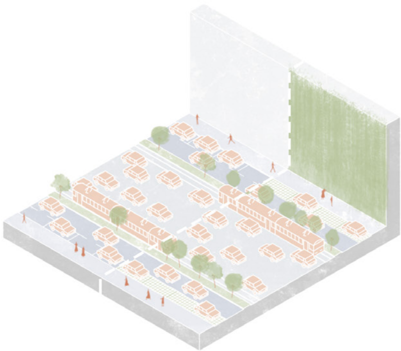
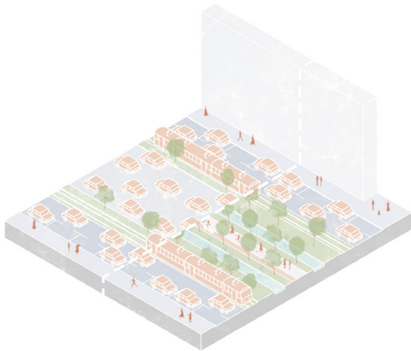
MICROCLIMATE MITIGATION, ANALYSIS AND DESIGN TOOLS: CASE STUDY OF CONTROVIALI IN TURIN



Master thesis

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Microclimate mitigation, analysis and design tools: Case study of controviali in Turin

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Master thesis

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0

0.1 Glossary

Albedo – the proportion of incident solar radiation reflected on a surface. It is expressed as a decimal value between 0 and 1 (Erell et al., 2011).

Computational Fluid Dynamics (CFD) – a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows (Erell et al., 2011).

Evaporation – the physical process by which a liquid is converted to its gaseous state (Erell et al., 2011).

Evapotranspiration – the total process of water transfer into the atmosphere from vegetated land surfaces, comprising the sum of evaporation and transpiration (Erell et al., 2011).

Mean Radiant Temperature (MRT) – the uniform temperature of an imaginary enclosure (or environment) in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure (Li, 2016).

Microclimate – the climate of a very small space, which differs from that of the surrounding area. Microclimatic conditions such as air temperature, wind flow and the radiation balance within an area in micro-scale are influenced by the physical nature of the immediate surroundings and the climate of the surrounding region (Erell et al., 2011).

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).

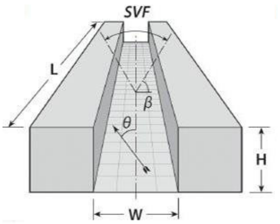


fig. 1 Urban canyon
source: Erell et al., 2011

Urban canyon – a linear space that represents a street with vertical elements on the sides as walls of the adjacent buildings (fig. 1). Three elements are used to describe the geometry of an urban canyon: height-width ratio (aspect ratio), axis orientation and sky view factor (Erell et al., 2011).

Urban Heat Island – a condition where the temperatures in the urban area are substantially higher than in the surrounding rural areas.

0.2 Abstract

The thesis evaluates the microclimate conditions in relation to mobility of Turin. The research is performed on the most common streets, unique to Turin, avenues with “controviali”, with the aim to examine the possibility of intervention relative to the type and scope of mobility and microclimate mitigation in accordance to the Sustainable Development Agenda.

The research investigates which elements contribute to the microclimate conditions and to which extent, and which strategies could be used for its mitigation.

The thesis consists of two phases. The first phase is a theoretical background which supports the research performed in the second phase. It is structured in two chapters. The first chapter includes a review of scientific literature on the sustainable development, microclimate, its mitigation and adaptation, and software for its analysis. The second chapter is dedicated to the best practices, the projects carried out recently, which include microclimate strategies and nature based solutions, and research case studies which investigate microclimate mitigation strategies using ENVI-met software for simulation.

The second phase consists of two parts. The first part represents the extensive research and urban-scale analysis of the streets with controviali in Turin, which resulted in the creation of a database containing their properties and typology. In the second part, six main case studies were selected based on the street section typology, different surface coverage, as-

pect ratio, orientation and mobility type. Microclimate analysis was performed on each case study in ENVI-met software and four main parameters were analysed: potential air temperature, surface temperature, wind speed and PET. The results were examined in relation to the parameters proven in the prior scientific research to have impact on the microclimate: urban canyon and its orientation, surface typology and presence of vegetation. The assessment of the results indicated which elements have the most impact on the climate conditions in the case studies, which allowed for the proposal of different mitigation strategies. Due to the rigidity of the already formed urban matrix, the same strategies could not be applied in all the spaces, which led to the prioritization of strategies.

0.3 Introduction

For the first time in history, the number of people living in cities exceeded the number of people living in rural areas in 2007 due to rapid urbanization. The population is expected to continue to urbanize but at a slower pace in the future. By 2050 it is predicted that 68% of people will be living in cities (World Urbanization Prospects, 2019). In the process of urbanization, the cities replace permeable and vegetated areas with built-up areas and impermeable surfaces. This leads to higher temperatures within urban areas compared to surrounding rural areas. This phenomenon is called Urban Heat Island (UHI). It exacerbates the thermal environment of the city, increases building cooling loads and reduces thermal comfort of open spaces. In combination with heat waves, caused by global warming, UHI is threat to human health leading to increased heat-related mortality rate (Lai et al., 2019).

Along with the heat waves, caused by climate change, UHI and rapid urbanization are considered key issues for sustainable city development (Imran et al., 2021). Mitigation and adaptation strategies are used to help people better adapt to the effects of global warming, as well as to improve thermal comfort in urban open spaces (Lai et al., 2019).

In order to propose and design those strategies, the climate conditions must be analysed. Climatic conditions within the urban area depend not only on the meteorological parameters but also on site-specific condition and features, such as the morphology, the presence of greenery, the surface materials, the use of the public space (Pollo et al., 2020). Therefore, different areas in the same city may still have different microclimates. Evolution and growth in technology allowed for development of different software and methods which enable the climate analysis at the smallest scale. This kind of analysis is an important basis for proposal of mitigation strategies and sustainable development of the cities.

0.4 Research questions

MAIN RESEARCH QUESTION

The main question that this research addresses is:

Which urban elements contribute to the microclimatic conditions of the streets of Turin and how?

- What characteristics of the urban elements shape the microclimate on the streets of Turin?

SUB-RESEARCH QUESTIONS

What microclimate strategies can be used to mitigate the urban heat island effects?
- What is the role of microclimate in urban and building design?
- What mitigation strategies can help address the impacts of global warming?

Which tools can be used to assess microclimate conditions?
- What kinds of tools are available for urban planners and architects?
- What thermal comfort indices can they simulate?

0.5 Methodology

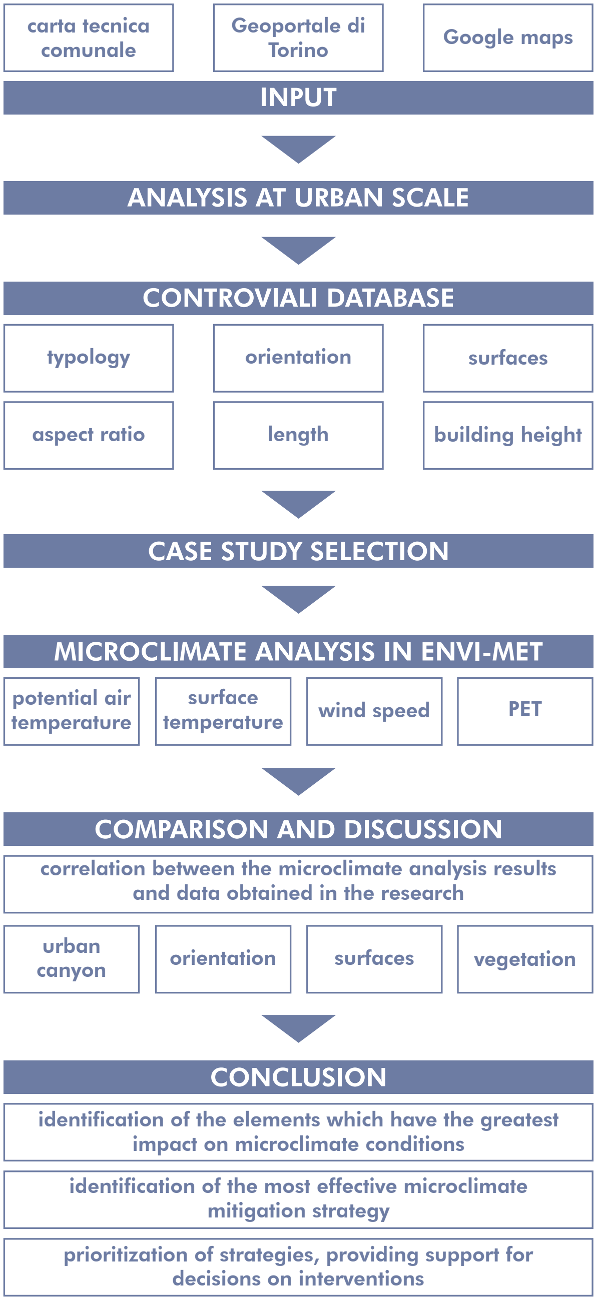
The thesis is divided in three main parts.

Part 1: Scientific background starts with a description of the relevant documents which address the impacts of global warming and climate change as the main problems the planet is facing. Microclimate adaptation and mitigation are described as the methods that contribute to the Sustainable Development Agenda. Finally, the overview of the software for analysing microclimate conditions provides insight in the possibilities of various tools for the design process and their connection with the Sustainable Development Goals Agenda.

Part 2: Best practices demonstrates examples of the successful implementation of microclimate mitigation strategies, along with its analysis. The case studies show the impact of the microclimate analysis on the sustainability of the projects in practice as well as the assessment of different strategies.

Part 3: Modelling and simulations represents a research of the streets specific for Turin, “controviali”. The research consists of mapping and analysing the controviali, their urban section, components and surfaces. Two clusters were distinguished, within which six main typologies are recognized. The simulations for six representative case studies are performed in the software ENVI-met for the assessment of microclimate conditions at the streets. Four parameters were analysed: potential air temperature, surface temperature, wind speed and PET. The results show the effects of different urban elements on the microclimate environment on different streets in Turin. Analysis of the results and the data obtained in the research of controviali indicates which elements have the most impact on the microclimate and which mitigation strategies have better effect.

fig. 2 Methodology scheme


carta tecnica comunale
Geoportale di Torino
Google maps
INPUT
ANALYSIS AT URBAN SCALE
CONTROVIALI DATABASE
typology
orientation
surfaces
aspect ratio
length
building height
CASE STUDY SELECTION
MICROCLIMATE ANALYSIS IN ENVI-MET
potential air temperature
surface temperature
wind speed
PET
COMPARISON AND DISCUSSION
correlation between the microclimate analysis results and data obtained in the research
urban canyon
orientation
surfaces
vegetation
CONCLUSION
identification of the elements which have the greatest impact on microclimate conditions
identification of the most effective microclimate mitigation strategy
prioritization of strategies, providing support for decisions on interventions

1
Scientific background

1.1 Sustainable Development

1.1.1 Sustainable Development Goals

Sustainable development was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" in the Brundtland Commission Report in 1987. In order to attain sustainable development, the three key elements must be harmonized: economic growth, social inclusion and environmental protection. These elements are interrelated and essential for the well-being of individuals and societies.
The world today faces many challenges: poverty, inequalities, unemployment, global health threats, natural disasters, terrorism, humanitarian crises, forced displacement of people, natural resource depletion, environmental degradation, climate change… These challenges place the survival of many societies as well as the biological support systems of the planet at risk. The United Nations have been trying to address them and promote sustainable development for decades through numerous summits, conferences, agendas and declarations (fig. 3). All this work lead to "The 2030 Agenda for Sustainable Development", which was adopted by all the Member States of the United Nations in 2015 and it came into effect on January 1st 2016. It is a document which establishes a common plan for peace and prosperity both for people and the planet, at present times and in the future. The core of the document are the 17 Sustainable Development Goals (fig. 4) with 169 targets which represent a universal policy agenda intended to guide the decisions made over the following 15 years. All the Member States agreed to implement the Agen-

1992

Earth Summit in Rio de Janeiro, Brazil

Agenda 21 - a plan of action to build a global partnership for sustainable development to improve human lives and protect the environment

2000

Millennium Summit in New York, USA

Millennium Development goals - an agenda aimed at reduction of extreme poverty by 2015

2002

World Summit on Sustainable Development in Johannesburg South Africa

The Johannesburg Declaration on Sustainable Development and The Plan of Implementation - reaffirmed the global community's commitments to poverty eradication and the environment

2012

United Nations Conference on Sustainable development (Rio+20) in Rio de Janeiro, Brazil

The Future We Want - a document in which it was decided to start a process for development of the set of SDGs to build upon MDGs and to establish the UN High-level Political Forum on Sustainable Development; it also contained measures for implementation of sustainable development

2013

Open Working Group - 30-member group set up by the General Assembly to develop a proposal on the SDGs

2015

Third UN World Conference on Disaster Risk Reduction in Sendai, Japan

Sendai Framework for Disaster Risk Reduction

Third International Conference on Financing for Development in Addis Abeba, Ethiopia

Addis Abeba Action Agenda on Financing for Development

United Nations Sustainable Development Summit in New York, USA

Transforming our world: the 2030 Agenda for Sustainable Development - 17 Sustainable Development Goals and 169 targets

United Nations Climate Change Conference (COP21) in Paris, France

Paris Agreement on Climate Change

fig. 3 Timeline of important conferences that lead to the Sustainable Development Goals
based on: https://sdgs.un-.org/goals

da on the national, regional and global level, with respect to their national policies and priorities, and to encourage and support its implementation within the developing countries. In order to fulfil the goals and targets described in the Agenda, the Global Partnership must be strengthened, with the intensive engagement of all the Member States. After the adoption of the Agenda, the progress is being verified on subnational, national, regional and global levels.

