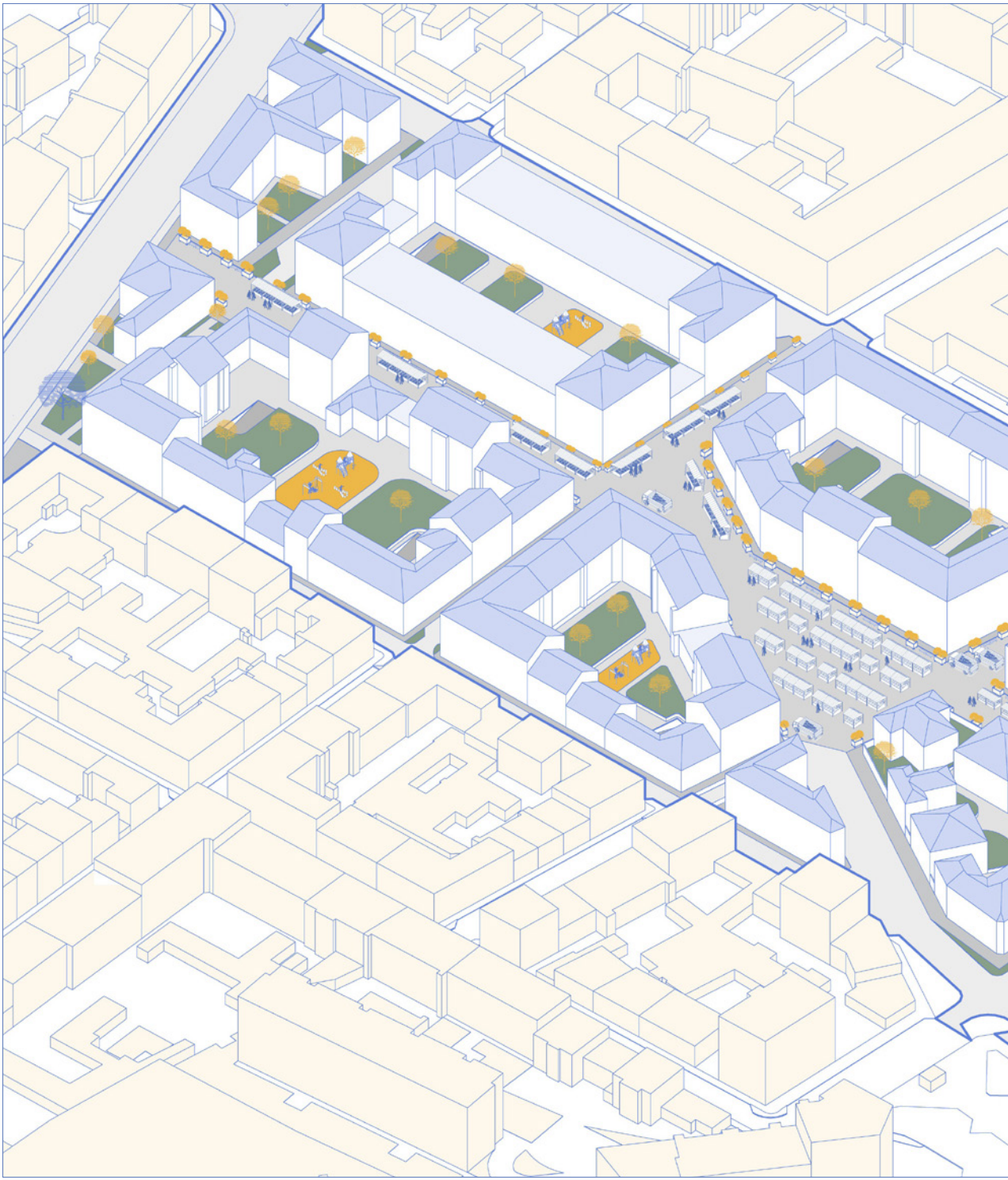
Wind speed simulations further reveal the influence of the existing urban morphology on local airflow. While wider streets facilitate greater air movement, the compact internal courtyards and enclosed street canyons experience substantially lower wind velocities. These sheltered conditions reduce natural ventilation and limit convective heat removal, particularly during the warmest hours of the day. Consequently, areas with restricted airflow generally correspond to locations with higher PET values and reduced outdoor thermal comfort.

The PET analysis provides the clearest representation of human thermal perception by integrating the combined effects of air temperature, radiation, wind speed, and humidity. The simulations show that thermal stress is primarily concentrated

in exposed paved spaces with limited shading, whereas areas benefiting from mature trees or building shadows maintain comparatively lower PET values throughout the day. These findings emphasize that mean radiant temperature (MRT), rather than air temperature alone, plays a dominant role in determining pedestrian thermal comfort within the study area.

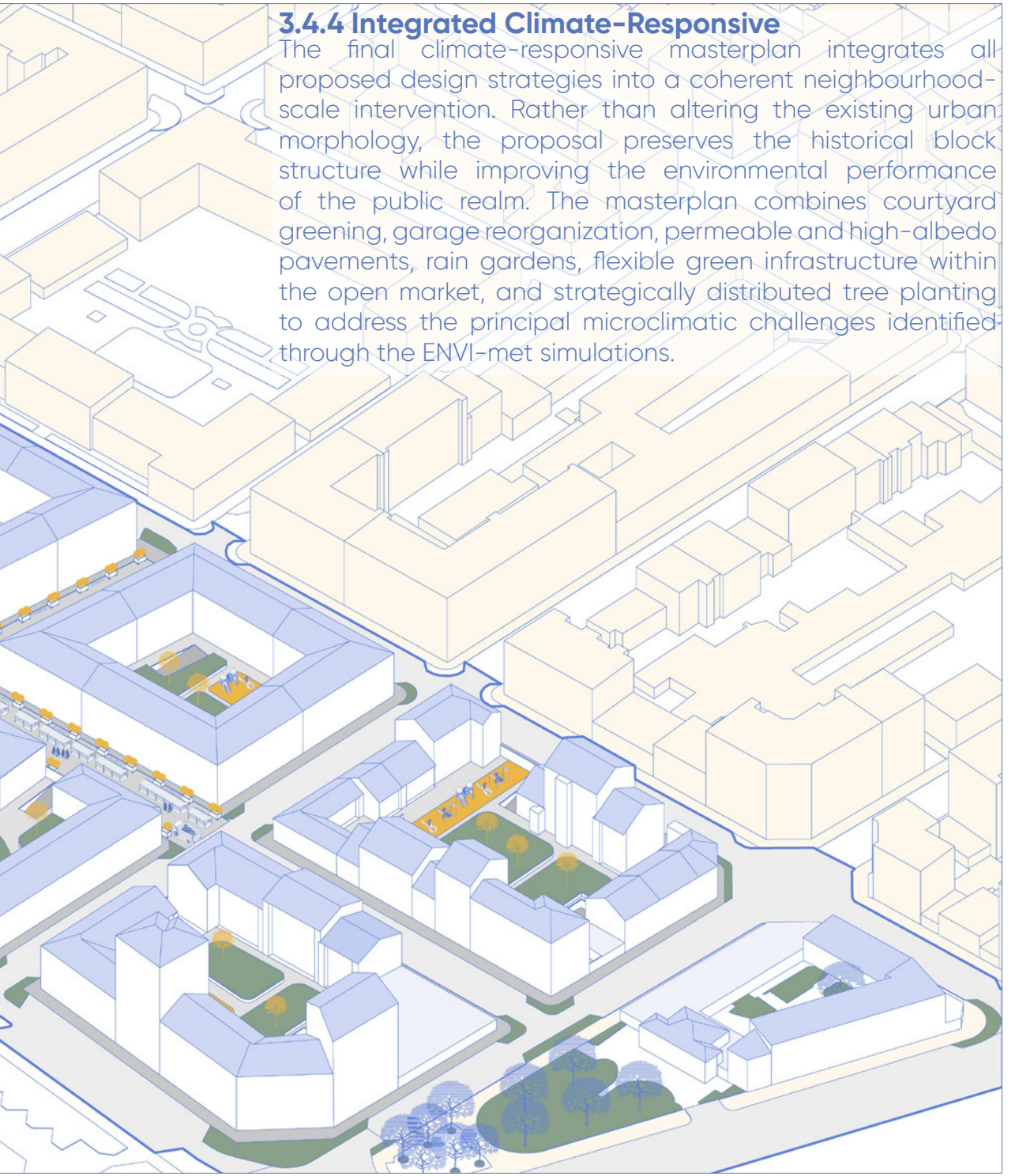
The combined interpretation of all environmental indicators identifies several recurring patterns. Existing vegetation already provides measurable cooling benefits where present; however, its spatial distribution is fragmented and insufficient to create a continuous network of thermally comfortable public spaces. Similarly, the predominance of conventional impervious paving contributes to elevated surface temperatures and increased radiant heat loads, particularly in large open spaces where shading opportunities are limited.

Overall, the baseline assessment demonstrates that the principal microclimatic limitations of the study area arise from the interaction between urban morphology, pavement materials, limited green infrastructure, and restricted airflow. These results provide a clear scientific basis for the subsequent climate responsive design proposals, The inefficient occupation of the internal courtyards by scattered garages further reduces the spatial efficiency and limits the potential of these spaces for environmental and social use, which aim to improve outdoor thermal comfort through targeted landscape interventions while preserving the existing urban structure, circulation patterns, and functional characteristics of the neighbourhood.



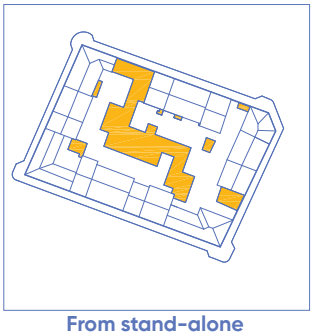
3.4.4 Integrated Climate-Responsive

The final climate-responsive masterplan integrates all proposed design strategies into a coherent neighbourhood-scale intervention. Rather than altering the existing urban morphology, the proposal preserves the historical block structure while improving the environmental performance of the public realm. The masterplan combines courtyard greening, garage reorganization, permeable and high-albedo pavements, rain gardens, flexible green infrastructure within the open market, and strategically distributed tree planting to address the principal microclimatic challenges identified through the ENVI-met simulations.

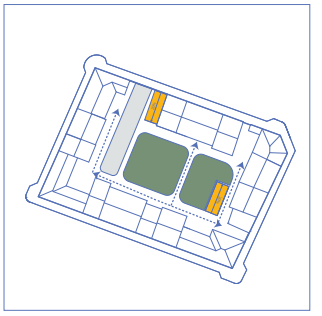


3.4.4.1 Middle Part Principles

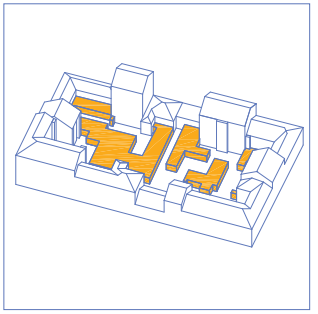
The existing scattered garage layout creates fragmented open spaces and inefficient land use. To improve the spatial organization, three design alternatives were explored, each proposing a different strategy for relocating the garages along the block perimeter. The selected alternative provides the most balanced solution by releasing the central area for green infrastructure and multifunctional public space, while improving spatial continuity and the microclimatic quality of the block.



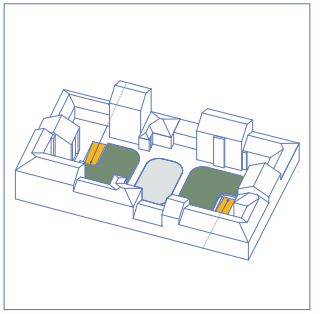
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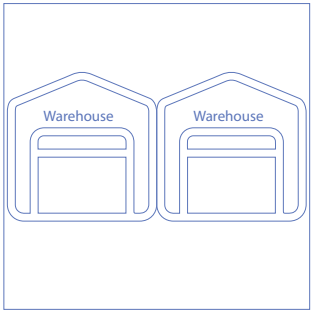
to concentrated and walkable



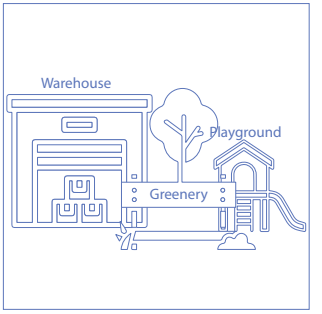
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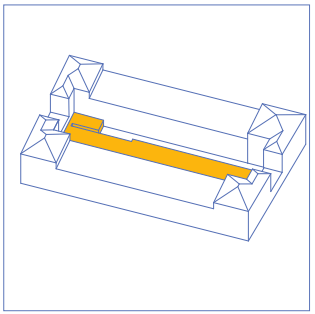
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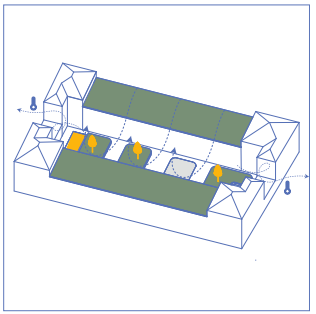
From monofunctional



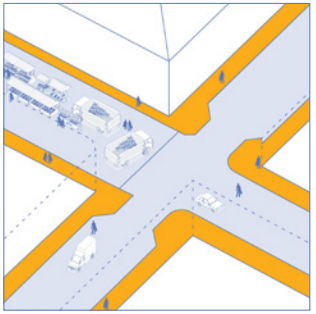
to multifunctional



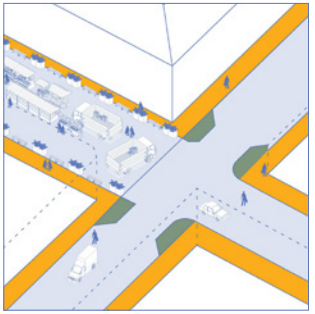
From unusable space



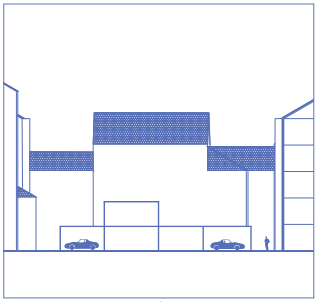
to pleasant microclimate



From unused spaces



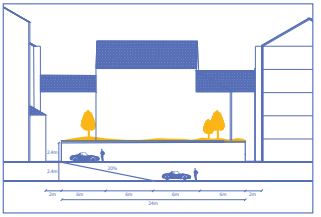
to green alternatives

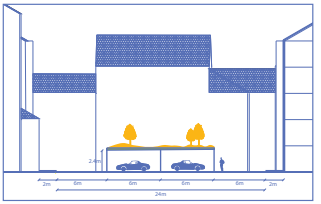


From unorganized garages



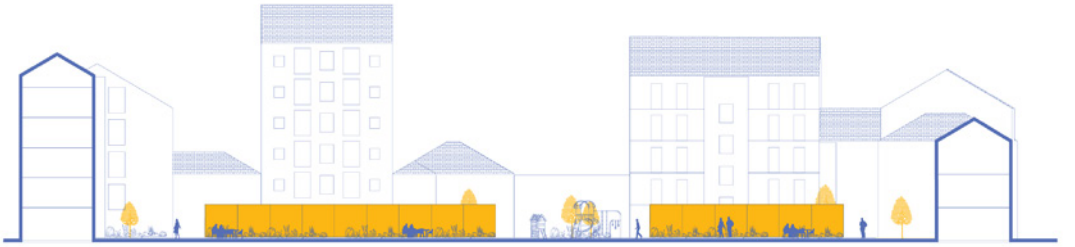
to consolidation alternative





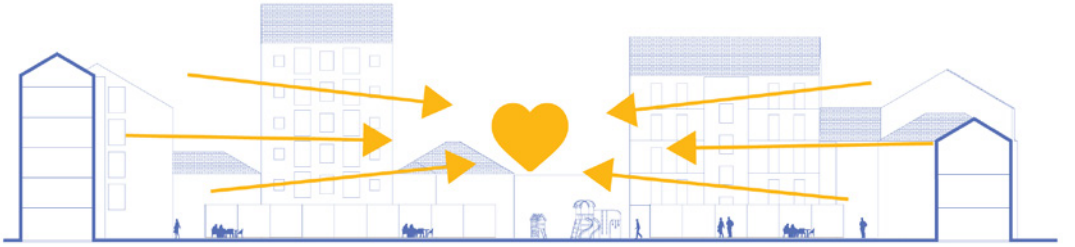
other alternative

3.4.4.2 What the middle parts can do?



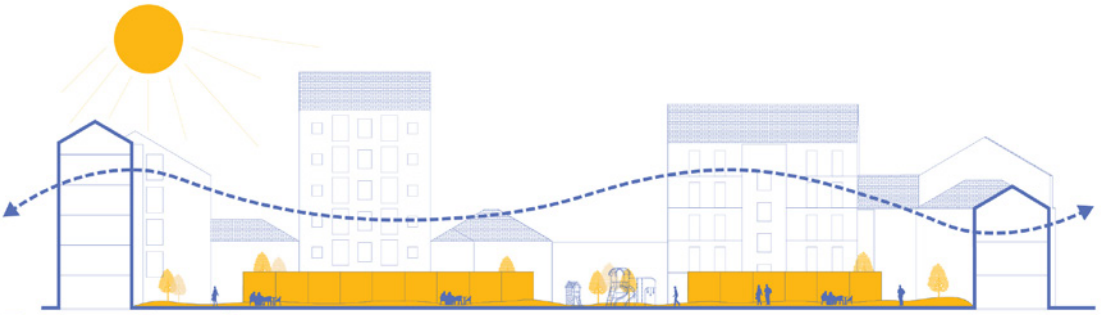
Private Space

The block system clearly defines public spaces at the fronts (or outside the block) and private space at the back (inside the block).
Two very different worlds can coexist in extremely close proximity to each other.



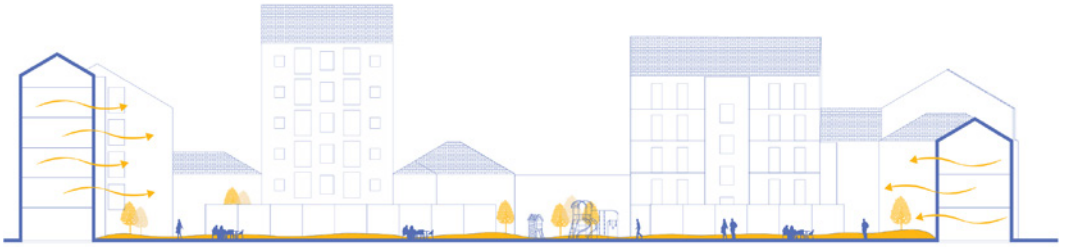
Common space and identity

The enclosed block creates a common space in the middle of the block, which can be the shared focus of residents and a point for local community building.



Better microclimate

The enclosed block creates a sheltered space, a protected micro-climate, shelter from the prevailing winds, and a way to capture the sun as required. Consistent building heights reduce the negative effects of turbulent winds.



Protected air space and walk-in access

The enclosed block creates a protected air space, meaning that the air inside can be cleaner than outside in the streets full of trat-fic. This gives major advantages for ventilation, as well as everyday benefits like cleaner windows and hanging washing.



Protected secure zone

The enclosed block creates a protected secure zone, independent from the street, effectively a gated community in the middle of an urban, public context. This translates into a safe place to leave your bike and a safe place for your children to play.



Protected acoustic space

The enclosed block creates a protected acoustic space. The surrounding wall of buildings shelters the inside space from the noise in the streets. This translates into sleeping with an open window in the summer and not being disturbed by traffic.

3.4.5 Block Analysis Workflow (First Strategies)

The design approach is informed by David Sim's concept of the "Soft City," which highlights the potential of enclosed urban blocks and their internal courtyards as sheltered, shaded, and environmentally responsive spaces. In Soft City, Sim refers to Copenhagen's Green Courtyards Programme, where underused and predominantly hard-surfaced inner courtyards were transformed into greener communal environments without fundamentally altering the existing urban fabric (Sim, 2019).

This principle is applied in the proposed intervention in Barrier di Milano by concentrating the main climate-responsive strategies within the interiors of the existing blocks. Rather than modifying the established street network or building morphology, fragmented and underused spaces are reorganised through vegetation, shading, and cooler surface materials. The ENVI-met comparison at 15:00 supports this approach: PET decreases from 33.66–58.11°C under the existing condition to 32.90–57.89°C in the proposed design. Although the overall numerical reduction is moderate, the spatial distribution shows more favourable thermal conditions within the redesigned block interiors. The intervention therefore focuses on transforming the centre of the blocks into greener and more comfortable shared spaces while preserving the existing urban structure (Sim, 2019).

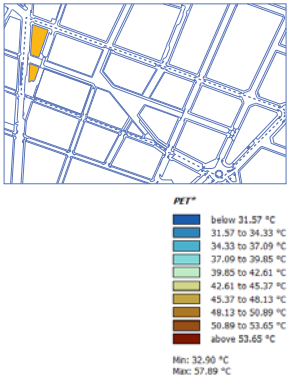
According to the PET classification, the proposed design remains within a range of strong to extreme heat stress at 15:00, reflecting the severe solar exposure and thermal conditions characteristic of the afternoon period. However, the reduction in PET values and the redistribution of cooler conditions within the redesigned courtyards indicate a localized improvement in pedestrian thermal comfort. The results therefore suggest that the strategy does not shift the entire study area into a lower thermal stress category, but instead creates more favourable microclimatic conditions within the targeted block interiors, where residents and pedestrians can benefit directly from increased vegetation,

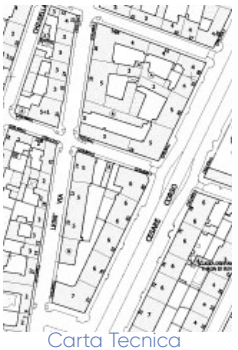
shading, and improved surface conditions.

PET (°C)	Thermal perception	Grade of physiological stress
< 4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
> 41.0	Very hot	Extreme heat stress

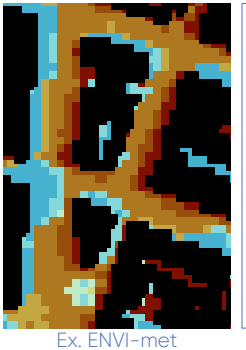
Table 9. Thermal perception and physiological stress categories based on PMV and PET values
Source: Adapted from Jendritzky et al. (1990) and Matzarakis and Mayer (1997).

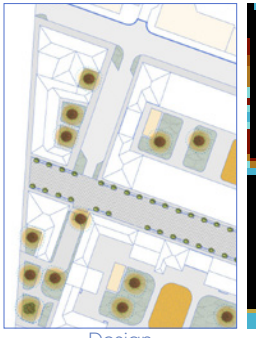
The comparison of Block 1 highlights the role of the redesigned internal courtyard in improving the local thermal conditions. In the existing condition, the interior of the block is largely occupied by exposed and impervious surfaces, resulting in higher PET values within the courtyard. The proposed design introduces vegetation, shaded areas, and cooler surfaces into this internal space, creating more favourable thermal conditions compared with the surrounding exposed areas. According to the PET classification, the intervention does not shift the block from heat-stress conditions to thermal comfort; however, the spatial distribution shows a localized reduction in thermal exposure within the redesigned courtyard. The strategy therefore focuses on improving the environmental quality of the block interior while maintaining the existing building structure and residential function.

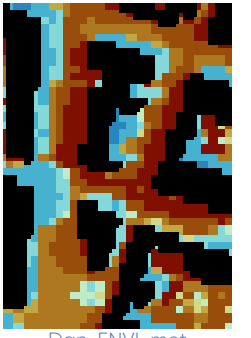


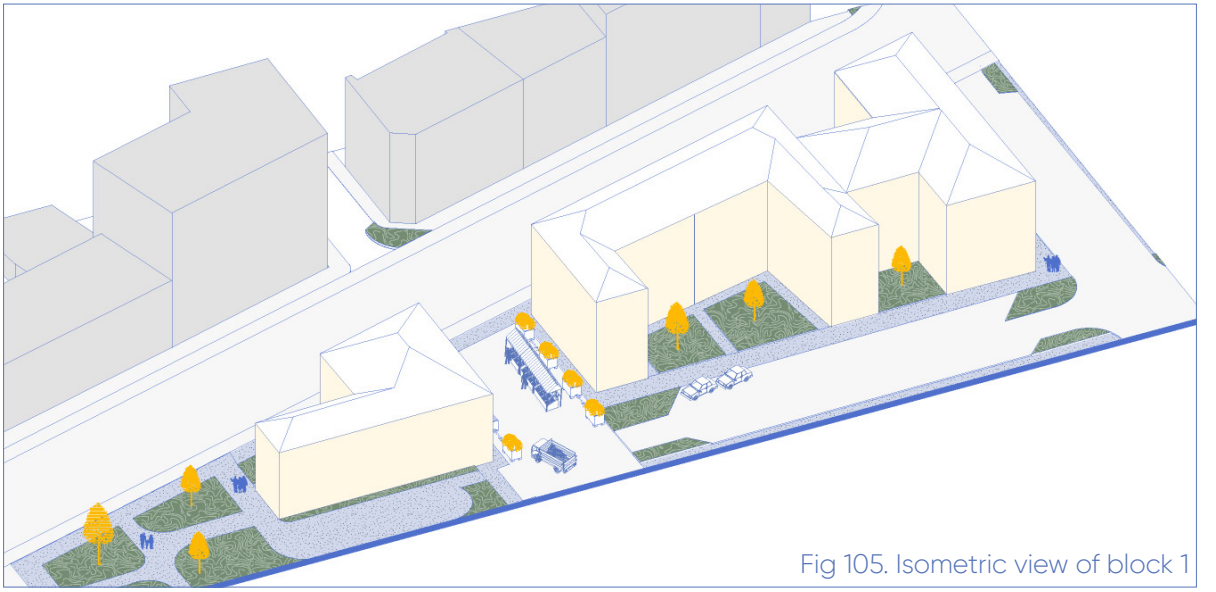

Carta Tecnica


Google Map

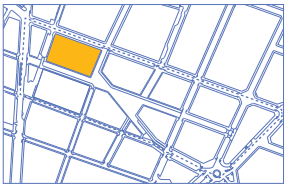

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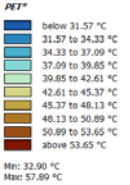

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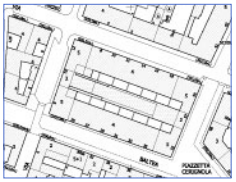

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Fig 105. Isometric view of block 1

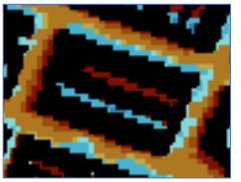
In Block 2, the intervention similarly concentrates on the internal areas of the block, where previously fragmented and predominantly hard-surfaced spaces are reorganised into greener shared environments. The proposed configuration introduces vegetation and shaded areas while maintaining access and the existing residential functions of the block. The ENVI-met comparison indicates that the most favourable thermal conditions are concentrated around the redesigned green areas, contrasting with the more exposed surfaces surrounding them. Although the PET values remain within the heat-stress range according to the classification, the intervention creates localized areas with reduced thermal exposure. This demonstrates how targeted improvements within the centre of the block can enhance outdoor environmental conditions without requiring major changes to the existing urban morphology.

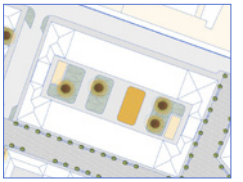


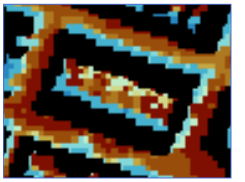



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Google Map


Ex. ENVI-met


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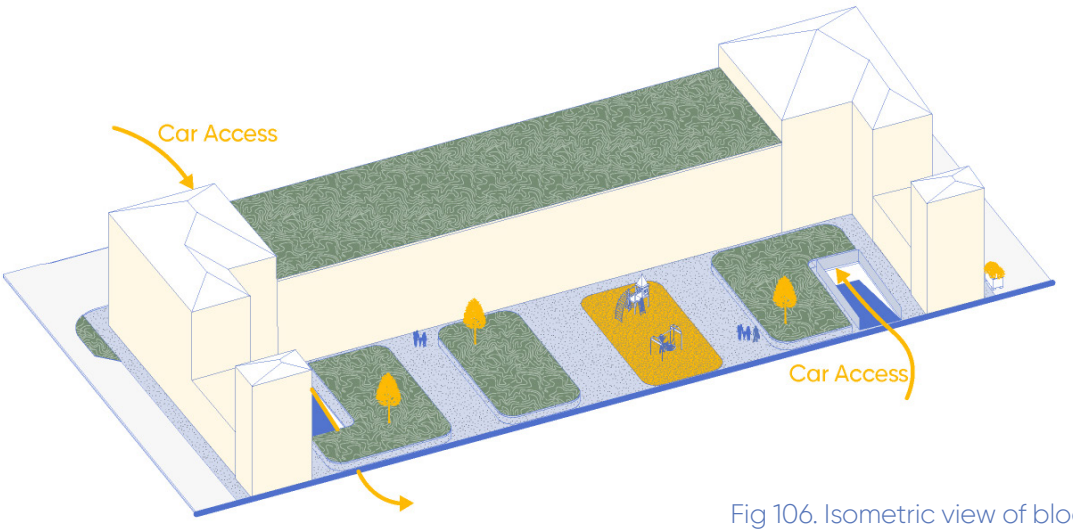
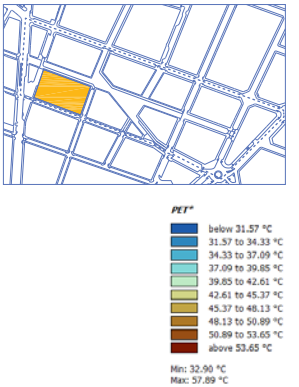


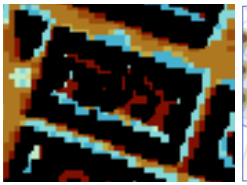
Fig 106. Isometric view of block 2

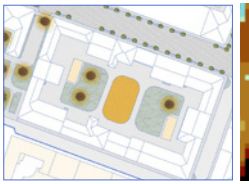
In Block 3, the intervention focuses on reorganising the internal courtyard as a greener and more usable shared space. The existing condition is characterised by a predominantly hard-surfaced courtyard with limited vegetation, resulting in greater thermal exposure within the block interior. The proposed design introduces larger planted areas, additional shading, and permeable or cooler surfaces, while retaining the existing building structure and necessary car access. The ENVI-met comparison shows more favourable thermal conditions within the redesigned courtyard, particularly around the vegetated areas, although the PET classification remains within the heat-stress range. The intervention therefore demonstrates how concentrating green infrastructure in the centre of the block can create localized improvements in outdoor thermal conditions while simultaneously providing a more functional communal space.

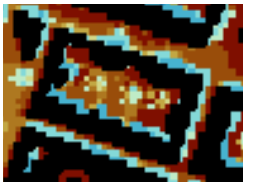



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Google Map


Ex. ENVI-met


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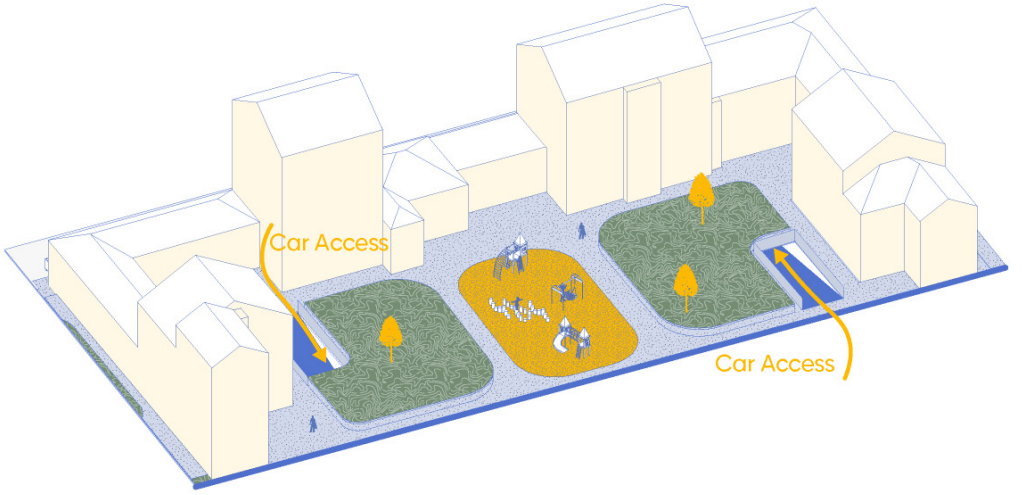
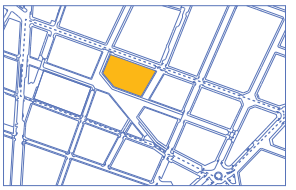
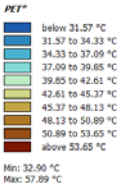


Fig 107. Isometric view of block 3

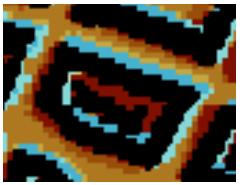
Block 4 applies a similar strategy, with the intervention concentrated within the internal courtyard rather than the surrounding urban structure. The redesign replaces fragmented hard surfaces with a combination of planted areas, shaded spaces, and cooler pedestrian surfaces, while maintaining the required vehicular access and residential functions. Compared with the existing condition, the ENVI-met results indicate a more favourable thermal distribution within the redesigned interior, particularly in the green areas located away from the most exposed surfaces. Although the overall PET category remains associated with heat stress, the spatial improvement within the courtyard supports the effectiveness of targeted green and shading strategies. This approach reinforces the potential of underused block interiors to function as climate-responsive shared spaces without altering the established urban morphology.