The aim of the 2030 Agenda is to provide peaceful, sustainable, prosperous and just world for everyone. It is directed towards saving the planet and all the species living on it from all the human-caused damages in the past and present. Its core lies in the change of behavioural patterns, the way the world is perceived today and ultimately its unsustainable functioning. The change must be comprehensive and include all the Goals and targets from the agenda, because all of them are interconnected and indivisible and cannot be addressed separately, but rather through their interlinkages and interactions (Global Sustainable Development Report 2019). However, the goals that have the most in common with urban development, microclimate and its mitigation strategies are Goal 11, Goal 13 and Goal 3.

fig. 4 Sustainable Development Goals
source: https://www.un-.org/sustainabledevelopment/news/communications-material/

1.1.2 Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable

More than half of the population lives in urban areas and the number of urban residents is growing constantly. Cities have become focal points of culture, science, ideas, commerce, productivity, social, human and economic development, accounting for 70 percent of the world's gross domestic product and generating economic growth and prosperity for the majority of people (United Nations: Sustainable cities and human settlements). Given their importance, much of the sustainable development issues, such as urban planning, transportation systems, water and waste management, sanitation, disaster risk reduction, access to information, education and capacity-building are addressed from the urban perspective.

The signatories of the Agenda 2030 agreed that the access to safe and affordable housing and basic services as well as sustainable and safe transportation systems should be guaranteed for everyone. The Agenda 2030 envisions sustainable and inclusive urban planning, reducing environmental impact of cities and encouraging the implementation of policies for resource efficiency, mitigation and adaptation to climate change and resilience to disasters.

fig. 5 Sustainable Development Goal 11
source: https://sdgs.un.org/goals

1.1.3 Goal 13: Take urgent action to combat climate change and its impacts

fig. 6 Sustainable Development Goal 13
source: https://sdgs.un.org/goals

The current scenario of climate change and global warming is expected to affect the availability of basic necessities such as fresh water, food security and energy. The climate change impacts are visible in the increase of global temperature, sea level rise, ocean acidification and they are severely affecting coastal areas and placing the survival of various societies and biological support systems at risk (United Nations: Climate change). Agenda 2030 promotes efforts to address climate change phenomena through mitigation and adaptation and their integration into the national policies. The signatories agreed to improve resilience and adaptive capacity to climate-related hazards and natural disasters. It is important to work towards raising awareness and educating people about the climate change and the implementation of policies and strategies for tackling its impacts. The mechanisms for improving the capacity for planning and management related to climate change should be encouraged in the least developed countries.

1.1.4 Goal 3: Ensure healthy lives and promote well-being for all at all ages

The Goal to "ensure healthy lives and promote well-being" does not appear to be linked to the microclimate and its mitigation, but more related to the treatment of illnesses. However, health and well-being are indirectly connected to the climate conditions induced by global warming and its consequences in numerous ways. The major environmental risks that impact the human health worldwide are poor air quality and the consequences of inadequate water and sanitation services (Global Sustainable Development Report 2016), as well as the exposure to extreme heat. About 23% of total premature deaths in 2012 were linked to environmental and modifiable factors (Prüss-Üstün, 2016), which designates the importance of the environmental influence in human health. Improvement of the environmental quality enhances the use of outdoor spaces, especially green areas, which benefits health in different ways. Spending time in natural environment promotes mental and physical health, enhances immune function, supports physical activity, and reduces exposure to air pollutants, noise and excessive heat (Cardinali et al., 2021). Vegetation helps reduce peak temperatures, the amount of harmful UV radiation, wind speed and air pollution (World Bank, 2021).

fig. 7 Sustainable Development Goal 3
source: https://sdgs.un.org/goals

1.1.5 Paris Agreement

The year 2015 is an important milestone for the sustainable future of the world, with major documents for sustainable guidance adopted (fig. 8). In December 2015, the Paris Agreement was adopted by196 Parties and it entered into force in November 2016. It is a legally binding international treaty on climate change, based on the United Nations Framework Convention on Climate Change which was adopted in New York on 9 May 1992. The aim of this Agreement is to enhance the global response to climate change through sustainable development and efforts to end poverty. The main goal of the document is to limit the increase in the global average temperature below 2°C above pre-industrial levels and to take efforts to limit it to 1.5°C above pre-industrial levels. It emphasizes the need to increase the capacity to adapt to the climate change impacts and strengthen climate resilience and low greenhouse gas emissions development along with the consistent finance flows. In order to achieve the climate neutrality by mid-century, the global peaking of greenhouse gas emissions should be reached as soon as possible.

All the Parties agreed to take immediate action, and to support the developing countries in doing so, to implement the goals of the Agreement into their policies and strategies. The contribution of each Party is verified at the Conference of Parties every five years, where all the Parties are required to present their nationally determined contributions. These are the documents which explain the countries' plans and strategies to achieve the goal set by the Agreement and to strength-

en the resilience to the impacts of the raising temperatures.
The challenges to provide a long-term global response to climate change must be faced on different levels – subnational, national, regional and intercontinental. The cooperation of the Parties is encouraged to improve the adaptation action and response through the exchange of information, knowledge and practices, institutional agreements and assistance to developing countries. All the Parties shall cooperate in raising public awareness and promoting education about climate change.
There are strong connections between climate change and sustainable development. Climate change impacts such as global warming, sea level rise, ocean acidification and many more are affecting many countries, putting societies and biological support systems at risk. That is why the climate change measures must be integrated into the national policies for successful implementation of mitigation and adaptation measures and strengthening resilience.

2009

Copenhagen Climate Change Conference (COP15) in Copenhagen, Denmark

The Copenhagen Accord - a non-binding document negotiated by the leaders of about 30 countries; it was not adopted as a UN decision but has been endorsed by over 140 UNFCCC Parties. All the key elements were defined on the following conference in Cancún

2010

Cancún Climate Change Conference (COP16) in Cancún, Mexico

The Parties agreed that:

- global warming must be kept below 2°C compared to pre-industrial temperatures.
- the rules for the monitoring, reporting and verification (MRV) of emissions and of climate finance must be stronger.
- developed countries should provide financial help for developing countries
- the Green Climate Fund should be established with new structures and institutions to strengthen the support to developing countries

2011

Durban Climate Change Conference (COP17) in Durban, South Africa

Durban Platform for Enhanced Action - formed to negotiate a new global legal framework covering all countries by 2015; made the Cancún Agreements operational and built on them

2012

Doha Climate Change Conference (COP18) in Doha, Qatar

The Parties finalised details of the 2nd period of the Kyoto Protocol and agreed on a work plan for negotiations on the new global agreement. They built upon the decisions established in Cancún and Durban.

2013

Warsaw Climate Change Conference (COP19) in Warsaw, Poland

Key decisions adopted:

- a timeplan for the countries intended contributions for the new global climate agreement
- setting up a mechanism to address losses and damage caused by climate change in vulnerable developing countries.
- strengthening the implementation of previously agreed measures

2014

Lima Climate Change Conference (COP20) in Lima, Peru

All the countries were required to describe their intended contributions for the 2015 agreement. They agreed on draft elements for the agreement and on accelerating pre-2020 action.

fig. 8 Timeline of conferences leading to Paris Agreement
based on: https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/road-paris_en

1.1.6 Progress in Sustainable Development Goals

The progress in the implementation and achievement of the Sustainable Development Goals is tracked in Global Sustainable Development Reports. The Report from 2019 shows that even though there is a certain level of progress in the achievement of the Goals and targets, some categories are not following the sustainable path set by the 2030 Agenda - rising inequalities, climate change, biodiversity loss and rising amounts of waste from human activities. In order to achieve the sustainable development, urgent and immediate action must be taken towards all the Goals and targets set in the 2030 Agenda. The Global Sustainable Development Report 2019 calls for people-centred policies and liveable cities which promote citizens' relationship with nature, strengthen resilience and address climate change.

The assessments show that the land occupied by cities will triple by 2050 in developing countries (UN, 2017; Angel et al., 2011; UNDESA 2018; UN Habitat, 2016), resulting in urban sprawl which could damage biodiversity and ecosystems. With this growing trend in urbanization, the sustainability must be the core of urban planning strategies, economic and political agendas of all the countries. Urban development should be a well-planned, integrated and inclusive process that implies the participatory cooperation between the city and national governments, civil society organizations and individuals as well as the neighbouring areas' authorities (Ayres, 2018). The impact of the cities on the environment is huge, since they are responsible for 70% of the greenhouse gas emissions from burning fossil fuel. If the goals from Paris Agreement are to be achieved, the cities must become carbon neutral (Global Sustainable Development Report 2019). Holistic, large-scale and integrated changes must be made in order to make cities more sustainable, resilient and liveable as well as to build capacity to cope with future events that may affect social economic and technological systems (Global Sustainable Development Report 2016). On the path of transformation towards liveable cities, governments and their partners must promote dissociation of growth from environmental degradation and inequality. That means promoting pro-poor development and access to decent jobs, quality public, health, educational services, transportation, safe drinking water, sanitation, nutritious food and safe public spaces for everyone (The World in 2050, 2018; PwC, 2017).

The studies show that high-rise housing imposes greater infrastructure and environmental stress and that more sustainable and effective option would be low-rise, high-density housing (Cheshmehzangia and Butters, 2016; Rahman, 2002). According to the Climate Economy Report by the Global Commission on the Economy and Climate the more sustainable, economically dynamic and healthier cities could be achieved by increasing connectivity and compactness within cities and enhancing mass public transportation (UN Secretary-General's High-Level Advisory Group on Sustainable Transport, 2014).

The cities should foster connection between people and nature – "naturbanity" in order to protect biodiversity, improve health and well-being and strengthen climate resilience. Naturbanity and urban metabolisms are ideas that perceive cities as ecosystems, connecting nature and people within a sustainable framework (International Resource Panel UNEP, 2018). That would mean the use of renewable energy, local and sustainable food production, better water management

GOAL	WITHIN 5%	5–10%	>10%	NEGATIVE LONG-TERM TREND
Goal 1		1.1. Eradicating extreme poverty	1.3. Social protection for all	
Goal 2		2.1. Ending hunger (undernourishment)	2.2. Ending malnutrition (stunting) 2.5. Maintaining genetic diversity 2.a. Investment in agriculture*	2.2. Ending malnutrition (overweight)
Goal 3	3.2. Under-5 mortality 3.2. Neonatal mortality		3.1. Maternal mortality 3.4. Premature deaths from non-communicable diseases	
Goal 4	4.1 Enrolment in primary education	4.6 Literacy among youth and adults	4.2. Early childhood development 4.1 Enrolment in secondary education 4.3 Enrolment in tertiary education	
Goal 5			5.5. Women political participation	
Goal 6		6.2. Access to safe sanitation (open defecation practices)	6.1. Access to safely managed drinking water 6.2. Access to safely managed sanitation services	
Goal 7		7.1. Access to electricity	7.2. Share of renewable energy* 7.3. Energy intensity	
Goal 8			8.7. Use of child labour	
Goal 9		9.5. Enhancing scientific research (R&D expenditure)	9.5. Enhancing scientific research (number of researchers)	
Goal 10			10.c. Remittance costs	Inequality in income*
Goal 11			11.1. Urban population living in slums*	
Goal 12				12.2. Absolute material footprint, and DMC*
Goal 13				Global GHG emissions relative to Paris targets*
Goal 14				14.1. Continued deterioration of coastal waters* 14.4. Overfishing*

tab. 1 Projected distance from reaching selected targets by 2030 (at current trends)
source: Global Sustainable Development Report 2019

(Elmqvist et al., 2018; Chiabaia, 2018), use of nature-based solutions.

The latest United Nations Climate Change Conference, COP26, was held in Glasgow in 2021. It is described as "the world's last best chance to get runaway climate change under control" (COP26 Explained). Before Paris Agreement, some scientists claimed that the temperatures might ultimately rise by 6°C. With the commitments from Paris Agreement, the rise would be limited to 2.7 – 3.7°C. If the pledges made at COP26 are implemented fully, the warming should be kept below 2°C, with the commitment to further action over the next decade to keep the rise of up to 1.5°C possible.