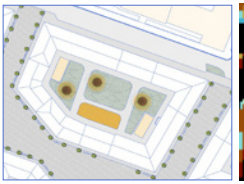





Carta Tecnica


Google Map


Ex. ENVI-met


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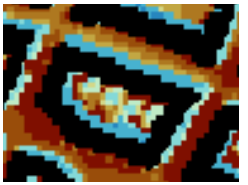
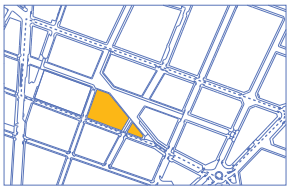
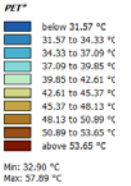

Dgn. ENVI-met



Fig 108. Isometric view of block 4

In Block 5, the proposed intervention focuses on upgrading the internal courtyard while preserving the existing block configuration. The redesign introduces additional vegetation, shaded areas, and permeable surfaces within the courtyard, creating a greener and more usable shared environment. The comparison between the existing and proposed ENVI-met results indicates a more favourable thermal distribution in the redesigned areas, particularly around the vegetated spaces. Although the PET values remain within the heat-stress range, the intervention reduces local thermal exposure and improves the environmental quality of the courtyard. The strategy therefore demonstrates the potential of targeted landscape interventions within the block interior to improve outdoor comfort without altering the established urban morphology.



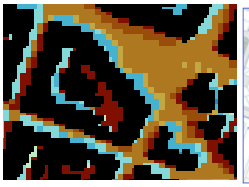




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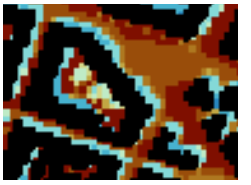
Google Map



Ex. ENVI-met



Design



Dgn. ENVI-met

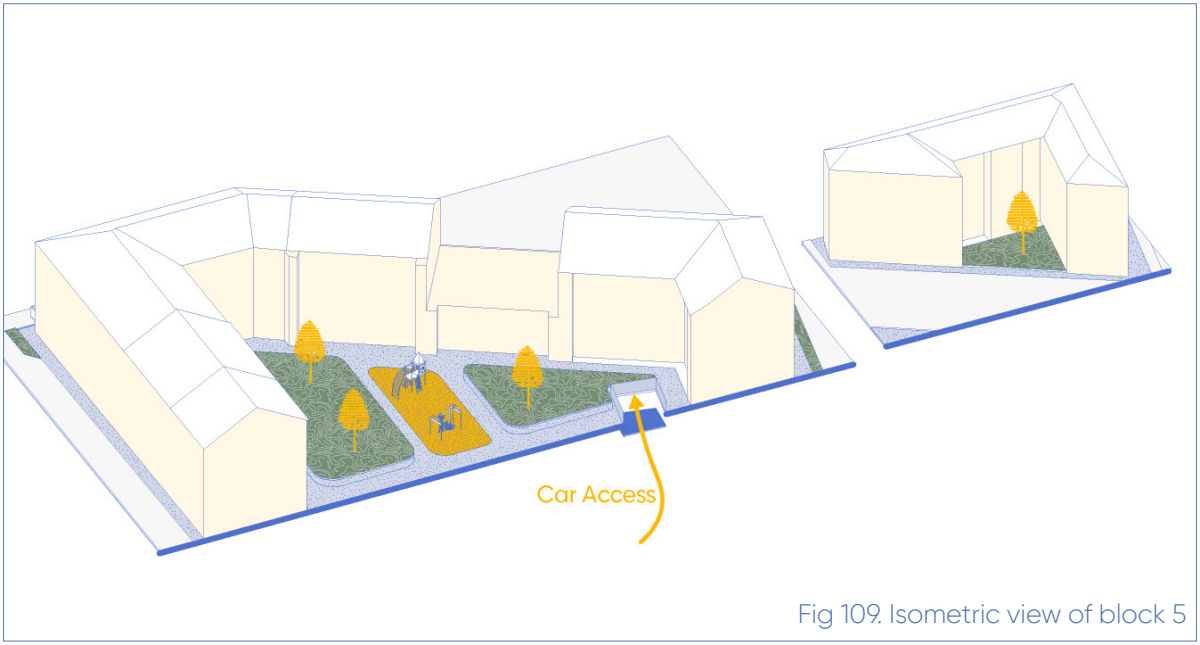
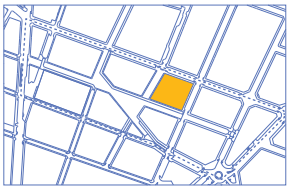
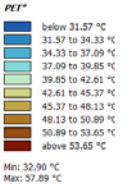


Fig 109. Isometric view of block 5

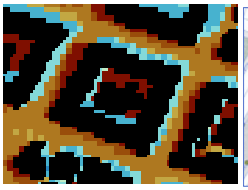
Block 6 applies the same principle of concentrating the intervention within the existing courtyard. Surface parking is relocated to the existing garage level through dedicated access ramps, releasing the central ground-level space for vegetation, shading, and shared outdoor activities. The ENVI-met comparison shows more favourable thermal conditions within the redesigned green areas, while the surrounding exposed surfaces remain comparatively warmer. Despite the persistence of heat-stress conditions according to the PET classification, the spatial redistribution of thermal conditions demonstrates a localized improvement within the courtyard. This transformation strengthens the role of the block interior as a shared, climate-responsive space while maintaining the existing buildings, access requirements, and overall urban structure.

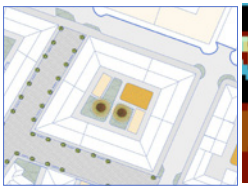


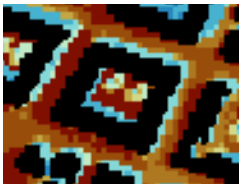



Carta Tecnica


Google Map


Ex. ENVI-met


Design


Dgn. ENVI-met

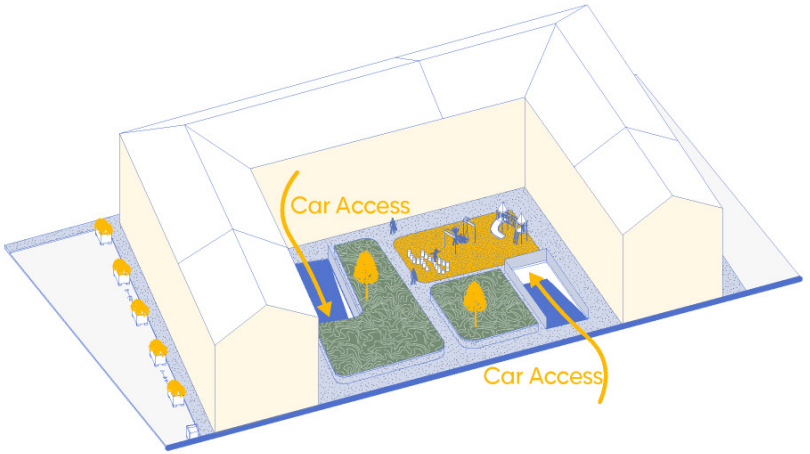
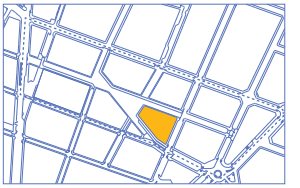
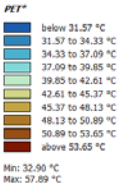


Fig 110. Isometric view of block 6

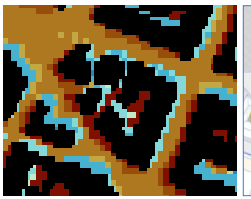
In Block 7, the intervention addresses the environmental quality of a block with multiple internal courtyards while preserving its existing spatial configuration. The proposed design introduces vegetation and permeable surfaces within the underused courtyard areas, creating greener and more sheltered spaces for shared use. The ENVI-met comparison indicates more favourable thermal conditions within the redesigned interiors, particularly around the newly vegetated areas, while the more exposed surfaces remain comparatively warmer. Although the PET values continue to indicate heat-stress conditions, the intervention provides a localized reduction in thermal exposure and improves the usability of the internal courtyards. The strategy demonstrates how even fragmented spaces within a complex block can be progressively transformed into climate-responsive communal environments without altering the existing building fabric.

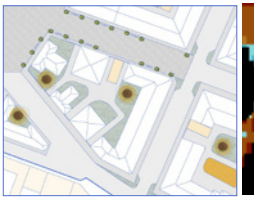


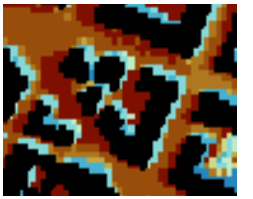



Carta Tecnica


Google Map


Ex. ENVI-met


Design


Dgn. ENVI-met

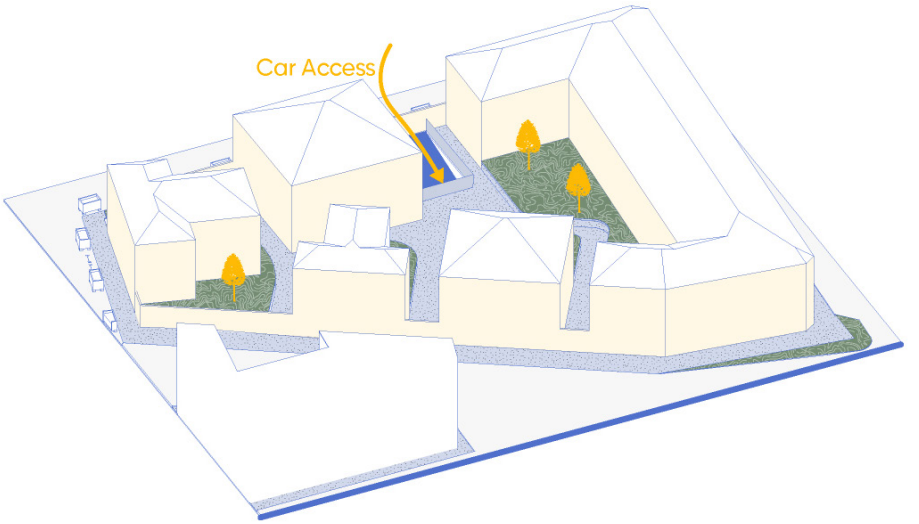
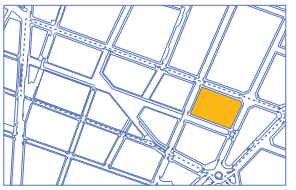
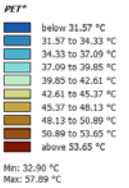


Fig 111. Isometric view of block 7

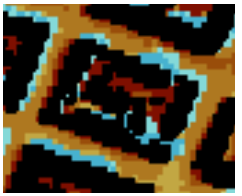
Block 8 focuses on transforming the elongated internal courtyard into a greener and more functional shared space. The existing parking areas are reorganised to release ground-level space for green infrastructure, shaded areas, and pedestrian use, while the existing buildings and access routes are maintained. The ENVI-met results show a more favourable thermal distribution across the redesigned courtyard, with the green areas providing localized improvements compared with the exposed surfaces of the existing condition. While the overall PET classification remains within the heat-stress range, the spatial redistribution of thermal conditions highlights the benefit of concentrating vegetation and shading within the block interior. This approach strengthens the courtyard as a climate-responsive communal space while maintaining the established urban morphology and residential functions.

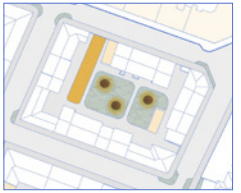


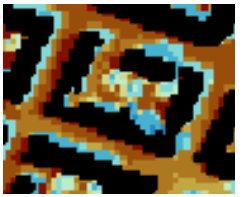



Carta Tecnica


Google Map


Ex. ENVI-met


Design


Dgn. ENVI-met

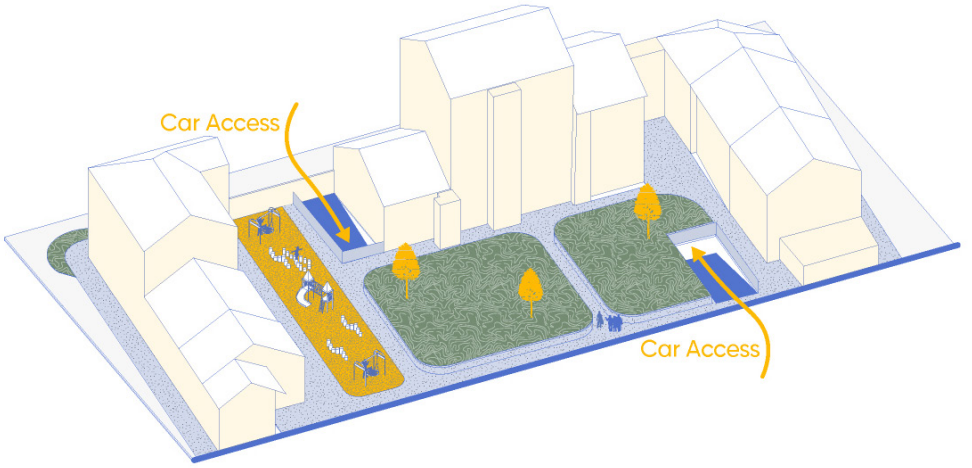
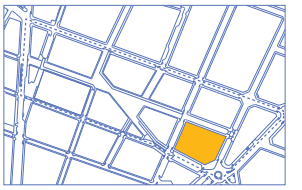
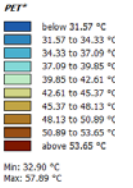


Fig 112. Isometric view of block 8

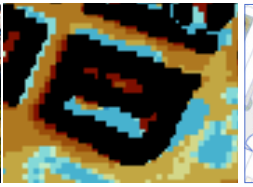
In Block 9, the intervention focuses on improving the environmental performance of the internal courtyard while preserving the existing residential fabric. The existing condition contains predominantly paved and parking areas with limited vegetation, contributing to higher thermal exposure within the block interior. The proposed design reorganises the parking arrangement and introduces additional vegetation, permeable surfaces, and shaded communal areas. The ENVI-met comparison shows a more favourable thermal distribution within the redesigned courtyard, particularly around the newly vegetated areas. Although the PET classification remains within the heat-stress range, the localized improvement demonstrates the potential of transforming underused internal spaces into greener and more comfortable shared environments while maintaining the existing circulation and building structure.

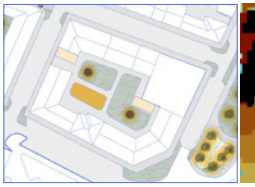


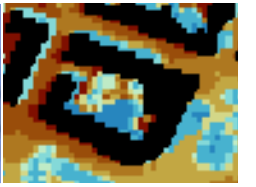



Carta Tecnica


Google Map


Ex. ENVI-met


Design


Dgn. ENVI-met

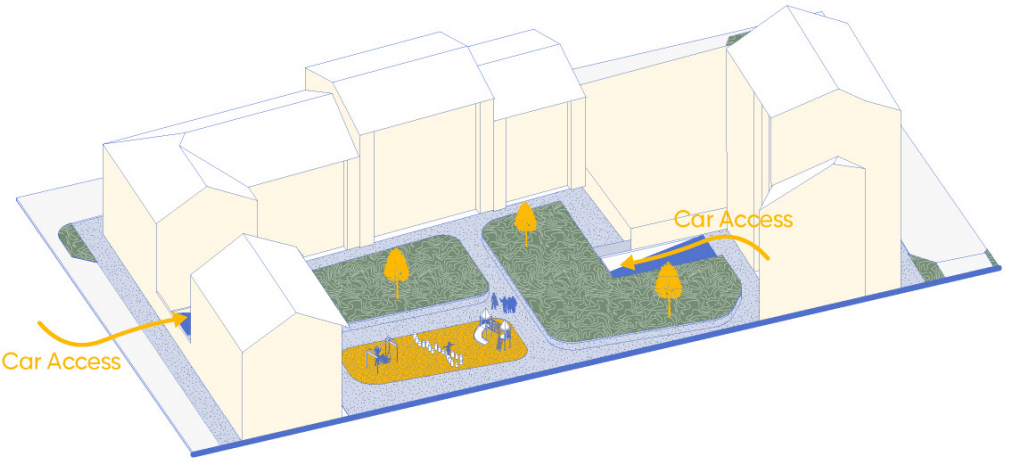
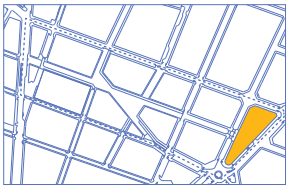
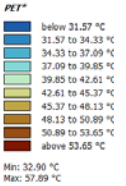


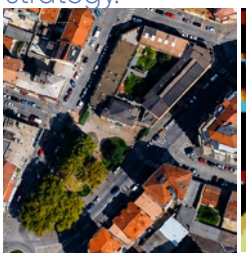
Fig 113. Isometric view of block 9

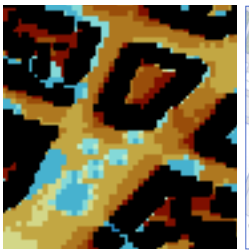
Block 10 differs from the other intervention areas, as the existing site already contains substantial mature vegetation and open green space. Consequently, the design prioritises preservation rather than extensive transformation. Based on the existing spatial and ENVI-met analysis, only targeted landscape improvements and minor spatial reorganisation are introduced to strengthen pedestrian use and enhance the existing environmental performance. The comparison indicates that the already vegetated areas provide more favourable thermal conditions within the block, while the intervention reinforces these cooler zones without substantially changing the landscape character. This approach demonstrates that climate-responsive design does not always require adding extensive new green infrastructure; in areas with existing ecological value, preserving and selectively enhancing vegetation can be the more appropriate strategy.

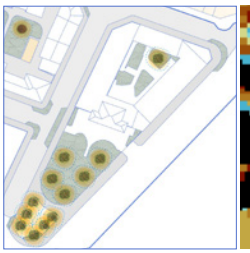


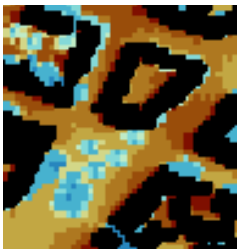



Carta Tecnica


Google Map


Ex. ENVI-met


Design


Dgn. ENVI-met

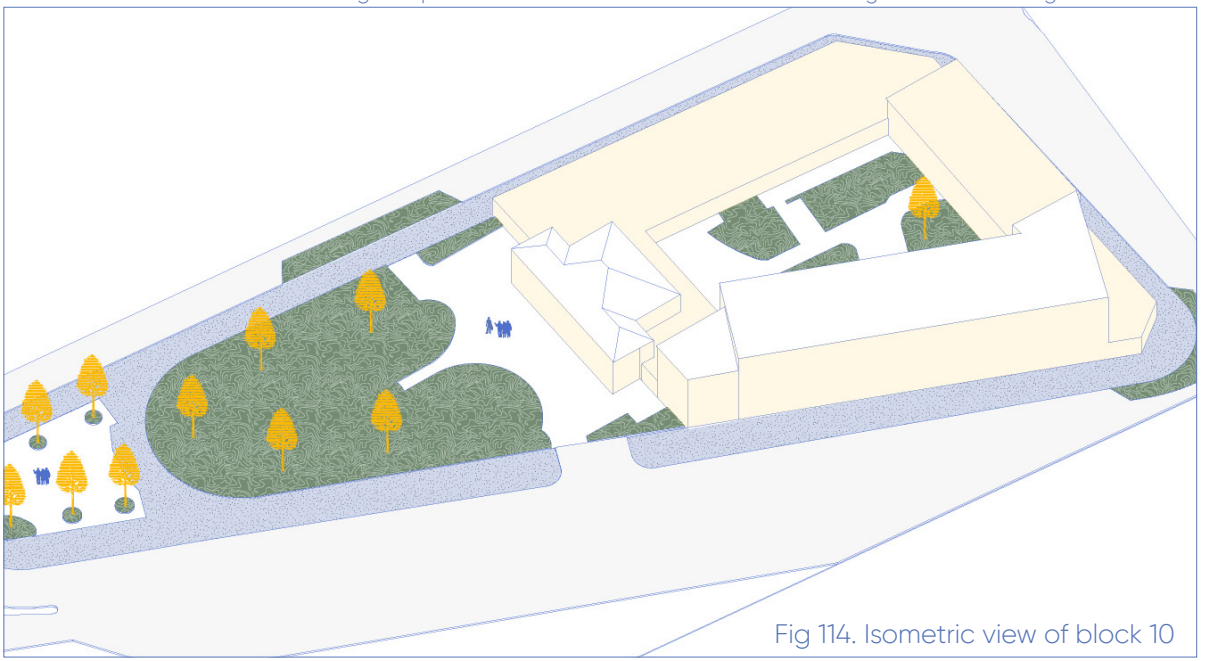


Fig 114. Isometric view of block 10

3.4.6 Climate-Responsive Landscape Masterplan(Second Strategies)

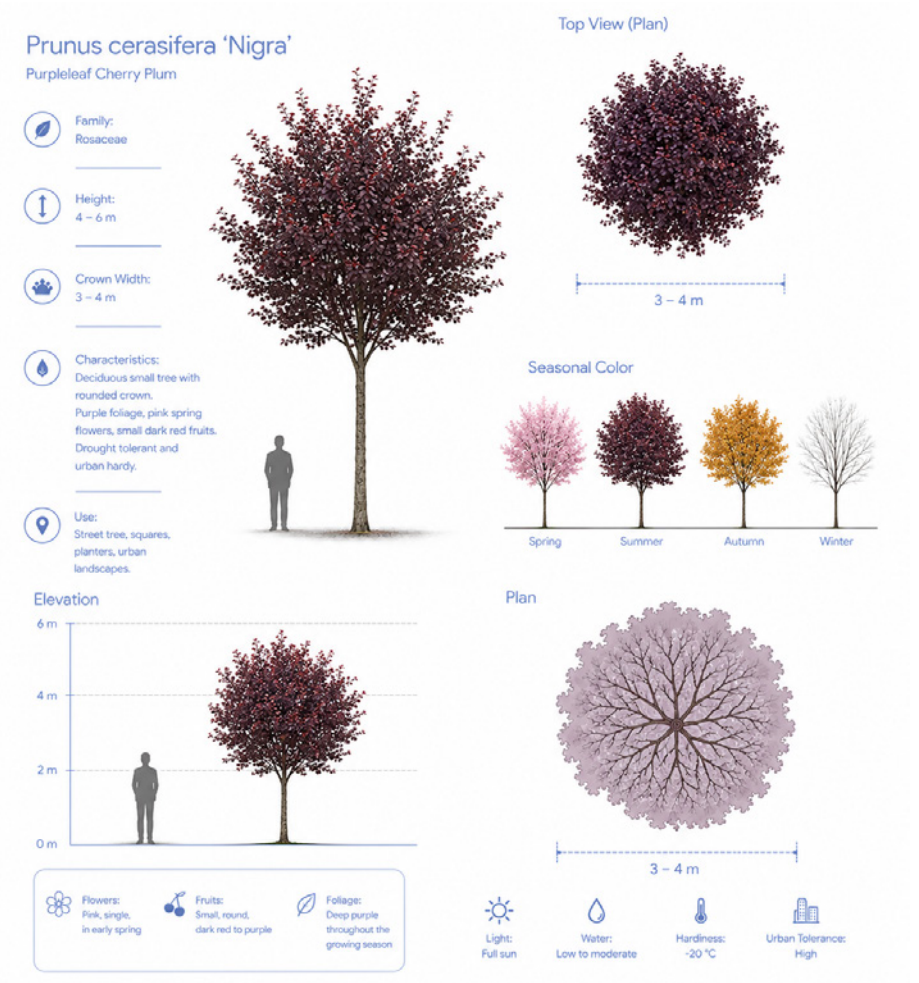
The planting strategy combines the preservation of the existing mature trees with the introduction of a limited number of additional trees selected for their environmental performance and suitability to Turin's climate. Existing Acer campestre and Ulmus minor are retained as the primary canopy species, providing extensive shade and contributing to the established urban ecosystem. New Prunus cerasifera 'Nigra' trees are introduced within courtyards and pedestrian spaces where additional shade, seasonal visual quality, and localized cooling are required.

Tree placement was determined according to canopy dimensions, summer shade patterns, and the estimated cooling influence of each species. Mature canopy radii were used to ensure continuous shaded pedestrian routes, while the cooling influence zone (approximately 3–5 m beyond the canopy edge) informed the spacing between trees to maximize microclimatic benefits. Summer shade areas were prioritized between 15:00 and 17:00, when outdoor thermal stress is typically highest.

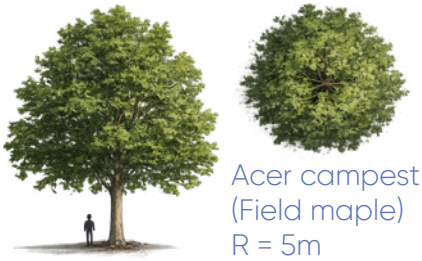
The overall planting layout creates an interconnected network of shaded public spaces while preserving existing vegetation wherever possible. Together with rain gardens and permeable landscape elements, the proposed tree strategy enhances thermal comfort, improves stormwater management, strengthens urban biodiversity, and contributes to a more climate-resilient neighbourhood without altering the existing urban structure.

3.4.6.1 Trees Plan

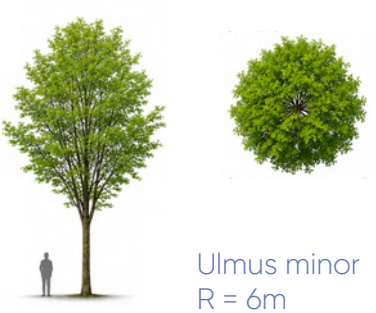
Addional Tree



Existing Tree



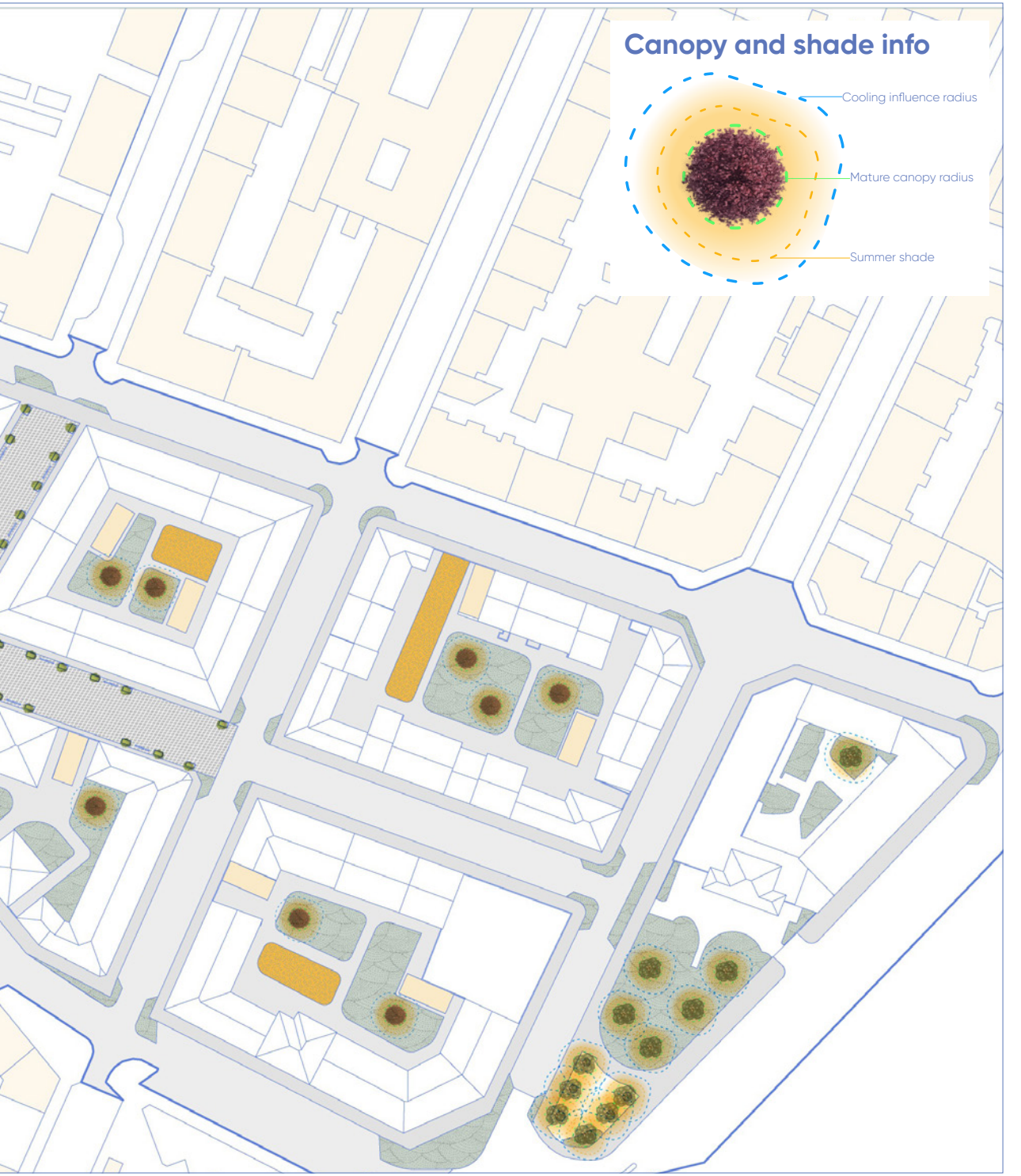
Acer campestre
(Field maple)
R = 5m



Ulmus minor
R = 6m

Fig 115. Tree Legend, Source: Author


LEGEND
Existing Tree
Addional Tree
Mature canopy radius
Summer shade area (15:00-17:00)
Cooling influence zone (3-5 m)
Rain garden


Canopy and shade info
Cooling influence radius
Mature canopy radius
Summer shade

3.4.7 Open Market (Third Strategies)

The open market represents one of the largest and most intensively used public spaces within the study area. Because the space accommodates daily vehicle access for market vendors, introducing permanent green infrastructure such as fixed planting beds or large landscape islands was not considered feasible, as these would interfere with the operational requirements of the market.

Instead, the intervention prioritizes the replacement of the existing pavement with a high albedo, permeable surface material, reducing solar heat absorption and lowering surface heat storage while maintaining the original functionality of the market. This approach improves the thermal behaviour of the open space without restricting vehicular circulation or market activities.

To compensate for the limited opportunities for permanent vegetation, the proposal introduces flexible and movable planters positioned around the perimeter of the market. These modular planters provide seasonal greenery, improve the visual quality of the space, and contribute localized shading and evapotranspirative cooling. Their movable nature allows the market layout to be reconfigured according to different operational or seasonal needs, while the spaces between individual planters can accommodate temporary seating areas for visitors and local residents.

Since the market operates primarily during the morning and midday hours, the same space functions as a neighbourhood public square during the afternoon and evening, when residents frequently use it for social activities and informal recreation. The proposed flexible planter system therefore supports both market operations and everyday community use, creating an adaptable public space capable of responding to changing patterns of occupation without compromising environmental performance or operational flexibility.