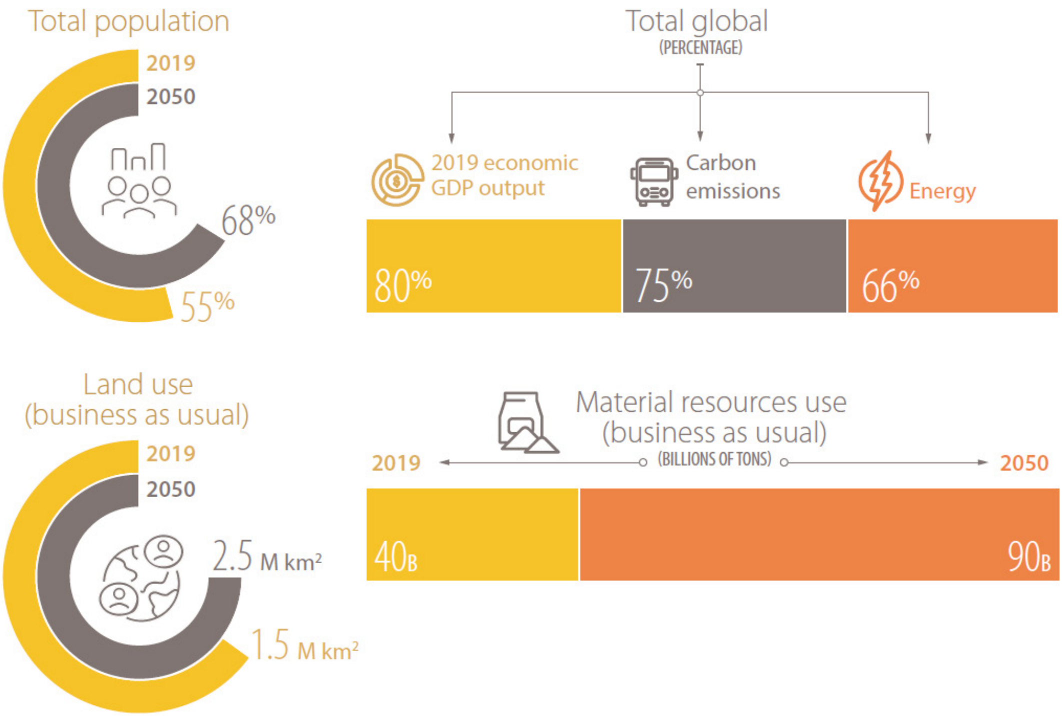
The main conclusion of the conference is that the goal to limit the temperature rise up to 1.5°C is still achievable, but it requires immediate and concerted global efforts. The Glasgow Climate Pact was adopted, with four main points agreed upon:

- Mitigation: The Parties have agreed to strengthen the mitigation policies, nationally determined contributions and long-term strategies that set out plans to reach net zero by mid-century. They have made commitments to recede from coal power, halt and reverse deforestation, reduce methane emissions and speed up the transition to electric vehicles.
- Adaptation & Loss and Damage: The Glasgow - Sharm el-Sheikh Work Programme on the Global Goal on Adaptation was agreed, which will take action to reduce vulnerability, strengthen resilience and increase the capacity of people and the planet to adapt to the impacts of climate change. New partnerships were announced to improve access to finance. The Santiago Network on Loss and Damage was resurrected through the functions and funding arrangements.
- Finance: Developed countries have made progress to-

wards the climate finance goal, with the prediction to reach it by 2023 at the latest. They also committed to increasing funds to the least developed countries. Certain countries and public finance institutions will stop international support for the unabated fossil fuel energy sector in 2022, while private financial institutions and central banks agreed to redirect the funds towards global net zero.

- Collaboration: The Glasgow Pact will advance collaboration between governments, businesses and civil society to accelerate the achievement of climate goals. The collaboration on energy, electric vehicles, shipping and commodities will help deliver on commitments.

fig. 9 Urban and peri-urban development: growing cities, growing impacts
source: Global Sustainable Development Report 2019



1.1.7 Possible future climate scenarios

Since the industrial revolution, human activities have increased the concentration of greenhouse gases in the atmosphere, leading to the increase of the mean average temperature for about 1°C. The emissions are constantly rising, and with the current trends, the benchmark of 1.5°C will be crossed between 2030 and 2052 (IPCC 2018).

The impacts of global warming are already apparent, registering the highest temperatures in the past years and causing many extreme events such as hurricanes, floods and forest fires. Even the temperature rise of 1.5°C could damage the potential of the Sustainable Development Goals due to the increase heat waves, water stress vulnerability, coastal flooding, species extinction and reduction of agricultural yields (Global Sustainable Development Report 2019). If the temperatures rise higher, the scope of devastation would be worse. Based on the current policies, the global warming caused by humankind is estimated to exceed 3°C by the end of this century (Climate Tracker).

The Intergovernmental Panel on Climate Change report (2018) on limiting global warming to 1.5°C above the pre-industrial levels analysed different scenarios, yet all of them showed that net zero CO2 emissions and major reduction of other greenhouse gases are imperative.

There are significant differences in regional climate characteristics between the present scenario, 1.5°C rise and 2°C rise. They include increases in mean temperature in most regions, hot extremes in the most inhabited regions, heavy precipitation in some and the probability of drought and precipitation deficits in some regions. The climate-related risks related to health, livelihoods, food security, water supply, human security, and economic growth increase with the increase of temperature, but they also depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options. By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C. The sea lever rise beyond 2100 will depend on future emission pathways. A slower rate of sea level rise allows better opportunities for adaptation in small islands, coastal areas and deltas. Biodiversity and ecosystems are projected to be less impacted at 1.5°C temperature rise compared to 2°C. If global warming is limited to 1.5°C compared to 2°C, the impacts on terrestrial, freshwater and coastal ecosystems are projected to be lower. The adaptation needs will be lower for the rise of 1.5°C than 2°C.

In model pathways with the goal of 1.5°C rise, global net anthropogenic CO2 emissions decline by about 45% from 2010 levels by 2030, reaching net zero around 2050. In the scenario of limiting global warming to below 2°C CO2 emissions are projected to decline by about 25% by 2030 in most pathways and reach net zero around 2070. The first scenario requires rapid and far-reaching transitions in energy, land, urban, infrastructural and industrial systems. It implies deep emission reductions in all sectors, a portfolio of mitigation policies and a substantial increase of investments.

Two scenarios of removing CO2 from the atmosphere were analysed in the IPCC 2018 Report. The first one relies on development of new technologies to capture and remove the gases from the atmosphere, while people keep the same lifestyle with unsustainable patterns of production and consumption and use of fossil fuels. The 1.5°C target from Paris Agreement would only be achievable if those kinds of technologies were widely deployed. However, such technologies do not exist yet and would probably have major impacts on agricultural and food systems, biodiversity and other ecosystem functions and services. The energy use and methane emissions would be sufficiently higher than in 2010.

The second scenario assumes the changes in human lifestyles that contribute to lower energy demand and reduction of greenhouse gases connected to food consumption. This would lead to creation of new technological and social innovations with lower energy demands, better nutrition and agriculture productivity. The CO2, which would be produced in a reduced amount, would be removed naturally by forests and therefore the energy demand as well as methane emissions would be lower than in 2010.

However, in order to implement a second scenario, the awareness among people must be raised.

1.2 Microclimate

One of the most important features of the design of urban spaces is urban climatology. Climate of a location is mainly comprised of aspects such as temperature, moisture content of the air, rain, wind, fog, snow, insolation, cloudiness and general air quality (Erell et al., 2011).

In order to create more comfortable and usable environments for humans, the planners must take into account the microclimatic conditions of the urban space throughout time. Microclimate is defined as the climate that prevails at the micro-scale level (Erell et al., 2011). At this scale, referring to an area of up to one kilometre (Oke, 1987), the individual structures and trees affect the climate conditions by casting shadows, reflecting sunlight and alter the wind flow, directly influencing the thermal comfort of people as well as the energy performance of the adjacent buildings.

Microclimate affects a wide range of urban planning aspects and elements. These include: land use optimisation in relation to different activities, identification of unfavourable microclimate factors which could affect the urban systems design, building form and design optimization in correspondence to its effect on the microclimate conditions, structural safety, selection of appropriate building materials, taking into account climate constraints when organizing construction process, water run-off control, assessment of building running costs prior to the construction, control of the environmental impact of the transportation systems on the adjacent urban area (Erell et al., 2011). Microclimate conditions of an urban area affect two main categories: people and their activities in the urban area, and building performance, especially in terms of energy conservation.

1.2.1 Urban Heat Island

One of the major consequences of urbanization and climate change is the formation of urban heat island (UHI). It is the condition where the temperature in the urban area is substantially higher than the one in the surrounding rural areas. The measure of the UHI is expressed as the temperature difference between the adjacent urban and rural locations (Erell et al., 2011).

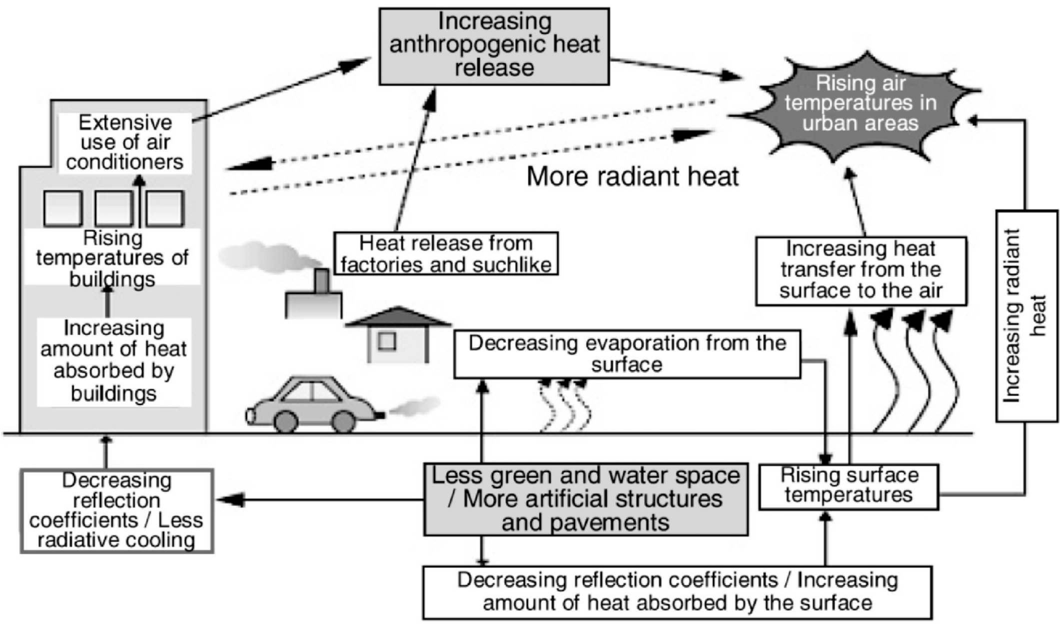
The factors that affect the formation and intensity of the UHI are the urban form of the city, weather conditions, anthropogenic heat and geographic location (Erell et al., 2011). Dense structure of the cities creates deep urban canyons, which trap solar energy through multiple reflection and absorption, increasing the heat stored within the canyon. The wind flow in dense urban areas is restricted and decreases ventilation cooling, contributing to the formation of the UHI.

Majority of the surfaces in urban spaces are impervious and due to the absence of moisture, positive net radiative balance causes the increase in air temperature above them. The properties of the materials have a substantial impact on the UHI intensity. Highly absorptive materials with low albedo, such as dark coloured asphalt, absorb solar radiation which they later release, resulting in the increase in temperature.

Presence of vegetation has multiple effects on the formation of UHI. Vegetation intercepts solar radiation and therefore shades the surface, blocks long-wave radiation, reduces wind speed and provides moisture through evapotranspiration.

Multiple studies have shown that the presence of vegetation has negative impact on the intensity of UHI (Erell et al., 2011).
Human activity in the cities affects the UHI both directly and indirectly. Anthropogenic heat, released mainly from the air conditioning and heating systems, raises outdoor air temperature, while the CO_2 emission from the fossil fuels combustion and industry contributes to the formation of greenhouse effect (Erell et al., 2011).

fig. 10 Causes of the urban heat island effect
source: Yamamoto (2016)



1.2.2 Thermal Comfort

Thermal preferences could be described as a combination of physical factors which influence thermal sensation (air temperature, humidity, air movement, radiation, clothing and activity) that a person would choose in a specific physical environment when restricted by climate and existing physical, social, cultural and economic influences (Erell et al., 2011).
The thermal preferences in relation to the thermal properties of environments can be divided into three sets: preferences concerning climatic environment (the air temperature, radiation, humidity and air movement of the internal or external climate of buildings), preferences regarding built environment properties (the buildings, technology, equipment and other physical means by which the climate set of preferences can be addressed) and preferences which concern (all the aspects of people's beliefs and behaviour which affect their other thermal preferences).
Thermal comfort can be measured with different indices: PET, PMV, UTCI, SET, WBGT...
PET is the physiological equivalent temperature at any given place (outdoors or indoors). It is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body is maintained with core and skin temperatures equal to those under the conditions being assessed (Höppe, 1999).
PMV, predicted mean vote, is one of the most widely used models for mathematical prediction of the average thermal sensation of a large group of individuals. It is based on four

thermal environmental parameters (indoor air temperature, radiant temperature, air speed and relative humidity) and two occupants' personal data: metabolic rate and clothing insulation (Li et al., 2020).

UTCI, universal thermal climate index, is expressed as an equivalent ambient temperature of a reference environment providing the same physiological response of a reference person as the actual environment. It is sensitive to variations in the environmental parameters like temperature, average radiation temperature, humidity, and air velocity (Blazejczyk et al., 2011).

SET, standard effective temperature, is defined as the dry bulb temperature of a hypothetical isothermal environment at 50% RH in which a human subject, while wearing clothing, standardized for activity concerned, would have the same skin wittedness and heat exchange at skin surface as he would have in the actual test environment (Gagge et al., 1986).

WBGT is wet-bulb globe temperature which mainly on three factors, the natural wet bulb temperature, globe temperature and the air temperature. It is one of the most used heat stress indices (Mahgoub et al., 2020).

1.2.3 Mitigation and Adaptation

The two main strategies for combating climate change and its impacts are adaptation and mitigation. Adaptation is an area of action whose aim is to moderate the damage of the climate change or exploit its benefits (IPCC, 2007). It means making the built environment resilient to the inevitable events (Pollo and Trane, 2021) and improving the living conditions of people and ecosystems in the current scenario of global warming (Pollo et al., 2020). Adaptation approach requires mainly short-term investments, with large sums of money required immediately. The effect of the adaptation measures is immediately noticeable (Pollo and Trane, 2021).

Mitigation approach means addressing the causes of climate change, with the aim of reducing the greenhouse gas emissions into the atmosphere through prevention and decarbonisation. In the urban areas this mainly refers to the improvement of buildings' energy efficiency, reduction of demand peaks, the use of alternative energy resources, urban densification and implementation of greenery (Pollo and Trane, 2021). Mitigation policies require short and long term investments and global political agreements (Goklany, 2007). Their effects are visible mostly in the medium-long term and on a national or global scale (Klein et al., 2007).

Mitigation and adaptation have significant differences regarding the aims, stakeholders, length of action. However, they are interrelated in many ways. They are both anthropogenic responses to the sudden changes induced by climate change (Pollo and Trane, 2021). The joint effort of mitigation and adaptation policies has appears to be the best approach in tackling climate change (Tunji-Olayeni et al., 2019). The combination of these policies is the most effective at local and micro-scales (Grafakos et al., 2018), when dealing with the climate crisis in the green infrastructure, urban and peri-urban agriculture, water management, and mobility domains (Grafakos et al., 2019). There is a profound correlation between climate change mitigation, climate adaptation and microclimate quality (Trane et al., 2021). The examples of the successful combination of mitigation and adaptation strategies are presented in table x.

tab. 2 Design strategies for win-win adaptation and mitigation and their effects on the urban microclimate source: Trane et al. (2021)

Domain	**Strategies**	**Adaptation**
Green Infrastructure	Green roofs	Urban drainage, decentralizing water management
	Green walls	Urban drainage
	Urban forestry	Urban drainage
Urban and peri-urban agriculture	Indoor Farming, outdoor Farming, Urban Gardens	Allocation of fertile soil to manage the risk of sudden floods, reducing soil consumption
Water management	Water ponds, floodable squares, rainwater reuse	Urban drainage, mitigating extreme events' effects
Urban mobility	Pedestrianization, reduction of vehicle road sections, depaving, traffic calming	Allocating areas for all aforementioned purposes

Mitigation	*Microclimate*
Reduction of long-wave radiation, thermal displacement, CO_2 absorption	Air quality improvement
Lowering building vertical and soild surface temperatures, reduction of building energy demand, CO_2 absorption	Air quality improvement, lowering of Mean Radiant Temperatures (MRT)
CO_2 absorption	
	Mitigation of the UHI, air quality improvement, safeguarding of biodivervisy and waters, lowering of MRT, wind speed reduction, suncreening
Reduction of the carbon footprint of the food, enhancing local production, CO_2 absorption, enhancing self-sufficiency dimension and bio-waste, limitating the use of chemical fertilizers, optimize water consumption, building redevelopment	Air quality improvement, lowering of MRT
Reduction of the energy demand for distribution, pumping, heating systems	Lowering of MRT
CO_2 absorption, preventing GHG emissions by enhancing soft mobility	Air quality improvement, lowering of MRT

1.2.4 Microclimate Mitigation Strategies

As a response to the impacts of global warming and UHI, microclimate mitigation strategies have been studied through research, simulations and in practice. However, due to the uniqueness of microclimate conditions of each site, there is no strategy that is guaranteed to improve the environment at every location. Therefore, the analysis and simulations must be performed for each location with its own climatic and urban characteristics. The most researched microclimate mitigation strategies are:

Cool materials

Cool materials could be placed on the roof, pavement or the facades. They are characterized by high albedo and therefore high solar reflectance and high infrared emittance (Al Touma and Ouahrani, 2019). Due to these properties, they are able to reflect most of the incident sunlight and emit faster the absorbed heat back to the atmosphere instead of allowing the heat transfer into the building interior (Zhu et al., 2021). This way they contribute to the surface and air temperature decrease as well as the reduction of building cooling loads and energy use (Garg et al., 2016; Testa and Krarti, 2017).

However, high albedo paving is more costly, could cause glare which creates discomfort with the pedestrians and might have negative impacts due to the larger amount of reflected solar radiation (Santamouris, 2013), so the individual analysis must be carried for each case. Use of cool materials on the roof has relatively little impact on the urban form and can be implemented or replaced at low price (Botham-Myint et al., 2015; Taleghani et al., 2016).

Water bodies

Water bodies, such as fountains or stretches, can contribute to the microclimatic conditions through evaporation (Battista et al., 2016). The studies have shown the decrease of surface temperature (Robitu et al., 2003), air temperature (Nakayama and Fujita, 2010) and mean radiant temperature (Robitu et al., 2006) in urban spaces with water bodies. Small water bodies have small thermal effect on their surroundings, which would make them irrelevant in the climate-responsive design practice (Jacobs et al., 2020). However, their implementation leads to cooling of urban space, especially if combined with strategies like vegetation and shading. The water elements have significant impacts on air temperature and relative humidity within the distance of 1-2 metres from the water bodies (Albdour and Baranyai, 2019).

Vegetation

Vegetation contributes to the environment cooling through two mechanisms (McPherson et al., 1995): higher albedo than common urban surfaces, which means it reflects more solar radiation and has lower heat capacity, and evapotranspiration, which is the sum of evaporation from the earth's surface and transpiration from the plants. Trees block the incoming solar radiation from reaching ground surface and cools the air space under their canopy, while presence of grass reduces the temperature near ground level (Bonan, 2000; Shashua-Bar et al., 2009). The studies have shown that presence of grass allows temperature reduction when compared to the same area with bare soil (Taleghani et al., 2014), presence of trees and shrubs next to the building can reduce air conditioning costs (Carter and Keeler, 2008).

Vegetative cover can be applied on the roofs, facades or in the urban space. Green roofs have multiple benefits for the environment, including reduction of storm water runoff, cooling the environment and decreasing the heat transfer into the buildings in summer (Moody and Sailor, 2013).
However, due to the initial cost, the need for irrigation and maintenance requirements, implementing this strategy could be challenging for the urban planners (Crank et al., 2018). In addition, the effect of trees is not beneficial in all the cases, since they could block the wind flow and prevent the removal of pollutants from the air (Erell et al., 2011).

Solar access

The degree of exposure to solar radiation is one of the most influential elements on the microclimate conditions. Outdoor thermal comfort at the pedestrian level is related to the radiant load to which they are exposed as much as to the air temperature (Erell et al., 2011). Since air temperature is not easy to control, the solar exposure is fairly simple to regulate solar exposure. Sunlight can be blocked by trees, canopies, buildings, shading devices and therefore the street orientation, canyon geometry and building forms have a great impact on the solar access and shading.
In winter months, exposure to sunlight is desirable both for buildings and pedestrians. For the buildings which rely on passive solar heating, solar access is a requirement for at least several hours every day. In order to guarantee this access, the concept of „solar envelopes" is introduced by Knowles (1981). It is a set of limits on the height or volume of the buildings that are determined from the position of the sun, in order to assure sufficient exposure to the sunlight. However, this concept is difficult to apply in dense urban structures at high-latitude locations (Erell et al., 2011).

Air-flow

Air-flow affects thermal comfort of the pedestrians in two ways: mixing energy and moisture, which gradually reduces the differences between adjacent microclimates, and promoting energy exchange at the human skin, which causes sweat evaporation in warm conditions or a wind-chill effect in cold ones (Erell et al., 2011). Wind speed can be reduced with solid and porous barriers. Studies have shown that the porous barriers are more effective than the solid ones because the porosity allows some flow through the barrier and prevents the formation of the vortex on the lee side and results in the decrease of the wind speed.

Controlling air-flow allows for the control of urban air quality. Urban form affects the pollutant diffusion and air quality could be improved by appropriate urban planning and strategies. Some of the strategies for pollutants removal are avoiding uniformity in urban height, canyon width and canyon length, using pitched roofs to increase turbulence and create stronger vertical mixing in street canyons, designing wider canyons which promote better pollutant diffusion, limiting the length of individual city blocks and avoiding long street canyons with continuous building fronts (Erell et al., 2011).

In order to obtain good air quality on a city level, emissions from sources within the city or in its immediate surroundings must be reduced, along with the exposure to emissions from source outside the city and an effective ventilation strategy to flush away pollutants in the urban canopy layer must be provided.

1.2.5 Nature-Based Solutions

Nature-Based Solutions (NBS) are defined as "actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN 2016). They use nature and natural processes to provide infrastructure, services and solutions in order to enhance urban resilience (World Bank, 2021). NBS provide multiple benefits to the cities such as reduction of greenhouse gas emissions and of disaster risk, building climate resilience, restoring biodiversity, improving health, water and food security (Canadian Society of Landscape Architects, n.d; World Bank, 2021). They are the most effective in increasing urban resilience when planned in a holistic manner, which means first addressing resilience and biodiversity changes through system-based approach and then integrating NBS into policies, plans, programs and projects (World Bank, 2021). Research has demonstrated that NBS can stimulate social innovation in cities and accelerate the transition to sustainability by promoting innovative planning and governance along with new models for business, finance, institutions and society (Faivre et al., 2017; Wolfram and Frantzeskaki, 2016).

In the sustainable urban development, NBS are used to restore degraded ecosystems, develop climate change adaptation and mitigation responses and improve risk management and resilience (European Commission, 2015). NBS are place-based, which means their effect depends on the functional needs and environmental characteristics of the site (Mussinelli, 2018). Some examples of NBS include green roofing, floodplain restoration and creating pocket parks (Faivre et al., 2017). Nature-Based Solutions also help address societal challenges by increasing human well-being, urban regeneration, enhancing coastal resilience, multi-functional watershed management and ecosystem restoration, increasing sustainable use of matter and energy, developing the insurance value of ecosystems, and increasing carbon sequestration (Faivre et al., 2017).

1.3 Software for climate analysis overview

1.3.1 Categorization

The research on the climate phenomena has been conducted at different scales, using various methods, such as field measurements, observations, climate modelling etc. Development of technology and computational abilities allowed development of more advanced approaches for microclimate analysis and modelling. Recently, the leading method has become simulation analysis due to its high capacity of solving complex phenomena and nonlinearity of urban climate systems (Liu et al., 2020). They allow the analysis of microclimate over a relatively wide area and are able to predict the microclimate conditions under different planning scenarios (Bartesaghi Koc et al., 2018).
Grimmond et al. (2010) classified urban climate models in four categories:

1. Scale models

Scale models have contributed to understanding the urban atmosphere. They have mainly been used for the simulation of urban flow, turbulence and dispersion phenomena in wind tunnels and water flumes or outdoors over idealized arrays of building-like obstacles.

2. Statistical models

Statistical models estimate the effects of cities on climate. They have low risk of producing unrealistic results. Their simplicity allows for approximation of meteorological parameters within the city. They have low computational requirements and demand small number of input parameters. However, they have some limitations, which include long observation periods or data from many different locations and limitation to the city or region in which they were developed (Grimmond et al., 2010).

3. Numerical models

Numerical models allow 3D simulation of urban space thermal environment (Wang and Li, 2016; Wong et al., 2013). They are able to provide information about any evaluated parameter in the entire computational domain (Moonen et al., 2012; Blocken, 2014; Rizwan et al., 2008) and conduct comparative analysis based on different scenarios (Blocken, 2015; Kanda, 2007), which is a huge advantage compared to direct monitoring and field measurements (Sharmin et al., 2017). Numerical methods are used to predict the impacts of different microclimates on the urban environment (Arnfield, 2003; Bruse, 1999). The most used numerical simulation approaches are Energy Balance Model (EBM) and Computational Fluid Dynamics (CFD).

Energy Balance Models (EBM)

EBMs calculate energy budget using the conservation energy law for a specific volume, taking into account atmospheric phenomena, velocity field and turbulence fluctuations as heat fluxes (Imran et al., 2021). EBMs were the leading tool for numerical analysis of microclimate in the late 1990s (Toparlar et al., 2017).

Urban Canopy Model (UCM) is obtained from energy balance equations for a control volume such as two adjacent buildings. The model evaluates the energy exchange between ambient and surface air in the Urban Canopy Layer (UCL) and is therefore able to predict ambient and surface temperatures in the urban environment. Surface and control volumes interact with each other like electric nodes, which results in the matrix of humidity and temperatures (Imran et al., 2021).

CFD models

Computational Fluid Dynamics is a microclimate modelling tool with high-resolution results for different spatial and temporal scales (Blocken, 2015; Holland et al., 2015). It can be used to study airflow, thermal comfort, pollutant dispersion, wind-driven rain and building energy performance (Moonen et al., 2012). It is one of the most used numerical simulation methods. It combines the advantages of fluid mechanics and heat transfer to simulate heat conduction and convection among surfaces in a city at a fine scale (Setaih et al., 2014).

CDF models include a variety of numerical models from Reynolds-averaged Navier-Stokes (RANS), through Large Eddy Simulation (LES) to Direct Numerical Simulation (DNS). These models allow calculation of the flows at the micro-scale level (Grimmond et al., 2010). They consider all principal fluid equations in urban areas simultaneously, solving the equations of temperatures, momentum and conservation of mass (Imran et al., 2021). CFD simulations can be used to study urban microclimate at different scales: meteorological meso-scale, micro-scale, building scale and indoor environment (Blocken, 2014; Blocken, 2015; Moonen et al., 2012).

4. Dispersion and air quality models

Dispersion and air quality models are used for evaluation of air quality and prediction of environmental phenomena that could affect the people's health. Urban dispersion models vary from simple single equation models which parameterize the UBL and its controls on dispersion to complex CFD models which perform calculations with high precision and resolution. The models' application varies from evaluation of long-term health effects to short-term emergency response. The models are widely being developed due to high demand (Grimmond et al., 2010).