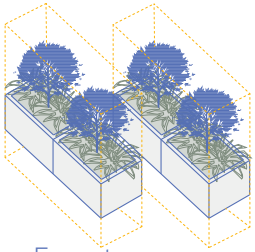


Fig 116. Open-Market

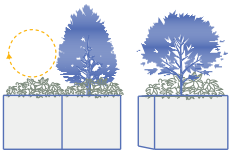
LEGEND

- Market Scope
- Seating Space
- Changing Ground Material
- Open Market
- Adaptable Pots
- Usable Route for Cars

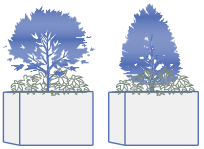
Flexible and adaptive design



Easy to move



Adaptable to different uses



Seasonal rotation

3.4.8 Result (Design Condition)
3.4.8.1 Air Temperature

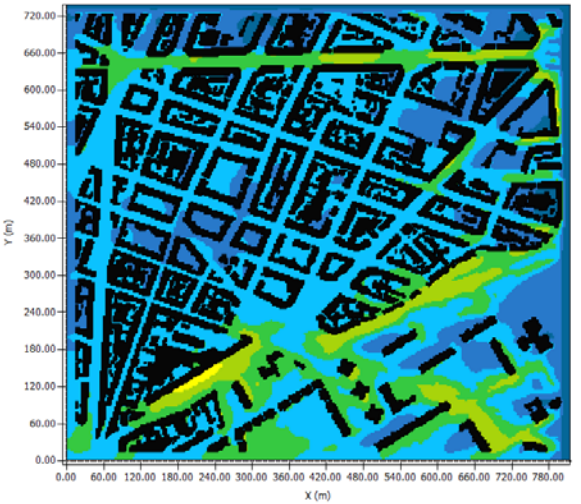
Figures 117–120 present the spatial distribution of air temperature at a height of 1.5 m under the proposed design scenario at 09:00, 12:00, 15:00, and 18:00. The simulated air temperature ranges from 19.68°C to 29.26°C, with clear temporal variations and localized spatial differences across the redesigned area. The distribution is influenced by solar exposure, urban morphology, building shading, vegetation, and the configuration of the redesigned open spaces. Compared with the existing condition, the intervention produces localized changes in air temperature rather than a uniform reduction across the entire study area.

At 09:00, air temperatures range from 19.68°C to 24.01°C, with cooler conditions distributed across most of the urban fabric and relatively warmer zones concentrated along exposed open corridors. The redesigned courtyards and vegetated areas contribute to localized cooler zones, although the overall temperature range remains close to the existing condition. At 12:00, temperatures increase to 23.94–27.45°C, with warmer conditions becoming more extensive as solar exposure increases. Cooler areas remain more evident within shaded courtyards and redesigned pedestrian spaces, while exposed roads and open surfaces exhibit higher temperatures.

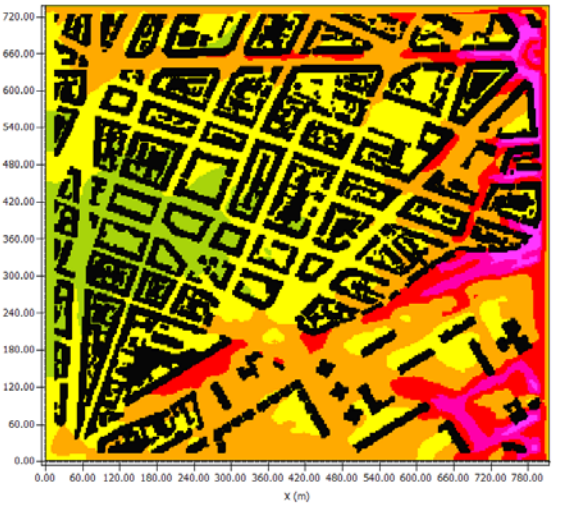
During 15:00, the highest air temperatures are recorded, ranging from 25.51°C to 29.26°C. The warmest conditions are concentrated across highly exposed areas and major open corridors, whereas shaded and vegetated spaces show comparatively lower temperatures. By 18:00, temperatures range from 25.46°C to 27.78°C, indicating a slight reduction in the maximum values as solar radiation decreases. Overall, the proposed design creates localized cooler areas within the intervention zones, particularly where vegetation and shading are introduced, while the broader air-temperature response remains moderate due to the persistence of the surrounding urban fabric.

AIR TEMPERATURE

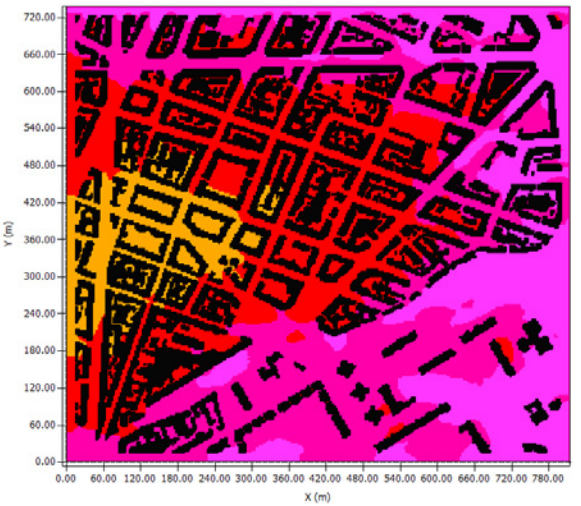
9:00 A.M



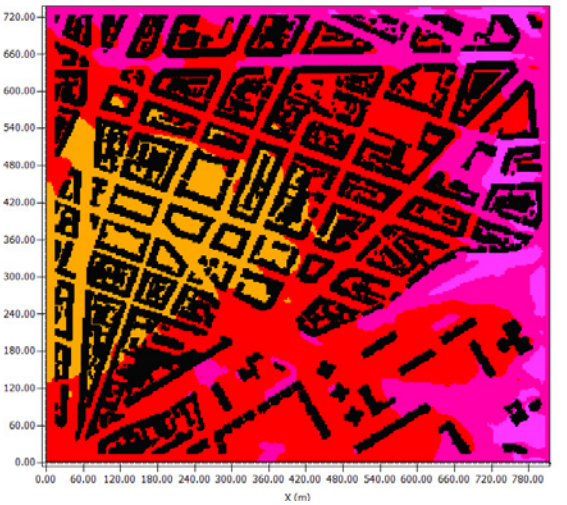
12:00 A.M



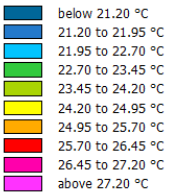
15:00 P.M



18:00 P.M



The figures 117-120, show Potential Air Temprature in the area with design condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)





3.4.8.2 Surface Temperature (Tsurface)

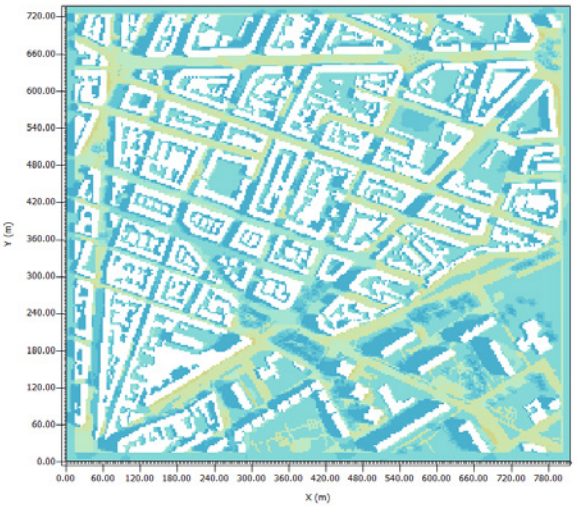
Figures 121–124 present the spatial distribution of surface temperature under the proposed design scenario at 09:00, 12:00, 15:00, and 18:00. Surface temperatures range from 19.20°C to 50.01°C, showing substantial spatial variability across the redesigned study area. Compared with the existing condition, the overall temperature ranges remain broadly similar, while localized differences can be observed within the intervention areas. The spatial distribution is primarily influenced by solar exposure, surface materials, vegetation, and building shading.

At 09:00, surface temperatures range from 19.20°C to 37.79°C, with cooler conditions visible in shaded and vegetated areas, while exposed paved surfaces remain relatively warmer. During 12:00, temperatures increase to 22.47–49.36°C as solar radiation intensifies. The highest values are concentrated along exposed roads and large impervious surfaces, whereas localized cooler areas appear within the redesigned green spaces and pedestrian areas. At 15:00, surface temperatures reach their highest values, ranging from 25.07°C to 50.01°C. The strongest heating remains associated with highly exposed impervious surfaces, while areas incorporating vegetation and shading show comparatively lower temperatures.

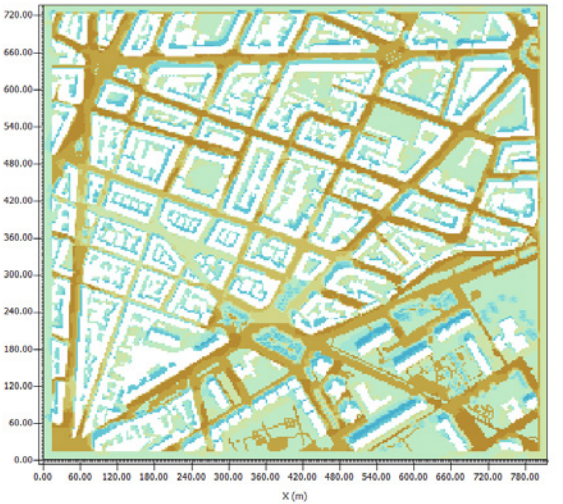
By 18:00, surface temperatures decrease to 24.94–40.11°C, although exposed paved surfaces continue to retain heat. Overall, the proposed design produces localized improvements in surface thermal conditions rather than a uniform reduction across the study area. The combination of vegetation, increased shading, and higher-albedo paving contributes to reducing surface heating within targeted intervention areas, while the major roads and open market remain comparatively warmer due to their exposed impervious surfaces and functional requirements.

T SURFACE

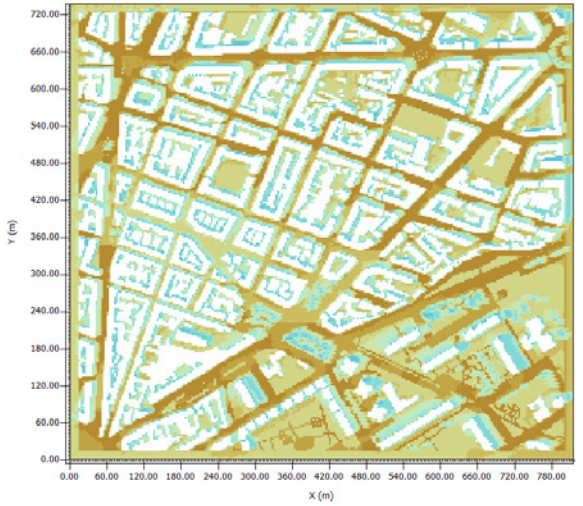
9:00 A.M



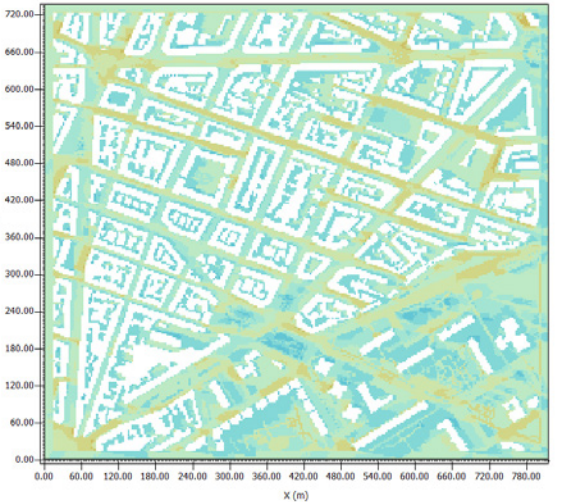
12:00 A.M



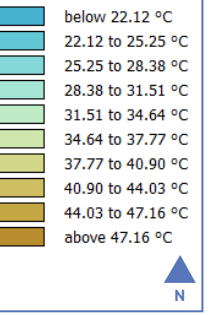
15:00 P.M



18:00 P.M



The figures 121-124 show Surface Temprature in the area with design condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)



3.4.8.3 Wind Speed

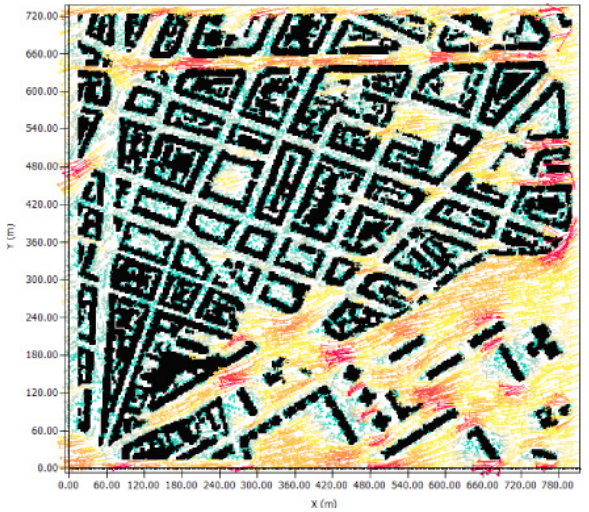
Figures 125–128 present the spatial distribution of wind speed at 1.5 m under the proposed design scenario at 09:00, 12:00, 15:00, and 18:00. Wind speeds are generally low across the study area, with values classified from below 0.23 m/s to above 1.11 m/s. Overall, the spatial airflow pattern remains broadly comparable to the existing condition, indicating that the proposed interventions do not substantially alter the main ventilation structure of the site. Wind distribution continues to be controlled primarily by building morphology, street orientation, and the degree of openness of urban spaces.

At 09:00, higher wind velocities are mainly concentrated along the wider streets and more open areas, while lower velocities dominate the enclosed urban blocks. The redesigned intervention areas show only localized variations in airflow, with no major disruption to the existing ventilation pattern. During 12:00 and 15:00, the same general spatial distribution is maintained. Higher wind speeds continue to occur along open road corridors and exposed spaces, whereas the interiors of the urban blocks remain characterized by weaker airflow. The introduction of vegetation and redesigned green areas produces localized reductions in wind velocity in some intervention zones, but these changes remain limited in spatial extent.

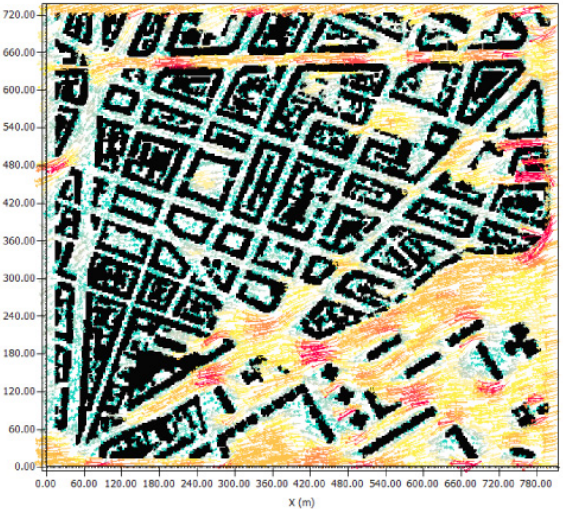
By 18:00, the overall airflow pattern remains relatively stable, with higher velocities continuing along the principal open corridors and lower values within the compact urban fabric. Overall, the proposed design preserves the existing ventilation network while producing localized modifications at the pedestrian scale. The limited change in wind conditions suggests that the thermal improvements achieved through vegetation, shading, and modified surface materials can be introduced without significantly compromising natural airflow across the study area.