1.3.2 Spatial scale of analysis

Tools for climate and microclimate analysis are typically categorized according to the scale of application and resolution. Oke (2006) classified climate phenomena into meso, local and micro-scales, while Lobaccaro et al. (2021) identified two main domains for climate tool application: macro-scale and micro-scale models. Meso-scale represents the region or city, local scale corresponds to neighbourhood or district are, while micro-scale varies from 10-102 m and includes street canyons or single buildings (Elbondira et al., 2021).

Meso-scale models

Tools and models for climate analysis on meso-scale focus on the overall area of the city as a whole system. The size of the model is usually a few tens of kilometres, with the grid of up to 10 or 20 kilometres on a city scale or up to 100 or 200 kilometres on a regional scale. The spatial resolution is usually 100 or 200 metres (Lobaccaro et al., 2021). Meso-scale models can be used for urban heat island (UHI) modelling and predicting phenomena in the order of 100 km, such as sea breezes (Lun et al., 2009).

The research on meso-scale climate is mostly done by two approaches: remote sensing and numerical modelling. The analysis of remotely sensed data and satellite images are used to obtain land surface temperature (LST), which is used for modelling UHI (Elbondira et al., 2021). However, these models have low spatial resolution and they are only valid for a specific location and cannot be extended to other regions (Mirzaei, 2015). The other approach uses numerical models, such as Weather Research and Forecasting model (WRF), to analyse impact of climate phenomena on the city (Elbondira et al., 2021). Numerical models are based on the equations of fluid dynamics and they also include radiation, cloud cover and soil models into the calculations (Mirzaei, 2015).

Local-scale models

Research on microclimate on this scale is mostly done by urban canopy models (UCM) or CFD models (Wong et al., 2021). Most studies on this scale use simulations to measure the effects of greening scenarios (Peng and Jim, 2013; Ramyar et al., 2019; Saito et al., 2017; Skelhorn et al., 2014) and neighbourhood form and street layout (Ramyar et al., 2019; Yin et al., 2019) on microclimate and thermal comfort.

CFD simulations for neighbourhood scale models are mostly based on area range of 200 metres to 2 kilometres (Huo et al., 2021). CFD-based research local scale is commonly based on the impacts of mitigation measures on the thermal environment of local-scale urban area (Ampatzidis and Kershaw, 2020; Anjos and Lopes, 2017; Peng et al., 2020), the relationship between the form and layout of buildings or blocks and the local urban thermal environment (Montazeri et al., 2015), the layout and planning of ventilation corridors and its impact on the thermal environment (Allegrini et al., 2014; Gousseau et al., 2011) and the relationship between the thermal environment and human thermal comfort indices (Blocken et al., 2012).

Micro-scale models

Micro-scale models are the most suitable for evaluating the impacts of urban environment on thermal comfort of pedestrians both in existing conditions and planning scenarios. Horizontal distances of micro-scale models range from a few hundred metres up to 2 kilometres, with a spatial resolution of a few metres (Lobaccaro et al., 2021). Mathematical modelling and simulations are mainly coupled with field measurements in order to evaluate the effects of urban environment on the microclimate and thermal comfort. The meteorological data for the models is either collected through field observations, simulated with simulation tools and models or obtained through the experiments (Ali-Toudert and Mayer, 2006; Lobaccaro and Acero, 2015). Micro-scale modelling parameters require more detailed measurements due to more complicated boundary conditions and higher variation at the surface layer than meso-scale models (Imran et al., 2021).

Two main types of micro-scale models are computational fluid dynamics (CFD) models and urban canopy models (UCM). CFD models are 3D models that can simulate different aspects of microclimate such as wind flow, heat convection, conductivity and storage, radiation exchange, water vapour transfer, pollutant dispersion and other (Brozovsky et al., 2021). Airflow in CFD models is calculated with Navier–Stokes equations (Mirzaei, 2015).

UCMs are mainly used for examining the energy budget of an urban canopy layer (Masson, 2000) and the airflow derives from the energy budget equations, unlike the CFD models (Mirzaei, 2015). Both types can assess the impact of various parameters such as building orientation, street aspect ratio, surface materials, vegetation, pedestrian comfort and urban ventilation (Haghighat, and Mirzaei, 2011; Mirzaei and Haghighat, 2010; Tominaga et al., 2015). However, they both have certain weaknesses. CFD models have limited domain size due to immense computational cost, while UCMs have less detailed presentation of airflow around the buildings (Mirzaei, 2015).

tab. 3 A comparison among the most used numerical software
source: Trane et al. (2022)

	Type of model		Model scale			Simulated variables					
	EBM	CFD	Meso	Local	Micro	T_s	T_a	W_s	W_d	Q	Other
TEB (Town Energy Balance)	●		●	●	●	●	●	●		●	●
UWG	●		●	●	●		●				●
ENVI_MET		●		●	●	●	●	●	●	●	●
RayMan	●				●	●	●			●	
SOLWEIG	●			●	●		●			●	
UMEP	●		●	●	●		●			●	
Solene-Microclimat		●		●	●	●	●	●	●	●	
Ladybug Ecosystem			●	●	●	●	●	●	●	●	●
ANSYS FLUENT		●		●	●		●	●	●		●
TownScope	●				●					●	
OpenFOAM®		●	●	●	●			●	●		
SkyHelios	●				●			●	●	●	

Simulated thermal comfort index							Simulating air pollution	Native module for modelling	Free Accessibility
PMV	PET	UTCI	SET	PT	MRT	Other			
		●							●
		●							●
●	●	●	●		●		●	●	only with very limited features
●	●	●	●	●	●			●	●
	●	●			●				●
	●	●			●				●
	●	●			●				●
●	●	●			●				open tools for pay per use software
●	●	●	●		●		●	●	
						●			
●							●		●
	●	●		●	●			●	●

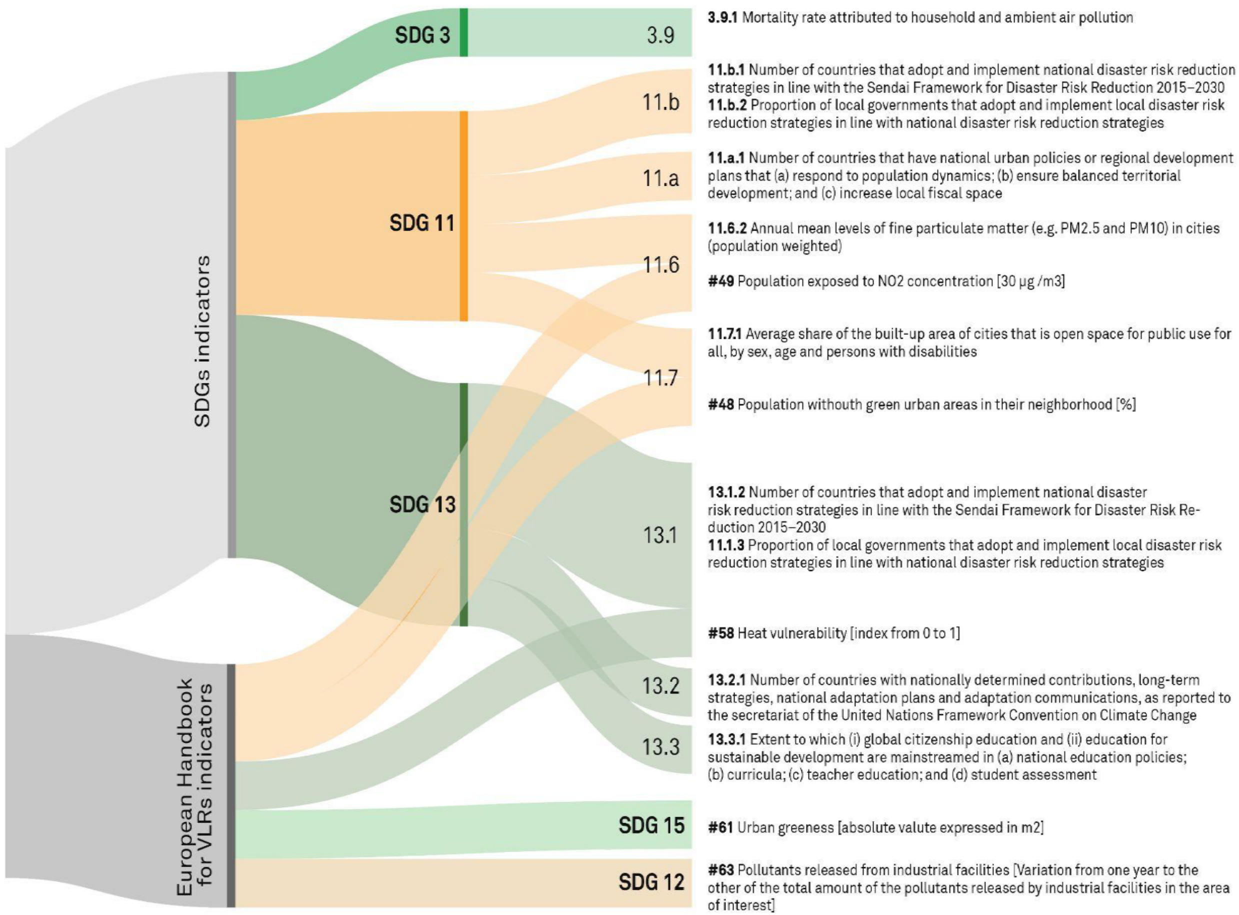
1.3.3 Correlation of climate and microclimate models with SDGs

Climate and microclimate modelling tools could be used to evaluate progress towards the achievement of SDGs or the effects of certain policies and design. The contribution of climate modelling is mainly linked to SDG 13 indicators, where the modelling approaches could be used to assess national policies facing disaster risk mitigation, local strategies for disaster risk reduction strategies, adoption of national adaptation plans, and the communication of risks arising from climate hazards (respectively, indicators 13.1.2, 13.1.3, 13.2.1, 13.3.1) (Trane et al., 2022). The climate models which have the ability to assess air pollution concentration could provide support to indicators 3.9.1 ("Mortality rate attributed to household and ambient air pollution") and 11.6.2 ("Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)") (Trane et al., 2022).

fig. 11 Climate and microclimate models in support of SDGs indicators measurement
source: Trane et al. (2022)

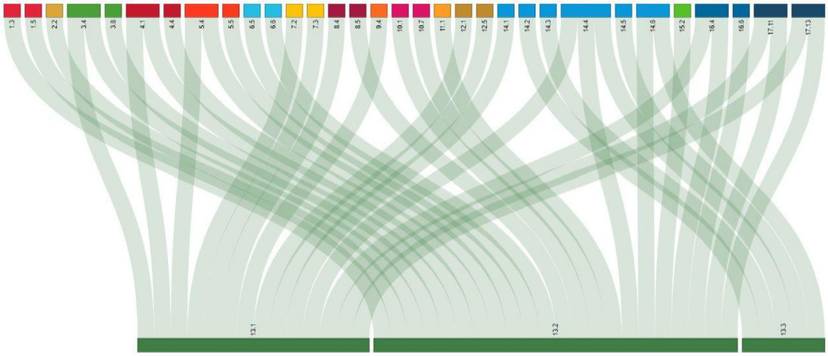
The European Handbook for SDG Voluntary Local Reviews (VLRs) provides a "fundamental instrument to monitor progress and sustain the transformative and inclusive action of local actors towards the achievement of the Sustainable Development Goals" in the specific European context. It contains 71 indicators, each related to one or more SDGs targets. The use of climate models may be effective in evaluation of indicators 49 and 53 (if a pollution concentration module is embedded in the software), 48, 58, 61 (Trane et al., 2022).
The contribution of climate and microclimate models in achieving the SDGs could have great benefits on SDG 11 and SDG 13. However, in order to achieve the SDGs, the

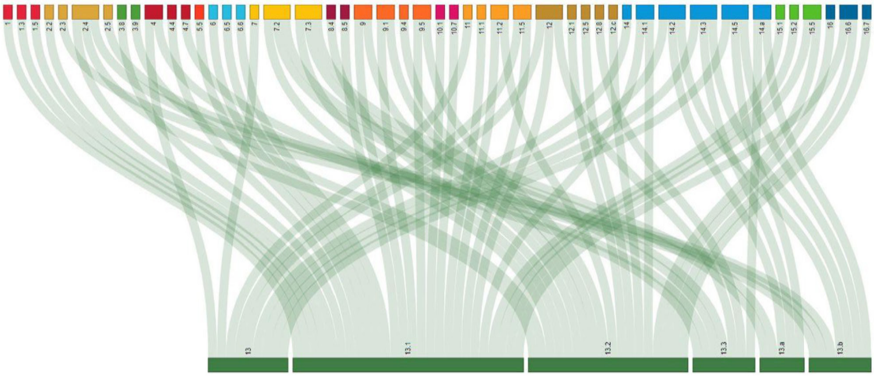
climate and microclimate models

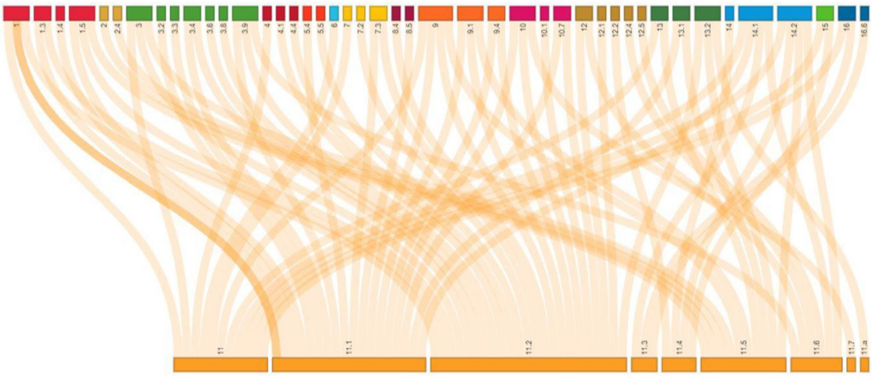


interlinkages and trade-offs among them must be addressed. The progress of the Sustainable Development Agenda depends on the understanding and addressing the interactions between goals and targets (Global Sustainable Development Report 2019). The main challenge is to identify and resolve conflicts (trade-offs) while establishing and enhancing potential synergies (co-benefits) between the 169 targets (Breu et al., 2021). Trane et al. (2022) analysed the interlinkages and trade-offs among the targets mostly supportable by climate and microclimate models and found that there are positive interlinkages and no trade-offs between SDG 11 selected targets and other targets. Positive interactions were found among targets 13.1, 13.2, 13.3 and other targets as well. Target 13.2 has major possible trade-offs, while the target 13.1 has the greatest number of interlinkages. The research has demonstrated that that the targets to which climate modelling may provide support could be achieved independently or providing benefits to other Agenda 2030 targets (Trane et al., 2022).