Wind Speed

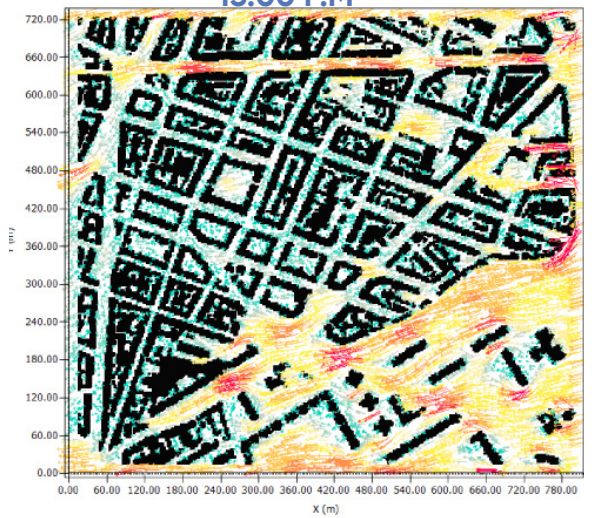
9:00 A.M



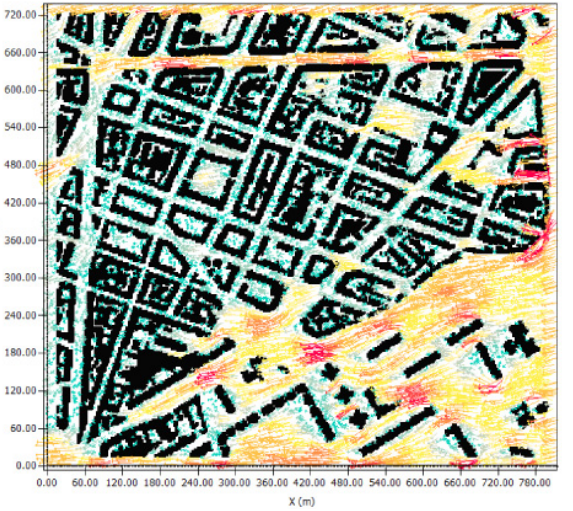
12:00 A.M



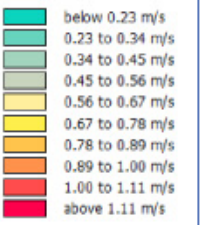
15:00 P.M



18:00 P.M



The figures 125-128 show Wind Speed in the area with design condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)





3.4.8.4 Physiological Equivalent Temperature (PET)

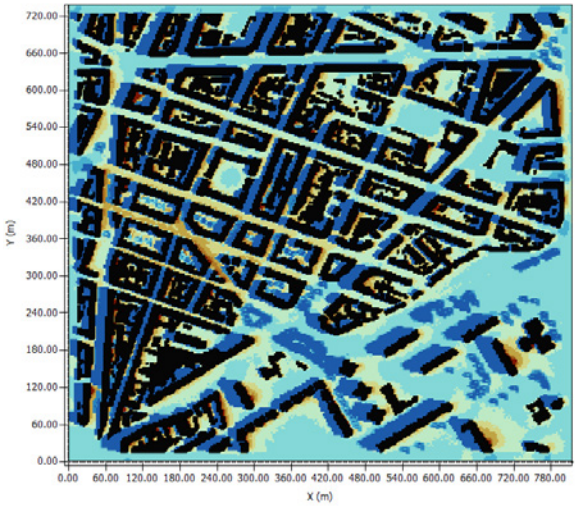
Figures 129–132 present the spatial distribution of Physiological Equivalent Temperature (PET) at 1.5 m under the proposed design scenario at 09:00, 12:00, 15:00, and 18:00. PET values range from 26.05°C to 57.89°C, indicating considerable spatial and temporal variation in outdoor thermal comfort across the redesigned study area. The distribution is mainly influenced by solar exposure, surface temperature, building shading, vegetation, and local wind conditions. Compared with the existing condition, the proposed scenario produces localized changes in PET, particularly within the redesigned courtyards and intervention areas.

At 09:00, PET values range from 26.05°C to 54.92°C, with comparatively lower values visible within shaded and vegetated areas, while exposed paved surfaces show higher thermal stress. During 12:00, PET increases to 30.81–57.29°C as solar radiation intensifies. Lower PET values remain concentrated in shaded courtyards and redesigned green areas, whereas exposed roads and open impervious surfaces continue to experience higher thermal loads. At 15:00, the highest PET values are recorded, ranging from 32.90°C to 57.89°C, with the strongest thermal stress occurring across highly exposed surfaces. Nevertheless, localized cooler conditions are maintained within areas benefiting from vegetation and shading.

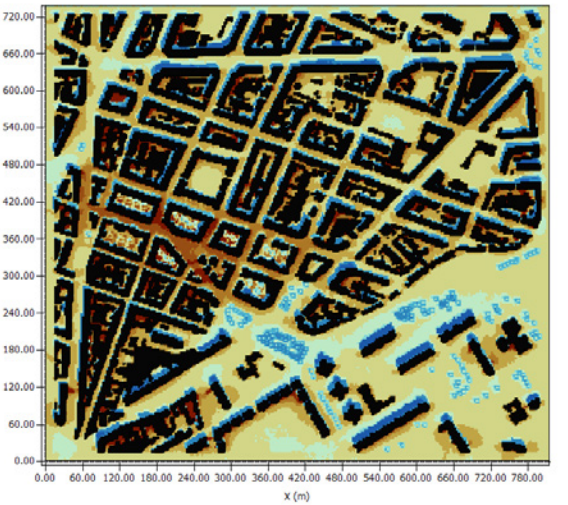
By 18:00, PET values decrease to 29.90–55.02°C as solar exposure weakens. Cooler conditions remain visible within the redesigned courtyards and shaded spaces, while exposed impervious surfaces continue to retain higher thermal loads. Overall, the proposed design produces localized improvements in outdoor thermal comfort, particularly through the combined effects of vegetation, shading, and modified surface materials, while maintaining the existing urban structure and street network.

PET

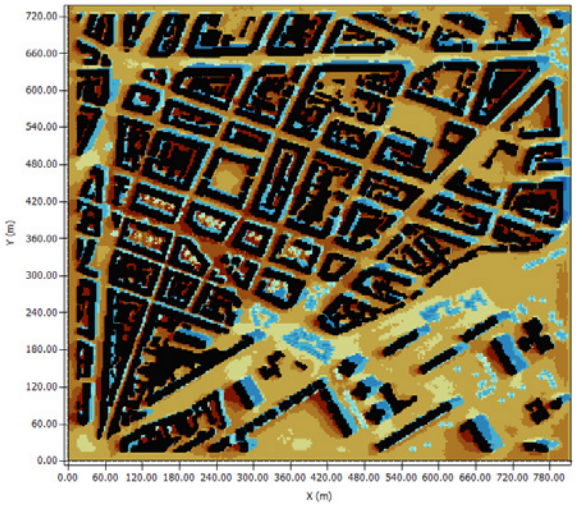
9:00 A.M



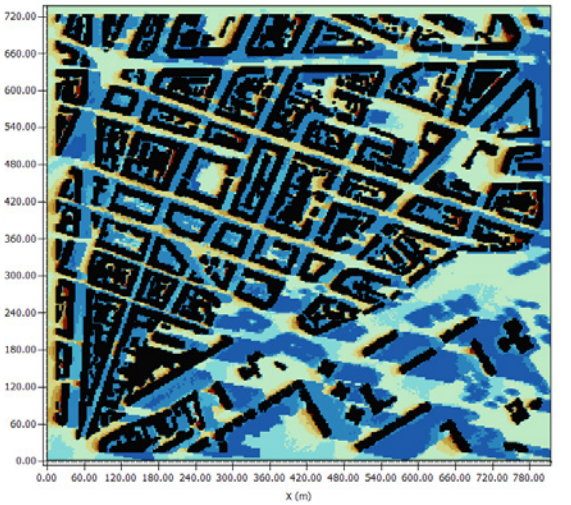
12:00 A.M



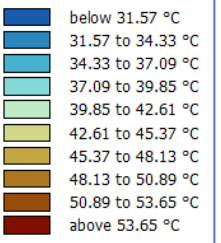
15:00 P.M



18:00 P.M



The figures 129-132 show PET in the area with design condition at 09:00, 12:00, 15:00, 18:00 h.
Date: 28.05.2025, x/y cut at K=2 (1.5 meters)



The integrated analysis of air temperature, surface temperature, wind speed, and Physiological Equivalent Temperature (PET) demonstrates that the proposed design produces localized microclimatic improvements while maintaining the overall characteristics of the existing urban environment. The intervention does not result in a uniform reduction in air temperature across the entire study area; instead, cooler conditions are mainly concentrated within the redesigned courtyards, vegetated areas, and pedestrian spaces. This indicates that the effect of the proposed interventions on air temperature is moderate and primarily localized at the pedestrian scale.

The most evident improvements are observed in surface thermal conditions. The introduction of vegetation, shading, and higher-albedo paving materials reduces surface heating within the targeted intervention areas, particularly during the periods of stronger solar exposure. However, major roads and the open market continue to exhibit relatively higher surface temperatures due to their extensive impervious surfaces and functional requirements. This demonstrates that material and landscape interventions can improve local thermal performance without requiring major changes to the existing urban structure.

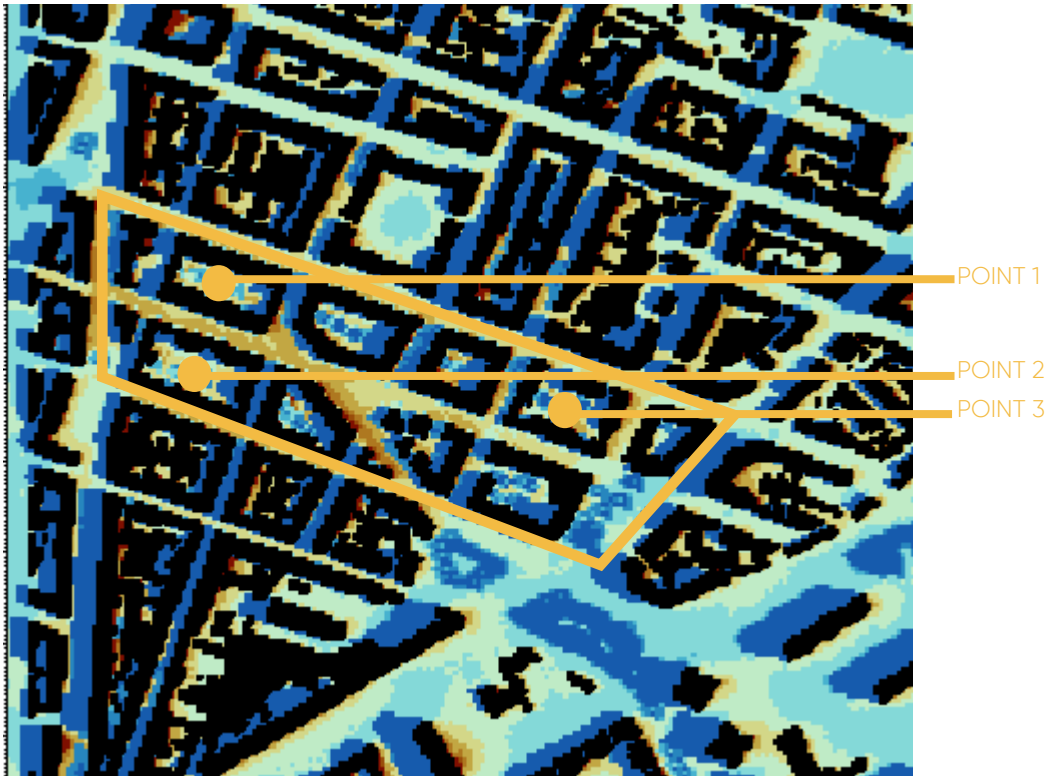
Wind speed remains generally low, but its overall spatial distribution is largely preserved under the proposed scenario. The main ventilation corridors along wider streets and open spaces remain functional, while localized reductions in airflow occur around some vegetated and redesigned areas. These changes do not significantly disrupt the existing ventilation network and contribute to creating more sheltered pedestrian environments.

The PET results integrate these microclimatic responses and indicate localized reductions in thermal stress within the redesigned

intervention areas. The combination of lower surface temperatures, increased shading, vegetation, and maintained airflow contributes to more favourable outdoor thermal conditions, particularly within residential courtyards and pedestrian spaces. Overall, the proposed design demonstrates that targeted interventions can improve pedestrian-scale thermal comfort without substantially modifying the existing urban morphology, street network, or functional role of the open market. The findings therefore support a context-sensitive strategy based on strategic vegetation, shading, and surface-material modification as practical measures for mitigating urban heat and improving outdoor thermal comfort in the study area.

3.4.9 Comparison of Existing and Design Conditions

The existing and proposed conditions were compared during the late spring period using four key microclimatic parameters: air temperature, surface temperature, wind speed, and Physiological Equivalent Temperature (PET). Three representative points were selected within the proposed design, specifically located in the internal spaces of the existing building blocks, to evaluate the effectiveness of the proposed intervention in improving the microclimatic conditions of these previously underused areas. The same points were then compared between the existing and proposed conditions to assess the spatial variation and the extent of improvement resulting from the design intervention.



The figures 91, Show points of analysis in the design area

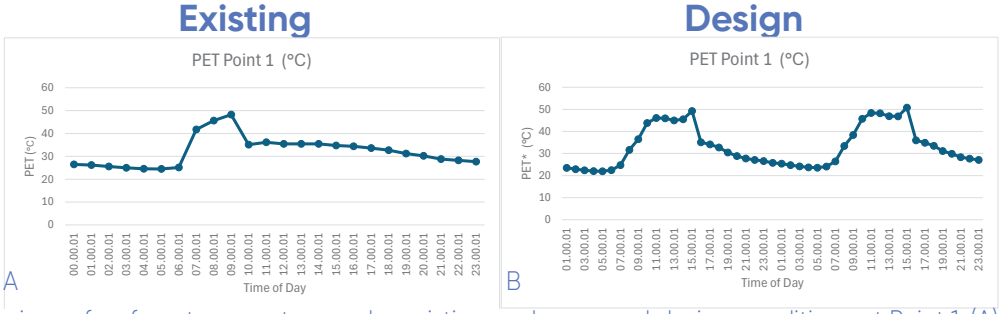


Table 10.11. Comparison of surface temperature under existing and proposed design conditions at Point 1. (A) Existing condition; (B) proposed design condition.

PET: At Point 1, the proposed design does not result in a consistent reduction in PET throughout the day. While lower values are observed during some periods, the peak PET remains similar to, or slightly higher than, the existing condition. This indicates that the thermal comfort response at this point is limited and varies throughout the day.

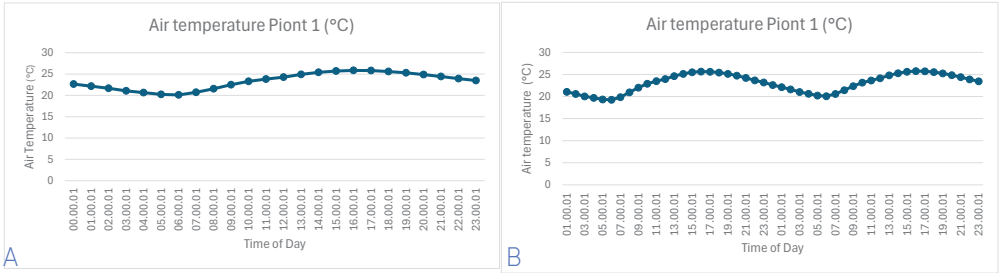


Table 12.13. Comparison of air temperature under existing and proposed design conditions at Point 1. (A) Existing condition; (B) proposed design condition.

Air Temperature: The proposed design produces a modest reduction in air temperature during the cooler periods of the day, while daytime maximum temperatures remain relatively similar to the existing condition. The overall change is therefore limited.

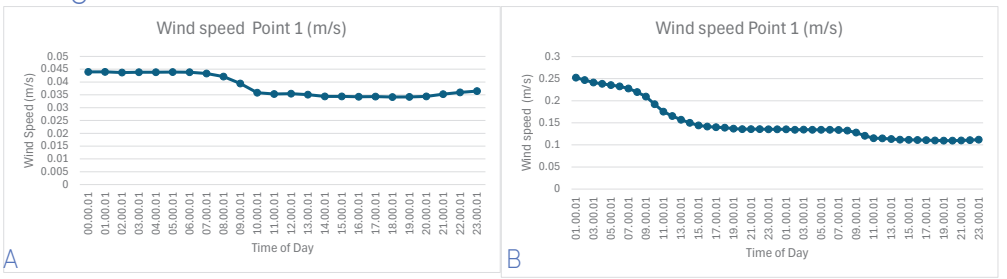


Table 14.15. Comparison of wind speed under existing and proposed design conditions at Point 1. (A) Existing condition; (B) proposed design condition.

Wind Speed: The proposed design substantially increases wind speed at Point 1, indicating improved local air movement and ventilation. This represents a positive microclimatic change that can contribute to outdoor thermal comfort.

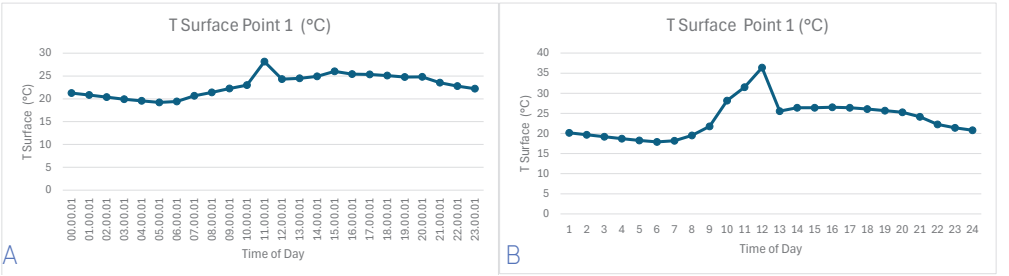


Table 16.17. Comparison of surface temperature under existing and proposed design conditions at Point 1. (A) Existing condition; (B) proposed design condition.

Surface Temperature: The proposed design slightly reduces surface temperature during the early morning hours; however, a higher peak temperature is observed around midday. Therefore, no overall reduction in surface temperature is achieved at Point 1.

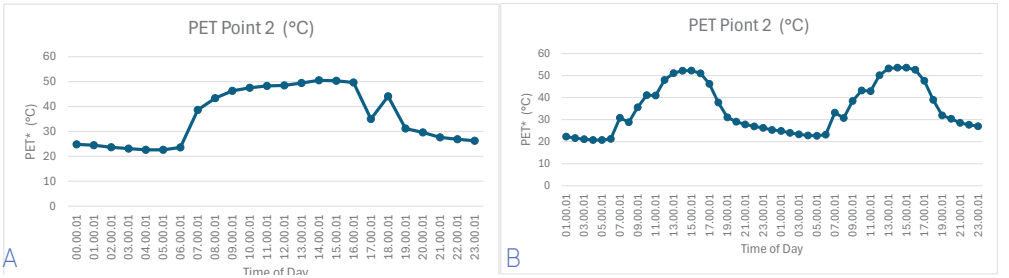
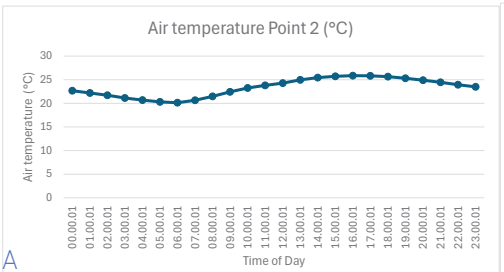
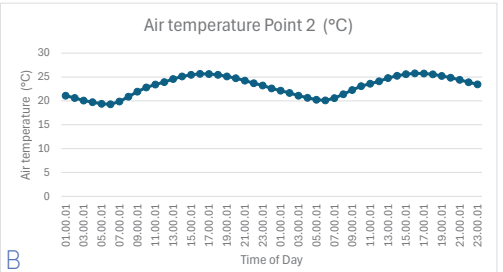


Table 18.19. Comparison of surface temperature under existing and proposed design conditions at Point 2 (A) Existing condition; (B) proposed design condition.

PET: At Point 2, the proposed design does not produce an overall reduction in PET. Although values remain relatively similar during some periods, higher PET values occur during the peak daytime hours. This indicates that thermal comfort improvement at this point remains limited.



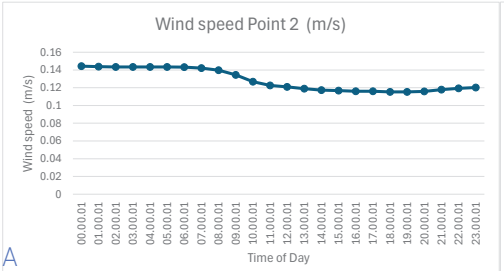
A



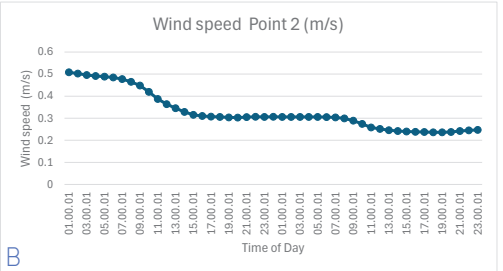
B

Table 20.21. Comparison of air temperature under existing and proposed design conditions at Point 2. (A) Existing condition; (B) proposed design condition.

Air Temperature: Air temperature shows only minor differences between the existing and proposed conditions. A slight reduction occurs during the early morning, while daytime temperatures remain similar or slightly higher. Overall, the effect on air temperature is limited.



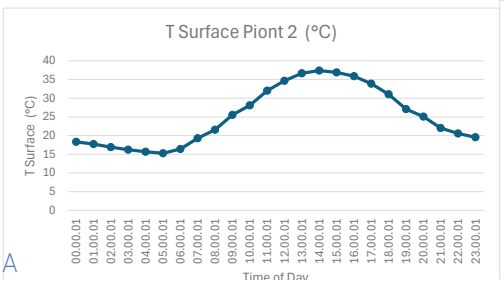
A



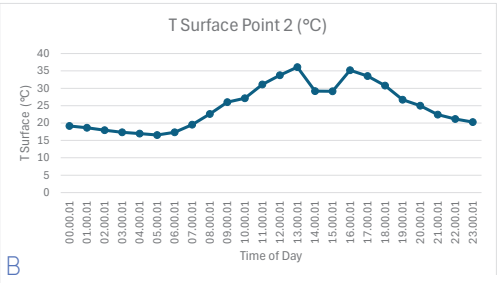
B

Table 22.23. Comparison of wind speed under existing and proposed design conditions at Point 2. (A) Existing condition; (B) proposed design condition.

Wind Speed: The proposed design substantially increases wind speed at Point 2, indicating a clear improvement in local air circulation and ventilation. This is one of the most evident microclimatic improvements observed at this point.



A



B

Table 24.25. Comparison of surface temperature under existing and proposed design conditions at Point 2. (A) Existing condition; (B) proposed design condition.

Surface Temperature: The proposed design slightly reduces the peak surface temperature during the afternoon, although higher values are observed during some earlier and later periods. The overall improvement in surface temperature is therefore moderate.

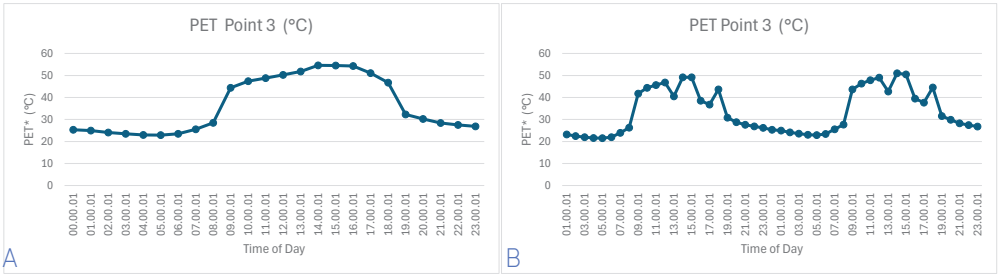


Table 26.27. Comparison of surface temperature under existing and proposed design conditions at Point 3. (A) Existing condition; (B) proposed design condition.

PET: At Point 3, the proposed design results in a limited change in PET. The peak values remain broadly comparable between the two conditions, indicating that the intervention does not produce a consistent improvement in thermal comfort at this specific point.

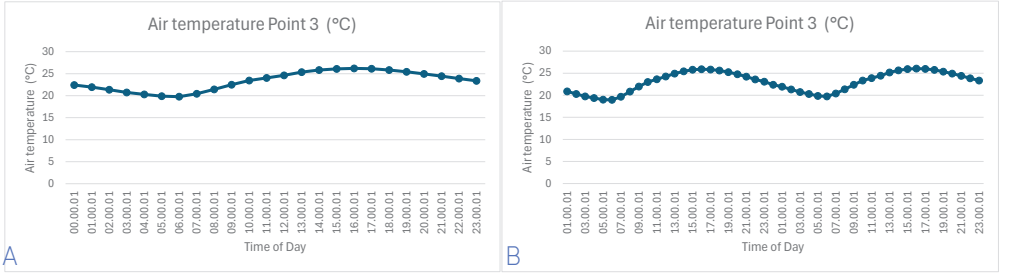


Table 28.29. Comparison of air temperature under existing and proposed design conditions at Point 3. (A) Existing condition; (B) proposed design condition.

Air Temperature: The proposed design produces a modest reduction in air temperature during the cooler periods, while the daytime maximum remains relatively similar to the existing condition. The overall change is therefore limited.

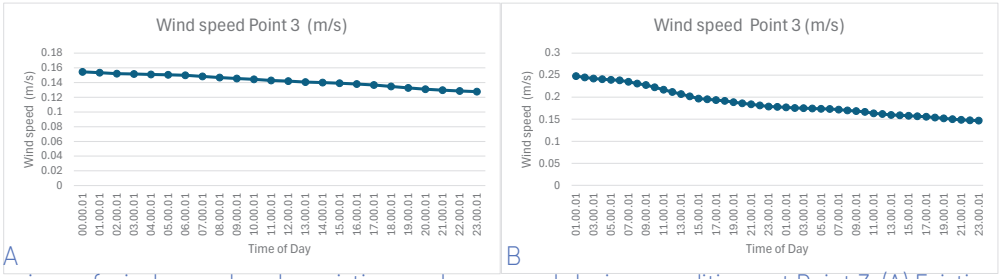


Table 30.31. Comparison of wind speed under existing and proposed design conditions at Point 3. (A) Existing condition; (B) proposed design condition.

Wind Speed: The proposed design increases wind speed at Point 3, indicating improved local air movement and ventilation. This represents a positive change in the microclimatic conditions of the internal space.

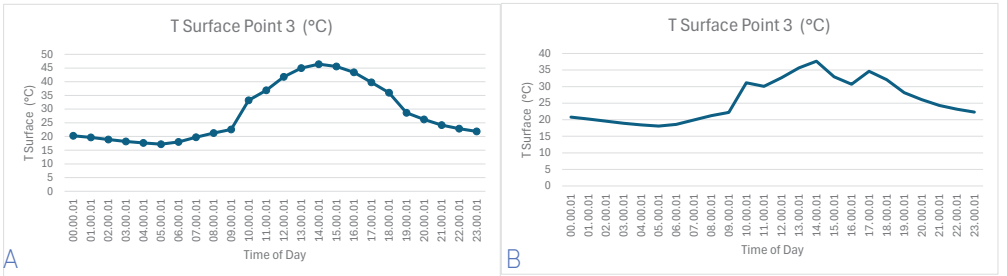


Table 32.33. Comparison of surface temperature under existing and proposed design conditions at Point 3. (A) Existing condition; (B) proposed design condition.

Surface Temperature: The proposed design substantially reduces the peak surface temperature at Point 3, from approximately 47°C to 36°C. This represents a reduction of around 11°C and indicates a significant improvement in surface thermal conditions.

Overall, the comparison between the existing and proposed conditions indicates a modest improvement in the microclimatic performance of the study area. At the neighbourhood scale, the spatial PET maps show lower maximum PET values under the proposed design at the analysed times. However, the point based comparison demonstrates that this improvement is not uniform across all locations. The most consistent improvement is observed in wind speed, indicating enhanced local ventilation, while changes in air temperature remain relatively limited. Surface temperature shows a more spatially variable response, with substantial reductions at some points but increases at others. Consequently, the effectiveness of the proposed intervention depends on the specific spatial conditions of each internal courtyard and surrounding urban configuration.

04
Conclusion

4.1 Conclusion

This thesis investigated the relationship between urban morphology, microclimatic conditions, and Urban Heat Island mitigation in the Barrier di Milano district of Turin. The research combined a theoretical review of urban climate and thermal comfort, an examination of relevant climate-responsive design precedents, contextual and morphological analysis of Turin and Barrier di Milano, and ENVI-met simulation of existing and proposed conditions. The overall approach was developed to move from the identification of urban heat vulnerabilities toward measurable and spatially targeted design responses.

The analysis of Turin established that urban heat vulnerability is influenced by the interaction of climatic conditions, urban morphology, surface characteristics, vegetation, and social exposure. Turin's location within the Po Valley and its surrounding topography can influence atmospheric circulation, while dense built areas and extensive impervious surfaces contribute to heat accumulation. The UHI risk assessment further demonstrated that thermal risk is spatially differentiated across the city and cannot be understood exclusively through city-wide climatic averages. This provided the broader rationale for investigating microclimatic conditions at the neighbourhood and pedestrian scales.

The Barrier di Milano study area was selected because it combines several characteristics relevant to urban overheating: a relatively dense urban fabric, extensive paved surfaces, limited continuous vegetation, and intensively used public spaces. At the same time, its historical character and ongoing urban transformation require interventions that improve environmental performance without fundamentally altering the existing urban structure. The analysis therefore demonstrates the importance of understanding the existing morphology before defining mitigation strategies.

The morphological analysis showed that thermal performance varies according to the geometry and orientation of the urban fabric. Street orientation, building height, street width, and urban canyon ratio influence solar exposure, shading, and airflow. The analysis also indicated differences between streets with different orientations, while deeper urban canyons generally showed more favourable conditions in some surface-temperature and PET patterns, although airflow responses varied spatially. These findings confirm that urban geometry cannot be separated from the evaluation of mitigation strategies: the same intervention may perform differently depending on the spatial configuration in which it is introduced.

The existing ENVI-met model demonstrated substantial spatial variation in surface temperature and PET across the study area. Higher values were particularly observed in exposed and impervious areas, while vegetated and shaded spaces generally exhibited more favourable thermal conditions.

Vegetation also demonstrated a clear relationship with thermal performance. Across the existing condition maps, areas benefiting from vegetation and tree shade generally showed more favourable thermal conditions than exposed areas without vegetation. This reinforces the role of vegetation not only as a landscape element but as a microclimatic mechanism capable of providing shade and contributing to evapotranspirative cooling. However, the precedent studies and the Barrier di Milano analysis also demonstrate that vegetation should be distributed strategically. Increasing vegetation indiscriminately is not necessarily the most effective solution; its location, canopy characteristics, relationship to pedestrian movement, and interaction with airflow must be considered.

Based on these findings, the proposed intervention focuses on a combination of cool surface materials, strategically introduced vegetation, and shading. The approach does not aim to completely transform the existing urban morphology. Instead, it seeks to modify the environmental characteristics of the most vulnerable spaces while retaining their existing spatial and functional roles. This principle is consistent with the lessons obtained from the precedent studies, particularly those demonstrating that combinations of

material modification, vegetation, and shading can perform more effectively than isolated interventions.

The ENVI-met comparison provides quantitative evidence of the effectiveness of the proposed strategies. At selected locations during the late spring period examined, the intervention scenario produced improvements of up to 16.38 K in PET, 15.45 K in surface temperature, and 3.18 K in potential air temperature compared with the existing condition. These values indicate that the proposed design can produce measurable and locally substantial reductions in thermal exposure in the most affected areas. Importantly, the results should be understood as spatially specific improvements rather than uniform reductions across the entire study area. The point-based comparison further indicates that PET improvements are more moderate at some locations, particularly during the daytime peak, while thermal conditions during nighttime and early morning remain broadly similar between the two scenarios.

The results therefore answer the third research question by demonstrating that climate responsive design can produce measurable improvements in pedestrian-level thermal conditions. They also support the second research question by showing the value of ENVI-met as a comparative design-assessment tool. Rather than using simulation only to represent an existing environmental condition, the research uses it as a means of testing design decisions and comparing their potential consequences before implementation. This creates a direct relationship between **urban analysis → design intervention → environmental simulation → quantitative evaluation.**

The findings also indicate that no single mitigation strategy should be considered sufficient on its own. Cool materials can reduce surface heat accumulation, but their effect on pedestrian comfort depends on the surrounding radiation environment. Vegetation can provide shade and evapotranspiration, while also influencing airflow. Shading structures can substantially reduce direct solar exposure, particularly in large open spaces, but their effectiveness depends on their placement and relationship with the existing urban geometry.

Consequently, the strongest design response is not the maximum application of one intervention but the coordinated integration of several strategies according to the characteristics and functional requirements of each space.

From an architectural and urban design perspective, this is one of the principal contributions of the research. The thesis demonstrates that UHI mitigation can be incorporated into existing urban environments without requiring a complete transformation of their morphology. Surface modification, selective vegetation, and strategically located shading can operate as relatively targeted interventions that respond to specific microclimatic weaknesses. This approach is particularly relevant to Barrier di Milano because the district is already undergoing urban transformation and because its public spaces as well as common residential spaces must continue to support everyday activities and movement.