fig. 12 In orange, the interlinkages among SDG 11 targets and the Agenda 2030. In green, interlinkages (left) and trade-offs (right) among SDG 13 targets and the Agenda 2030 source: Trane et al. (2022)







1.3.4 ENVI-met

The software used for the simulations of microclimatic conditions in this research is ENVI-met. ENVI-met is a 3D microclimate modelling software based on the fundamental laws of fluid dynamics and thermodynamics (Sharmin et al., 2017). It was designed by Michael Bruse in 1994 and has been under constant development and scientific expansion ever since (ENVI-met, 2022). The software uses an urban weather generator to predict the meteorological parameters based on which the most probable weather conditions are created (Bande et al., 2019). It reconstructs the microclimate dynamics of the urban environment through the interaction between climate parameters, vegetation, surfaces and built environment (Bruse & 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 physiologically equivalent temperature (PET), the predicted mean vote (PMV), Universal Thermal Comfort Index (UTCI) and many others (Lobacarro et al., 2021). ENVI-met simulations are based on computational fluid dynamics (CFD) which can solve the problems of wind flows in complex environments. ENVI-met has been used widely in the microclimate research, urban design and thermal comfort studies due to its ability to recreate microclimatic conditions within the urban canopy layer (Ali-Toudert & Mayer, 2007; Krüger et al., 2011; Ng et al., 2012). It is used by architects and urban planners as a decision support tool for designing the microclimate in

terms of mitigation and adaptation measures. The application of the software has been validated through numerous studies under different climate conditions (Lobacarro et al., 2021).
ENVI-met includes also plant physiology and soil science. It can be used to evaluate the effect of green architecture or plants in the urban area on the local microclimate through surface-plant-air interactions (Lauzet et al., 2019). The software takes into account transpiration, evaporation and sensible heat flux from vegetation and air, as well as physical parameters of the plants, water and heat exchange from soil and plant water uptake (Petri et al., 2019).
The software is used for both generating existing microclimate calculations in a precise manner and the analysis of the effects of the future design or planning on the microclimate. It is one of the rare programmes that can be used to explore relationships between urban forms and the microclimate (Sharmin et al., 2017). The particular planning scenario is simulated for particular meteorological conditions, most commonly in the size of a neighbourhood.
The software is grid-based and has high temporal and spatial resolution, allowing accurate microclimate analysis on a street level (Sharmin et al., 2017). The horizontal resolution is typically 1-10 m (ENVI-met, 2022) and it is therefore suitable for small-scale interventions within urban canyons. Typical simulation periods vary from 1 to 5 days. The model area size is commonly between 50x50 and 500x500 grid cells horizontally and 20-50 cells vertically. Due to the complexity of the calculation processes and a fine resolution, the software requires great computational capacity. ENVI-met can be used for microclimate calculations for areas of various sizes, even for meso-scale models. Meso-scale models would have lower accuracy in modelling and calculations due to the coarser grid resolution.

Due to the holistic approach and complexity of the calculations, ENVI-met has certain limitations (Sharmin et al., 2017). As an example, wind velocity and direction are constant throughout the simulation period, although one injected meteorological data about wind speed and direction with 30 minutes timesteps. Due to the selected model for calculating turbulence, the turbulence production is often overestimated in areas with high acceleration or deceleration, especially when air flow is modified by an obstacle (Huttner, 2012). Finally, the computation time – due to the high spatial resolution and holistic approach, is usually high, but this can be partially overcome by reducing the resolution, especially in the z axis. Finally, due to the high spatial resolution and holistic approach, the computation time is usually high but this can be partially overcome by reducing the resolution, especially in the z axis.

2
Best practices

2.1 Design case studies

2.1.1 Clarke Quay

The importance of analysing microclimate conditions on the site may be seen in design solutions. The representative case studies, showing the significance of the analysis are shown.

Project: **Clarke Quay**
Architect: Will Alsop
Location: Singapore
Year: 2006

fig. 13 Photo of the completed project
source: https://www.clouarchitects.com/projects/clarke-quay/

The former centre of commerce in Singapore, Clarke Quay, was developed into Clarke Quay Festival Village in 1993. Further development in 2006 resulted in a more comfortable and weather protected environment. The aim of the project was to regenerate the riverside area and refurbish the existing buildings.

The climate of Singapore is equatorial, it has no true distinct seasons. It is characterized by almost uniform temperature all year round, high atmospheric humidity and abundant rainfall. Combination of high humidity and warm temperature causes some level of discomfort in pedestrians at almost all times.

The most important components of the design strategies implemented were shading and ventilation. An artificial canopy was introduced to balance daylight, shading, view and breeze. It is consists of individual canopies, supported independently of the buildings, and covers almost the entire cross section of the two main streets. ETFE with patterned sections was used as a canopy material.

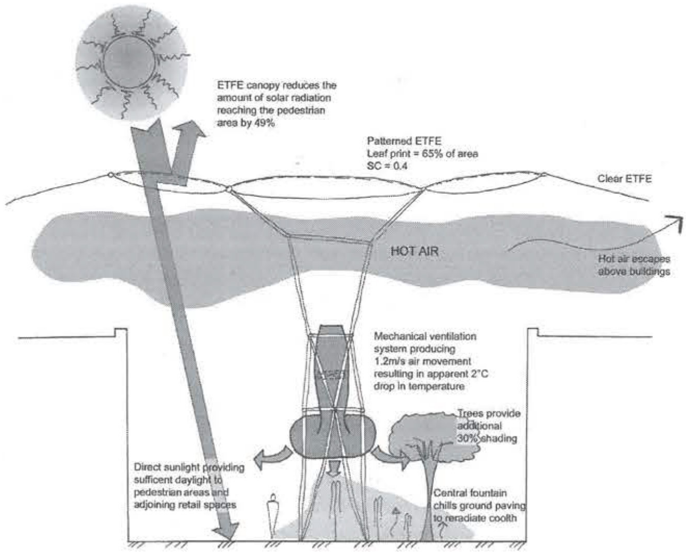


fig. 14 Concept of the microclimatic strategies applied
source: Erell et al., 2011

The canopy projects above roof-top height to allow breezes from the river to permeate the urban streets. This breeze is augmented by air blowers that increase the air movement. The structural support of the canopy incorporates fans into the design to provide a low-energy method of increasing air velocity at the street level.

Trees in the streets are added to enhance the shade and provide cooling through evapotranspiration. The canopy materials were selected to ensure enough light transmission for the vegetation but also to limit the heat gain.

The fountain was designed at the intersections of the two main streets to provide evaporative cooling. The water flows over the paving slabs before being collected, which prolongs the cooling effect.

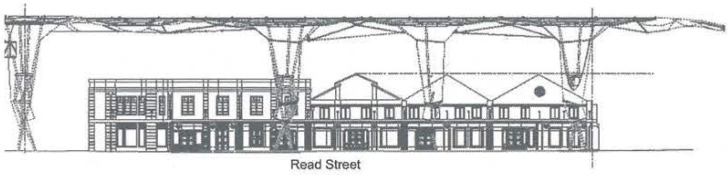


fig. 15 Street section showing canopies projectiong above roof height
source: Erell et al., 2011

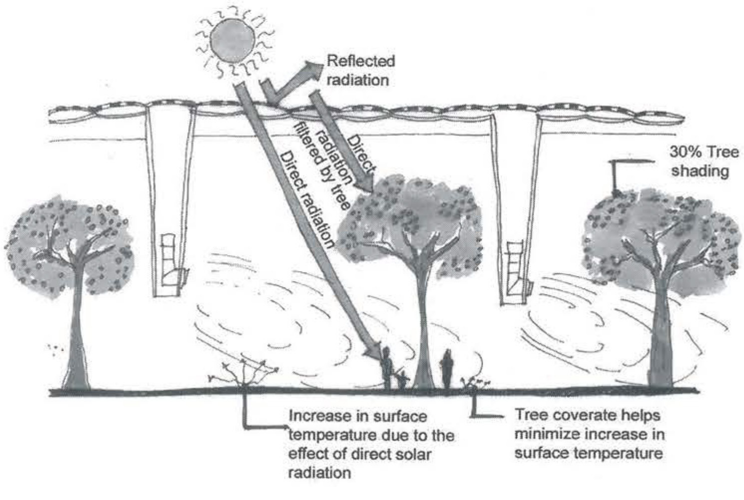


fig. 16 Diagram of the shading strategies
source: Erell et al., 2011

Due to the effects of the canopy and the fans, the thermal comfort in the space was increased - the amount of the most comfortable hours was increased from 41% to 80%. The water fountain reduced the temperature for 1.5 to 2K. The fans designed to work with the wind created a constant light breeze. The air movement helped decrease the temperature for about 2K. As a result of all the applied strategies, the thermal comfort of the pedestrians improved, with the temperature reduction of 3 to 4K.
This space is estimated to be ten times more energy efficient than an equivalent air-conditioned atrium space.
The daylight level was sufficient to provide visual comfort and enough light for the trees, while reducing the need for artificial lighting in the storefronts.
Other environmental impacts of the project include:

- reducing thermal loads (reducing energy need for air conditioning)
- waste management (refurbishing instead of demolishing existing buildings)
- air pollution (low carbon emissions)
- noise pollution (restricted vehicle access, soft surfaces of trees and water elements, open canopy - no noise reflection)

fig. 17 The urban space showing applied strategies
source: https://www.clouarchitects.com/projects/clarke-quay/

2.1.2 Neve Zin

Project: **Neve Zin masterplan**
Architect: Desert Architecture Unit at the Jacob Blaustein Institute
Location: Sde Boqer, Israel
Year: 1984

The project represents a unique masterplan and building regulations aimed at promoting energy-conscious building design and creating an outdoor environment that responds to the local climate.
The neighbourhood consists of 79 single-family detached houses. It is located in the Negev desert in Israel.
The climate is characterized by hot dry summers and cool but sunny winters. Prevailing northwest winds are strong in

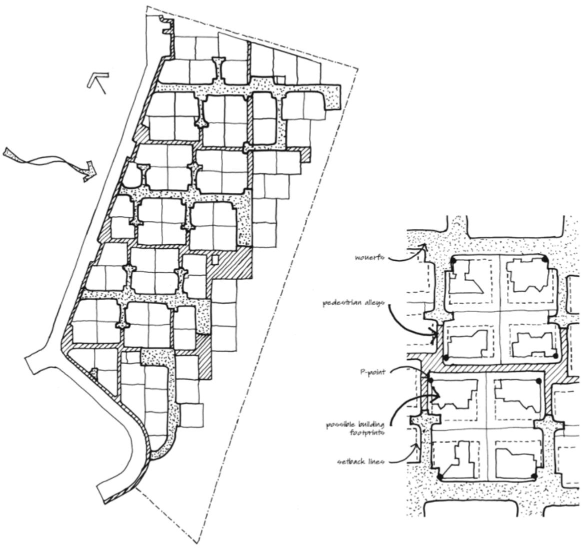


fig. 18 Two circulation systems
source: https://greenvisionstudio.org/4-bundles

fig. 19 Narrow pedestrian passage
source: https://www.bgu.ac.il/CDAUP/neve-zin.htm

summer afternoons and evenings, often carry dust. In winter daytime temperature is comfortable but the nights are cold. There is water deficit due to the high amount of evapotranspiration. Air is typically dry, with low relative humidity in summer.

Circulation is achieved through two networks: pedestrian-only and mixed pedestrian and vehicular (woofnerfs). Woofnerfs are wide enough to ensure that buildings on the south side do not shade the ones on the north in winter. Pedestrian-only paths are narrow, north-south oriented and bounded with 2m high masonry walls on both sides and pergolas at certain points, which provide shade in summer and reduce exposure to cold wind in winter.

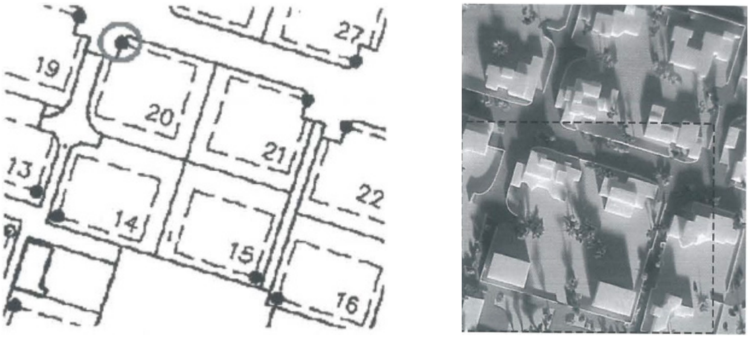


fig. 20 Cluster scheme
source: Erell et al., 2011

Each cluster consists of four plots. Buildings are placed in the outside corner. Adjacent buildings on the north-south axes are separated as far as possible, reducing the obstruction of direct sunlight.
East and west facing walls of the buildings close to the borders of the clusters are placed close to the narrow north-south pedestrian alleys providing shade and protection from the wind. North facing walls help shade east-west oriented roads.
Solar envelope was introduced to define the maximum height of any part of the building in respect to its location on the site. It was presented as an imaginary plane intersecting the southernmost setback line of the plot at a certain angle, limiting height of adjacent building on the south, which guarantees solar exposure in winter for south facades for a certain period of a day.
Most of the public space is covered with brick paving. Greater use of vegetation in this case is unsustainable because it would require additional irrigation. Spaces that are vegetated are confined to small areas and shaded with trees or buildings.

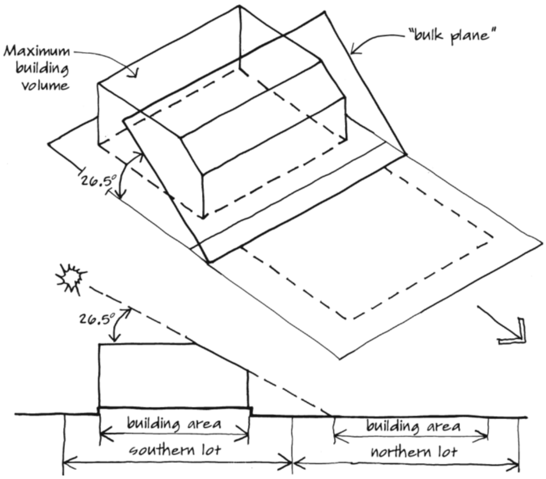


fig. 21 Solar envelope
source: https://greenvisionstudio.org/4-bundles

2.1.3 The Green Corridors in Medellin

Project: **The Green Corridors**
Initiator: City of Medellin
Location: Medellin, Colombia
Year: 2016 - 2019

The project addresses the environmental needs of the city. It was a winner of the 2019 Ashden Award for Cooling by Nature.
As a response to the temperature rise and urban heat island effect, the city of Medellin transformed the verges of 18

fig. 22 Medellin Green Corridors project
source: https://www.leekuanyewworldcityprize.gov.sg/resources/features/medellin-model-city-greater-heights/

roads and 12 waterways, which were previously abandoned and isolated spaces, into green corridors in areas that lacked green spaces.
The Green Corridors project included the planting of trees, shrubs, palms and hedges in a network that connects streams, hills, parks and roads. The corridors provide shade for cyclists and pedestrians, contributes to the cooling of air and reduction of air pollution.
The project connects existing green spaces, improves biodiversity by creating more wildlife-friendly habitats, reduces

fig. 23 Medellin Green Corridors project
source: Cities100 2019 Report

fig. 24 Medellin Green Corridors project cycling paths
source: Cities100 2019 Report

the urban heat island effect, improves air quality and sequesters a significant amount of CO_2 thanks to new vegetation growth.
As a result of the initiative, in the three year period the temperature was reduced for more than 2°C. The further decrease of 4-5°C is expected in the period of 28 years. A single corridor captures around 161K kg of CO_2 annually, during a period of significant plant growth.
Within the project, 75 new gardeners were trained, creating new employment opportunities for people with disadvantaged backgrounds.
"The Green Corridors project demonstrates how integrated, nature-based policies like widespread urban tree planting can have a far-reaching impact on the local and global environment, as well as significantly improving citizens' lives and well-being."

fig. 25 Medellin Green Corridors project
source: https://www.japantimes.co.jp/news/2021/08/01/world/medellin-green-corridors/

2.1.4 Etobicoke Civic Centre

Project: **Etobicoke Civic Centre**
Architects: Henning Larsen, Adamson Associates, PMA-Landscape
Location: Toronto, Canada
Year: 2017 - 2020

fig. 26 Project render
source: https://www.skyfish.com/p/henninglarsenarchitects/etobicokeciviccenter?predicate=created&direction=desc

The Etobicoke Civic Centre includes a range of programmes - municipal offices, community recreation centre, public library, child care centre and outdoor civic plaza. The project consists of squares, courtyards and buildings in different scales, promoting the interaction among the users of the space.
The aim of the project was to give priority to pedestrians, balance transportation and infrastructure, increase the comfort and improve the sense of scale, introduce new facilities, "greenify" the Centre as well as de-isolate and connect the areas around the Centre.
The four guiding principles in the design were mobility, identity, liveability, and sustainability.
Sustainability is reflected in the design, land use, transportation, and landscaping. The importance of environmental sustainability was reinforced by tree planting, the use of low-polluting and recycled materials and a focus on public transportation. Innovative storm water management strategies would relieve pressure on the City's sewage system while also ensuring a healthy tree canopy through storm water reuse.
The architects conducted the microclimate analysis in order

fig. 27 Project render
source: https://www.skyfish.com/p/henninglarsenarchitects/etobicokeciviccenter?predicate=created&direction=desc

to create a comfortable environment for the users, both indoors and outdoors. The research showed that temperatures in Toronto were perceived as too cold for 60 per cent of the year.

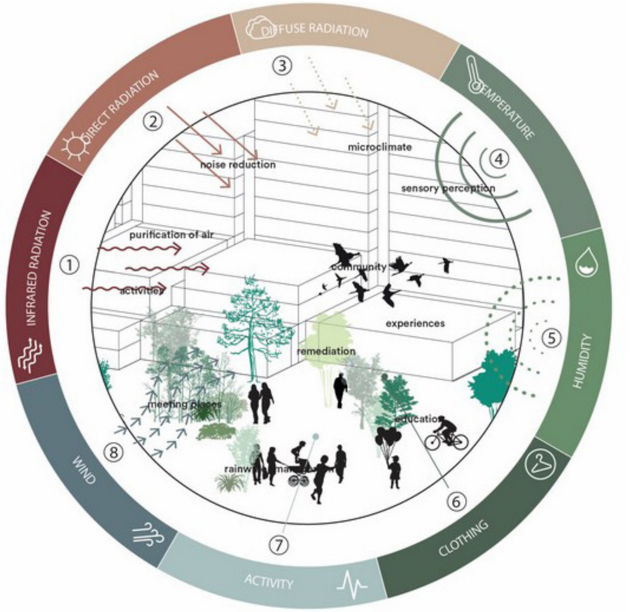


fig. 28 Parameters of outdoor comfort
source: https://www.re-thinkingthefuture.com/rtfsa2017-public-building-concept/etobicoke-civic-center-henning-larsen-adamson-associates-architects-usa/

The architects considered eight parameters of the outdoor thermal comfort for the microclimate mitigation strategies.
The buildings block out cold wind flows and drive them upwards along the structure. The wind is directed by the towers' orientation and the way they gradually grow upwards. This provides wind protection in the open square and on the rooftop terraces. The structure's orientation allows the square and all of the terraces to be exposed to sunlight throughout the day, while the towers provide the most suitable shade to each other.
The use of various design strategies enabled the architects to prolong the comfortable outdoor season by five weeks.

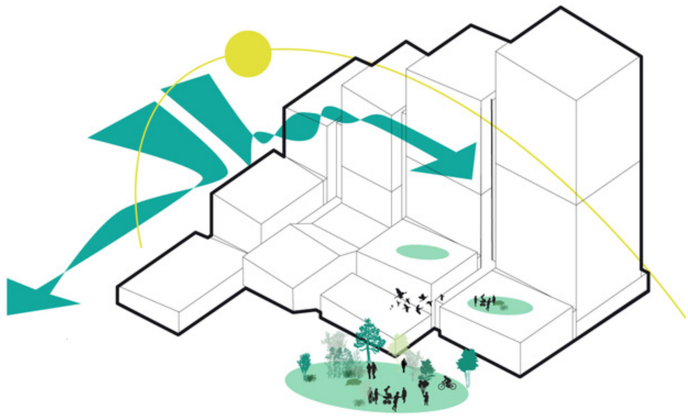


fig. 29 Using masses to create comfortable micro-climate
source: https://www.re-thinkingthefuture.com/rtfsa2017-public-building-concept/etobicoke-civic-center-henning-larsen-adamson-associates-architects-usa/

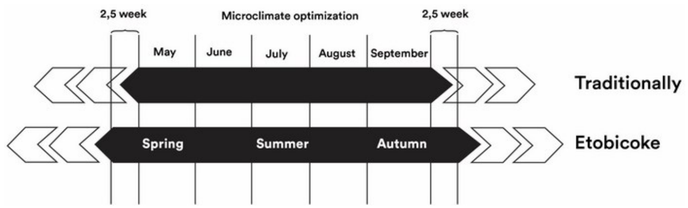


fig. 30 Extending comfortable period
source: https://www.re-thinkingthefuture.com/rtfsa2017-public-building-concept/etobicoke-civic-center-henning-larsen-adamson-associates-architects-usa/

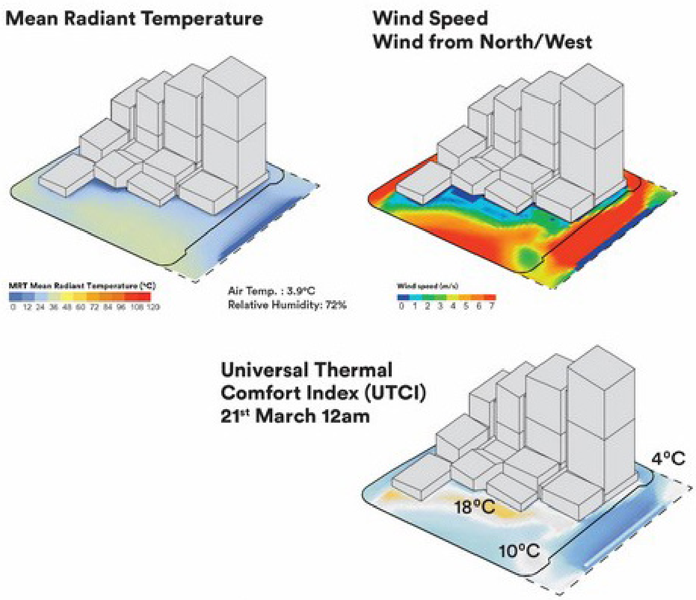


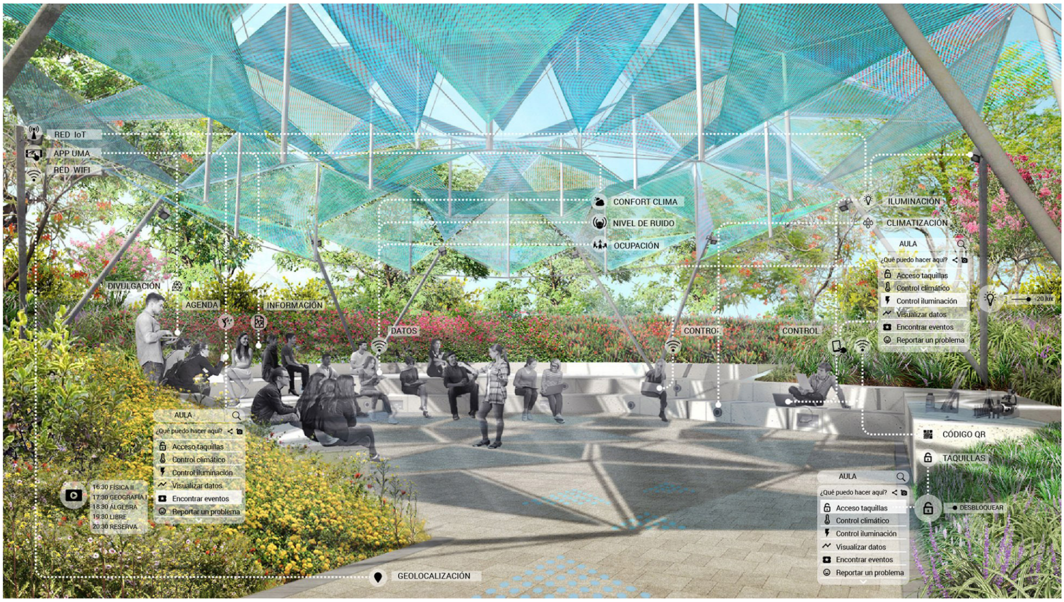
fig. 31 Microclimate simulations' results
source: https://www.re-thinkingthefuture.com/rtfsa2017-public-building-concept/etobicoke-civic-center-henning-larsen-adamson-associates-architects-usa/

2.1.5 Malaga University Campus

Project: **Malaga University Campus**
Architects: Ecosistema Urbano
Location: Malaga, Spain
Year: 2017 - ongoing

The project provides an open campus with comfortable natural environment which incorporates new technology, provoking interaction between the physical and digital environments. The goal of the proposal is to enable the university activities to take place in public spaces while also providing a new green infrastructure for the city.

fig. 32 Open classroom render
source: https://www.metalocus.es/en/news/malaga-university-campus-a-new-natural-and-digital-environment-ecosistema-urbano



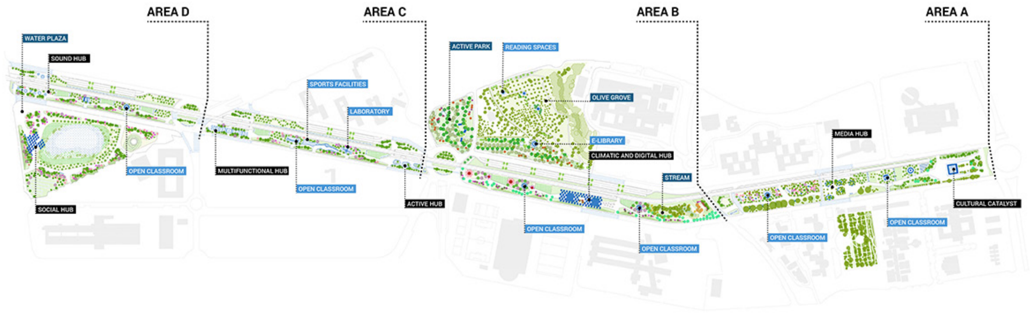


fig. 33 Masterplan
source: https://ecosistemaurbano.com/malaga-university-campus/

One of the most important aspects of the project is the use of technology to improve people's interaction with the environment. It will be the first public space that users can control through an application. The design implements four different strategies: connected, green, interactive and open campus.