At the same time, the results should be interpreted within the methodological limitations of the study. ENVI-met represents a simulated environmental condition based on defined input data, material properties, vegetation characteristics, boundary conditions, and selected simulation periods. The results therefore indicate the potential performance of the proposed strategies under the modelled conditions rather than guaranteeing identical improvements after physical implementation. Furthermore, the strongest reductions reported in the thesis occur at specific points and times, and should not be interpreted as a uniform change across the entire study area. The spatial and temporal variability observed in PET, surface temperature, air temperature, and MRT further emphasizes that the effectiveness of the intervention depends on the specific environmental conditions of each location and time. This reinforces the importance of reading the simulation maps spatially and understanding the relationship between intervention location and environmental response.

Overall, the research demonstrates that climate-responsive urban design can provide a viable approach to improving the thermal performance of existing urban environments in Turin. The Barrier di Milano case shows that urban morphology, surface materials, vegetation, and shading interact strongly in determining pedestrian level thermal conditions. The ENVI-met results further indicate that targeted combinations of these strategies can produce

measurable and locally substantial reductions in thermal stress, particularly in highly exposed spaces. The thesis consequently supports a design approach in which urban heat mitigation is treated as an integrated spatial design problem rather than as a purely technical environmental intervention. Considering the residential character of the study area, the proposed intervention also aims to improve the quality of everyday life for residents by transforming underused internal courtyards into greener and more usable shared spaces. This transformation represents a key challenge within the existing urban fabric, as the courtyards are currently occupied by fragmented functions and garages. The proposed strategy therefore seeks to recover these internal spaces and introduce green areas that can contribute to both environmental improvement and the everyday quality of the residential environment. For Barrier di Milano, the most promising direction is therefore a context specific combination of cooler surfaces, vegetation, and shading, calibrated according to urban geometry, solar exposure, pedestrian use, and spatial constraints. Such an approach can contribute not only to reducing thermal stress but also to improving the environmental quality, resilience, and long-term usability of public urban spaces in Turin as well as common areas of the residential blocks.

05
Bibliography

5.1 References

Ahmed, N. M., Altamura, P., Giampaoletti, M., Hemeida, F. A., & Mohamed, A. F. A. (2024). Optimizing human thermal comfort and mitigating the urban heat island effect on public open spaces in Rome, Italy through sustainable design strategies. Scientific Reports, 14, 19931. https://doi.org/10.1038/s41598-024-65794-8

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X

Alcoforado, M. J., Andrade, H., Lopes, A., & Vasconcelos, J. (2009). Application of climatic guidelines to urban planning: The example of Lisbon. Landscape and Urban Planning.

Ambrosini, D., Galli, G., Mancini, B., Nardi, I., & Sfarra, S. (2014). Evaluating mitigation effects of urban heat islands in a historical small center with the ENVI-Met® climate model. Sustainability, 6(10), 7013–7029. https://doi.org/10.3390/su6107013

Baldinelli, G., & Bonafoni, S. (2015). Analysis of albedo influence on surface urban heat island by spaceborne detection and airborne thermography. In Image Analysis and Processing – ICIAP 2015 Workshops (Lecture Notes in Computer Science, Vol. 9281). Springer.

Basagaña, X., Sartini, C., Barrera-Gómez, J., Dadvand, P., Cunillera, J., Ostro, B., Sunyer, J., & Medina-Ramón, M. (2011). Heat waves and cause-specific mortality at all ages. Epidemiology, 22(6), 765–772. https://doi.org/10.1097/EDE.0b013e31823031c5

Biesbroek, G. R., Swart, R. J., & van der Knaap, W. G. M. (2009). The mitigation–adaptation dichotomy and the role of spatial planning. Habitat International, 33(3), 230–237. https://doi.org/10.1016/j.habitatint.2008.10.001

Bishara, A., Kramberger-Kaplan, H., & Ptatschek, V. (2017). Influence of different pigments on the facade surface temperatures. Energy Procedia, 132, 447–453. https://doi.org/10.1016/j.egypro.2017.09.662

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landscape and Urban Planning, 97(3), 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006

Bruse, M., & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three-dimensional numerical model. Environmental Modelling & Software, 13(3–4), 373–384. https://doi.org/10.1016/S1364-8152(98)00042-5

Buccolieri, R., Sandberg, M., & Di Sabatino, S. (2010). City breathability and its link to pollutant concentration distribution within urban-like geometries. Atmospheric Environment, 44, 1894–1903. https://doi.org/10.1016/j.atmosenv.2010.02.022

Cai, M., Ren, C., Xu, Y., Lau, K. K.-L., & Wang, R. (2018). Investigating the relationship between local climate zone and land surface temperature using an improved WUDAPT methodology: A case study of Yangtze River Delta, China. Urban Climate, 24, 485–502. https://doi.org/10.1016/j.uclim.2017.05.010

Erell, E., Pearlmutter, D., & Williamson, T. (2011). Urban Microclimate: Designing the Spaces Between Buildings. Earthscan.

Ellena, M., Melis, G., Zengarini, N., Di Gangi, E., Ricciardi, G., Mercogliano, P., & Costa, G. (2023). Micro-scale UHI risk assessment on the heat-health nexus within cities by looking at socio-economic factors and built environment characteristics:

The Turin case study (Italy). Urban Climate, 49, 101514. https://doi.org/10.1016/j.uclim.2023.101514

Frumkin, H., et al. (2010).

Givoni, B. (1979). Man, Climate and Architecture. Applied Science Publishers.

Gorsevski, V., Quattrochi, D., & Luvall, J. C. (1998). Air pollution prevention through urban heat island mitigation: An update on the Urban Heat Island Pilot Project.

Hadavi, M., & Pasdarshahri, H. (2021). Investigating effects of urban configuration and density on urban climate and building systems energy consumption. Journal of Building Engineering, 44, 102710. https://doi.org/10.1016/j.jobe.2021.102710

Höppe, P. (1999). The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. International Journal of Biometeorology, 43(2), 71–75. https://doi.org/10.1007/s004840050118

International Organization for Standardization. (1998). ISO 7726:1998: Ergonomics of the thermal environment—Instruments for measuring physical quantities.

International Organization for Standardization. (2005). ISO 7730:2005: Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

International Union for Conservation of Nature. (2016). Nature-based Solutions to address global societal challenges. IUCN.

Intergovernmental Panel on Climate Change. (2001). Climate Change 2001: Impacts, Adaptation and Vulnerability. Cambridge University Press.

Intergovernmental Panel on Climate Change. (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press.

Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press.

Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Mitigation of Climate Change. Cambridge University Press.

Jamei, E., Rajagopalan, P., Seyedmahmoudian, M., & Jamei, Y. (2016). Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. Renewable and Sustainable Energy Reviews, 54, 1002–1017. https://doi.org/10.1016/j.rser.2015.10.104

Jendritzky, G., de Dear, R., & Havenith, G. (2012). UTCI—Why another thermal index? International Journal of Biometeorology, 56, 421–428. https://doi.org/10.1007/s00484-011-0513-7

Kabisch, N., Korn, H., Stadler, J., & Bonn, A. (Eds.). (2017). Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages Between Science, Policy and Practice. Springer. https://doi.org/10.1007/978-3-319-56091-5

Klein, R. J. T., Schipper, E. L. F., & Dessai, S. (2005). Integrating mitigation and adaptation into climate and development policy: Three research questions. Environmental Science & Policy, 8(6), 579–588. https://doi.org/10.1016/j.envsci.2005.06.010

Konijnendijk, C. C. (2021). The 3-30-300 rule for greener, healthier, more equitable cities.

Kouklis, G.-R., & Yiannakou, A. (2021). The contribution of urban morphology to the

formation of the microclimate in compact urban cores: A study in the city center of Thessaloniki. Urban Science, 5(2), 37. https://doi.org/10.3390/urbansci5020037 Lau, K. K.-L., et al. (2016).

Locatelli, B. (2011). Synergies between adaptation and mitigation in a nutshell. Center for International Forestry Research. https://doi.org/10.17528/cifor/003619

Memon, R. A., Leung, D. Y. C., & Liu, C.-H. (2010). Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons. Building and Environment, 45(1), 176–188. https://doi.org/10.1016/j.buildenv.2009.05.015

Memon, R. A., & Leung, D. Y. C. (2010). Impacts of environmental factors on urban heating. Journal of Environmental Sciences, 22(12), 1903–1909. https://doi.org/10.1016/S1001-0742(09)60337-5

Mullaney, J., Lucke, T., & Trueman, S. J. (2015). A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning, 134, 157–166.

Nazarian, N., et al. (2019).

Oke, T. R. (1982). The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society, 108(455), 1–24. https://doi.org/10.1002/qj.49710845502

Oke, T. R. (1987). Boundary Layer Climates (2nd ed.). Routledge.

Pollo, R., & Trane, M. (2021). Adaptation, mitigation, and smart urban metabolism towards the ecological transition. In Possible and Preferable Scenarios of a Sustainable Future: Towards 2030 and Beyond, 74–89.

Qin, Y. (2015). A review on the development of cool pavements to mitigate urban heat island effect. Renewable and Sustainable Energy Reviews, 52, 445–459.

Rajagopalan, P., Lim, K. C., & Jamei, E. (2014). Urban heat island and wind flow characteristics of a tropical city. Solar Energy, 107, 159–170. https://doi.org/10.1016/j.solener.2014.05.042

Rastinifard, M., & Ramezani, M. (2024). Mitigating Urban Heat Islands: The Role of Green Building Strategies. International Journal of Environment and Climate Change, 14(12), 647–662.

Rossi, F., Pisello, A. L., Nicolini, A., Filipponi, M., & Palombo, M. (2014). Analysis of retro-reflective surfaces for urban heat island mitigation: A new analytical model. Applied Energy, 114, 621–631.

Salvati, A., Monti, P., Coch Roura, H., & Cecere, C. (2019). Climatic performance of urban textures: Analysis tools for a Mediterranean urban context. Energy and Buildings, 185, 162–179.

Santamouris, M. (2013). Energy and Climate in the Urban Built Environment. Routledge.

Santamouris, M. (2014). Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy, 103, 682–703.

Santamouris, M., Synnefa, A., & Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. Solar Energy, 85(12), 3085–3102.

Sarofim, M. C., Saha, S., Hawkins, M. D., Mills, D. M., Hess, J., Horton, R., Kinney, P.,

Schwartz, J., & St. Juliana, A. (2016). Temperature-related death and illness. In A. Crimmins et al. (Eds.), The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment (pp. 43–68). U.S. Global Change Research Program. https://doi.org/10.7930/J0MG7MDX

Shashua-Bar, L., & Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. Energy and Buildings, 31(3), 221–235. https://doi.org/10.1016/S0378-7788(99)00018-3

Sheng, L., Tang, X., You, H., Gu, H., & Hu, X. (2017).

Smargiassi, A., et al. (2009).

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. Bulletin of the American Meteorological Society, 93(12), 1879–1900.

Sola-Caraballo, J., López-Cabeza, V. P., Roa-Fernández, J., Rivera-Gómez, C., & Galán-Marín, C. (2024). Assessing and upgrading urban thermal resilience of a Spanish MoMo neighbourhood over the span of 1960–2080. Building and Environment, 256, 111485. https://doi.org/10.1016/j.buildenv.2024.111485

Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban form and extreme heat events: Are sprawling cities more vulnerable to climate change than compact cities? Environmental Health Perspectives, 118(10), 1425–1428. https://doi.org/10.1289/ehp.0901879

Synnefa, A., Santamouris, M., & Apostolakis, K. (2007). On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Solar Energy, 81(4), 488–497. https://doi.org/10.1016/j.solener.2006.08.005

Taubenböck, H., Debray, H., Qiu, C., Schmitt, M., Wang, Y., & Zhu, X. X. (2020). Seven city types representing morphologic configurations of cities across the globe. Cities, 105, 102814. https://doi.org/10.1016/j.cities.2020.102814

Tominaga, Y., Sato, Y., & Sadohara, S. (2015). CFD simulations of the effect of evaporative cooling from water bodies in a micro-scale urban environment: Validation and application studies. Sustainable Cities and Society, 19, 259–268. https://doi.org/10.1016/j.scs.2015.03.011

Tumini, I., Higueras García, E., & Baeriswyl Rada, S. (2016). Urban microclimate and thermal comfort modelling: Strategies for urban renovation. International Journal of Sustainable Building Technology and Urban Development, 7(1), 22–37. https://doi.org/10.1080/2093761X.2016.1152204

United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development.

United Nations Development Programme. (2015). Human Development Report 2015: Work for Human Development.

United Nations Human Settlements Programme (UN-Habitat). (2023).

Vidal Kume, E. (2020). Urban micro-climate implications of Barcelona's superblocks strategy: A computational assessment [Diploma thesis, Technische Universität Wien]. reposiTUm. https://doi.org/10.34726/hss.2021.66497

Villanueva, K., Badland, H., Hooper, P., Koohsari, M. J., Mavoa, S., Davern, M., Roberts, R., Goldfeld, S., & Giles-Corti, B. (2015). Developing indicators of public open space to promote health and wellbeing in communities. Applied Geography, 57, 112–119. https://doi.org/10.1016/j.apgeog.2014.12.003

Watson, D., & Labs, K. (1983). Climatic Design: Energy-Efficient Building Principles and Practices. McGraw-Hill.

World Health Organization. (2016). Urban Green Spaces and Health: A Review of Evidence. WHO Regional Office for Europe.

World Health Organization & World Meteorological Organization. (2015). Heatwaves and Health: Guidance on Warning-System Development.

Zhou, D., Zhao, S., Liu, S., Zhang, L., & Zhu, C. (2014). Surface urban heat island in China's 32 major cities: Spatial patterns and drivers. Remote Sensing of Environment, 152, 51–61. https://doi.org/10.1016/j.rse.2014.05.017

Crank, P. J., Middel, A., Coseo, P., & Sailor, D. J. (2023). Microclimate impacts of neighborhood redesign in a desert community using ENVI-met and MaRTy. Urban Climate, 52, 101702. https://doi.org/10.1016/j.uclim.2023.101702

Erell, E. (2008). The application of urban climate research in the design of cities. Advances in Building Energy Research, 2(1), 95–121. https://doi.org/10.3763/aber.2008.0204

Garzena, D., Acquaotta, F., & Fratianni, S. (2018). Analysis of the long-time climate data series for Turin and assessment of the city's urban heat island. Weather, 74(10), 353–359. https://doi.org/10.1002/wea.3292

Kotharkar, R., & Dongarsane, P. (2024). Investigating outdoor thermal comfort variations across Local Climate Zones in Nagpur, India, using ENVI-met. Building and Environment, 249, 111122.

Lauzet, N., Rodler, A., Musy, M., Azam, M.-H., Guernouti, S., Mauree, D., & Colinart, T. (2019). How building energy models take the local climate into account in an urban context – A review. Renewable and Sustainable Energy Reviews, 116,

109390. https://doi.org/10.1016/j.rser.2019.109390

Matzarakis, A., Mayer, H., & Iziomon, M. G. (1999). Applications of a universal thermal index: Physiological equivalent temperature. International Journal of Biometeorology, 43(2), 76–84. https://doi.org/10.1007/s004840050119

Mirzaei, P. A. (2015). Recent challenges in modeling of urban heat island. Sustainable Cities and Society, 19, 200–206. https://doi.org/10.1016/j.scs.2015.04.001

Toparlar, Y., Blocken, B., Maiheu, B., & van Heijst, G. J. F. (2017). A review on the CFD analysis of urban microclimate. Renewable and Sustainable Energy Reviews, 80, 1613–1640. https://doi.org/10.1016/j.rser.2017.05.248

Pasqui, G., & Calvaresi, C. (n.d.). Turin – Towards the Metropolitan Regional Strategy.Torino Strategica.

Kleerekoper, L., van Esch, M., & Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. Resources, Conservation and Recycling, 64, 30–38. https://doi.org/10.1016/j.resconrec.2011.06.004

Prataviera, E., Romano, P., Carnieletto, L., Pirotti, F., Vivian, J., & Zarrella, A. (2021). EUReCA: An open-source urban building energy modelling tool for the efficient evaluation of cities energy demand. Renewable Energy, 173, 544–560. https://doi.org/10.1016/j.renene.2021.03.144

Leku Studio. (n.d.). Superblock project.

Sim, D. (2019). Soft City: Building Density for Everyday Life. Island Press.

Taleghani, M., Kleerekoper, L., Tenpierik, M., & van den Dobbelsteen, A. (2014). Outdoor thermal comfort within different building blocks. A+BE | Architecture and the Built Environment, 4(18), 211–244.

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