The urban layout is created through the connections of different facilities and opening the campus to its surroundings and the whole city, with the focus on public transportation and pedestrian areas. The green route is established by recovering and enhancing the existing green spaces, through a global strategy of sustainable management.

Due to the technology involved, the users can interact with various aspects of the public space and adapt them to their needs, including the configuration of the bioclimatic conditioning systems to achieve optimal environmental conditions. The project provides access for university students and other residents to a wide range of educational meeting venues and devices, bringing academic activity into the public realm and making it more accessible and dynamic.

The project uses a network of sensors and actuators to provide a new level of interactivity by allowing people to control bioclimatic conditioning systems, change lighting settings, send audio-visual content to screens and sound systems,

know the atmospheric conditions of the spaces in each area of the park or events scheduled, share comments or photos associated with specific spaces, unlock lockers to gain access to extra equipment, and check out books in the university library outdoor extension.
Technology has a significant impact on the project's environmental conditions as well. Bioclimatic conditioning technologies, such as evaporative cooling or geothermal air circulation, have been installed to increase the comfort of the main outdoor spaces. All of these devices require little energy and are powered by solar panels incorporated into the new structures. These systems, in combination with the passive bioclimatic strategies implemented, will encourage the use of the space all year-round.
Artificial topographies covered in vegetation protect the main path from traffic, generating different landscapes that enhance the character of the empty suburban environment.

fig. 35 Diagrams of technology uses
source: https://ecosistemaurbano.com/malaga-university-campus/

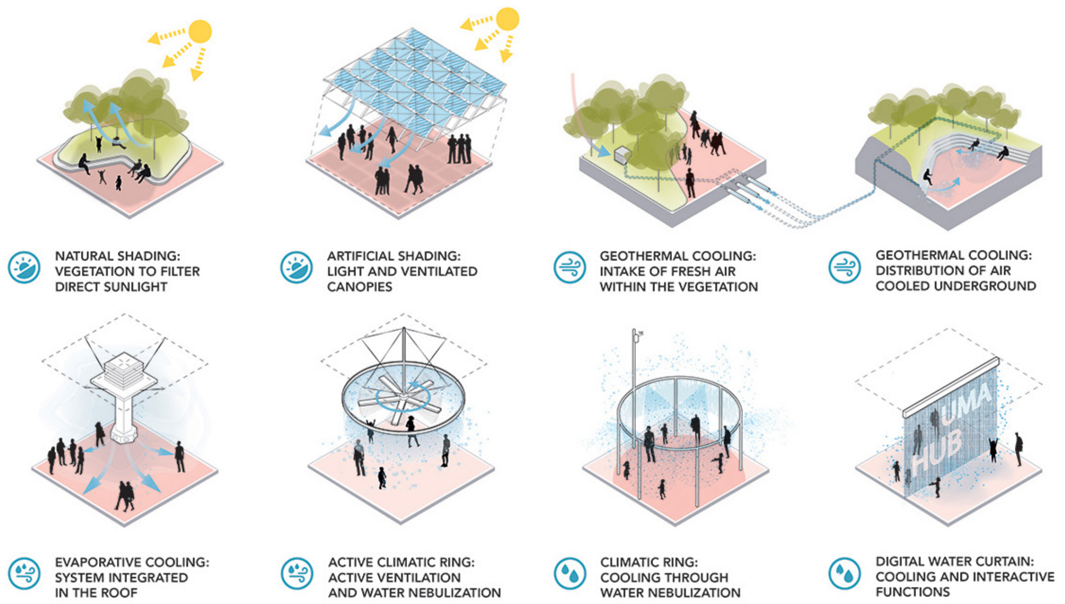
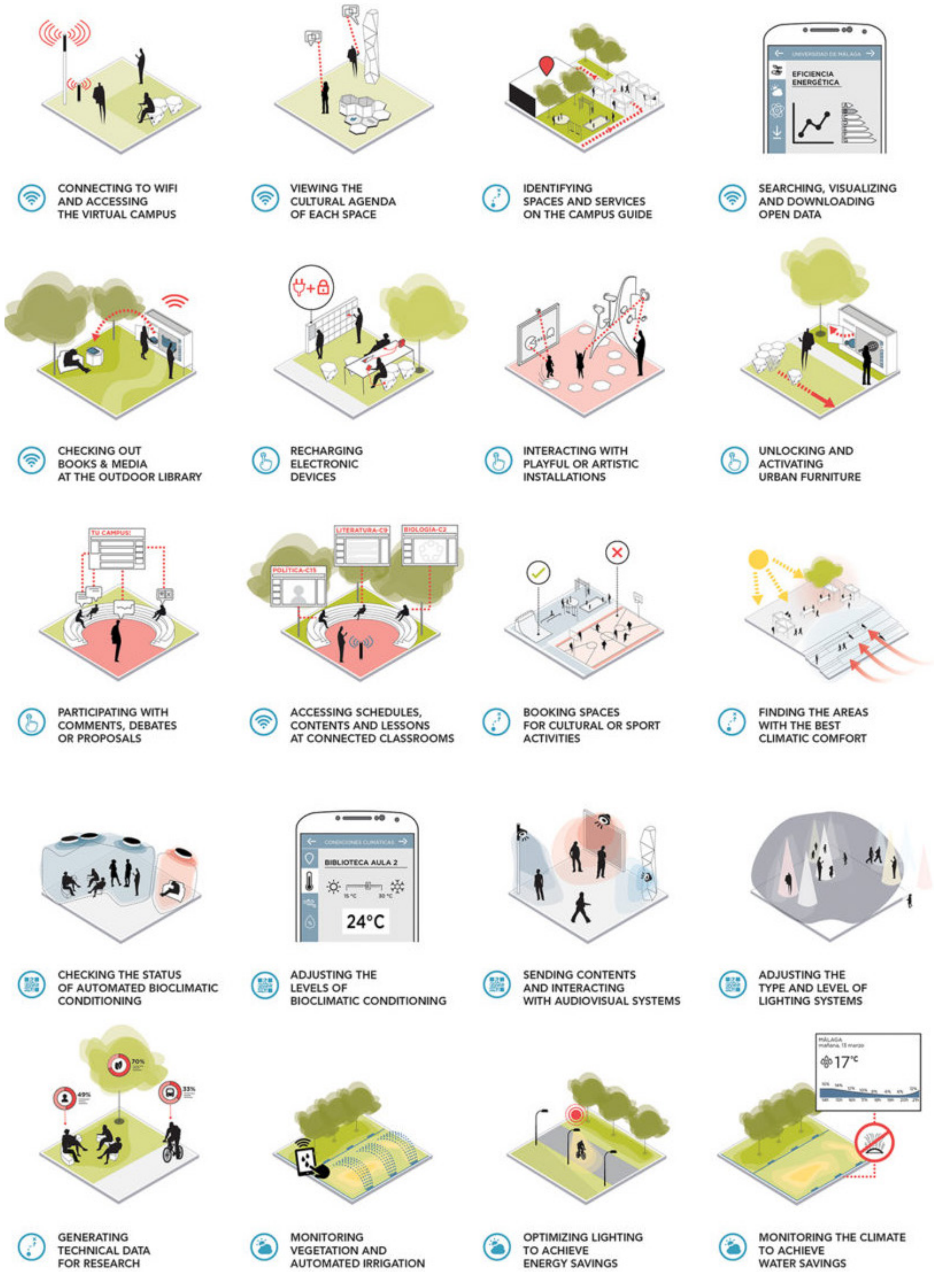
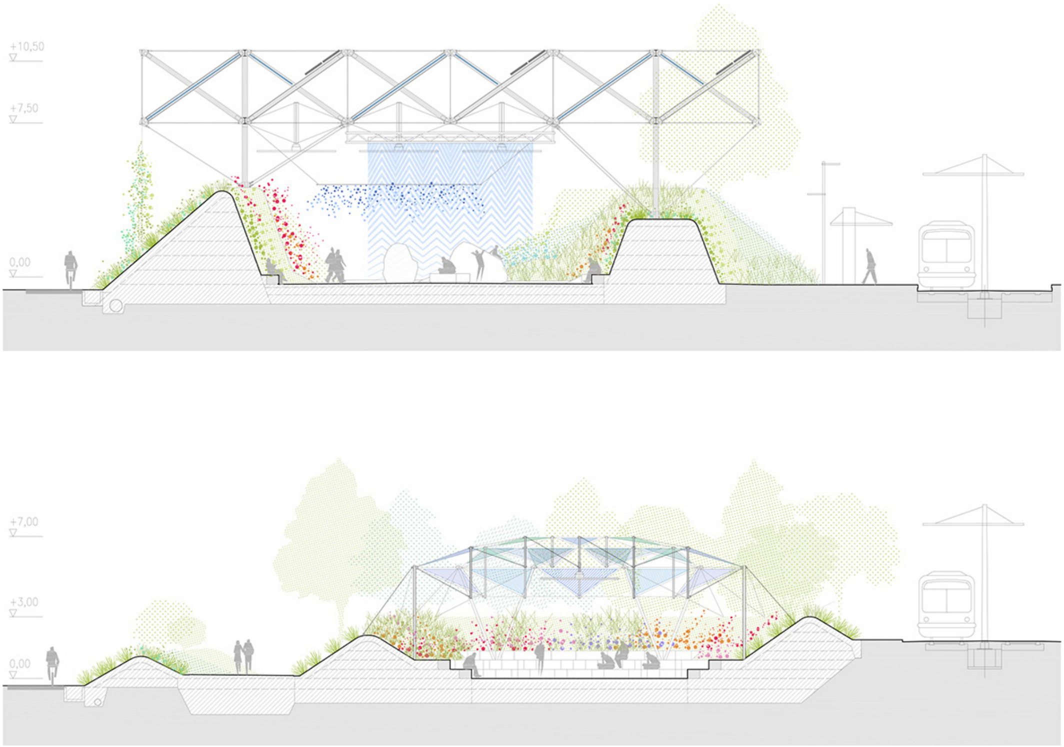


fig. 34 Diagrams of microclimate strategies
source: https://ecosistemaurbano.com/malaga-university-campus/


EFICIENCIA ENERGÉTICA
CONNECTING TO WIFI AND ACCESSING THE VIRTUAL CAMPUS
VIEWING THE CULTURAL AGENDA OF EACH SPACE
IDENTIFYING SPACES AND SERVICES ON THE CAMPUS GUIDE
SEARCHING, VISUALIZING AND DOWNLOADING OPEN DATA
CHECKING OUT BOOKS & MEDIA AT THE OUTDOOR LIBRARY
RECHARGING ELECTRONIC DEVICES
INTERACTING WITH PLAYFUL OR ARTISTIC INSTALLATIONS
UNLOCKING AND ACTIVATING URBAN FURNITURE
TU CAMPUS!
LITERATURA-C9
BIOLOGÍA-C2
POLÍTICA-C15
PARTICIPATING WITH COMMENTS, DEBATES OR PROPOSALS
ACCESSING SCHEDULES, CONTENTS AND LESSONS AT CONNECTED CLASSROOMS
BOOKING SPACES FOR CULTURAL OR SPORT ACTIVITIES
FINDING THE AREAS WITH THE BEST CLIMATIC COMFORT
BIBLIOTECA AULA 2
24°C
CHECKING THE STATUS OF AUTOMATED BIOCLIMATIC CONDITIONING
ADJUSTING THE LEVELS OF BIOCLIMATIC CONDITIONING
SENDING CONTENTS AND INTERACTING WITH AUDIOVISUAL SYSTEMS
ADJUSTING THE TYPE AND LEVEL OF LIGHTING SYSTEMS
70%
49%
33%
17°C
GENERATING TECHNICAL DATA FOR RESEARCH
MONITORING VEGETATION AND AUTOMATED IRRIGATION
OPTIMIZING LIGHTING TO ACHIEVE ENERGY SAVINGS
MONITORING THE CLIMATE TO ACHIEVE WATER SAVINGS

Bioclimatic conditioning is enabled due to these new landscapes, which generate enclosed and protected spaces.
By reducing runoff, building a network of infiltration zones and planting low-water-consumption species, the project aims to regulate water circulation in a more sustainable and effective manner. The area along the Stream is cleaned and re-naturalized, by introducing new vegetation that restricts soil erosion, establishing water collection systems and infiltration areas, promoting biodiversity and managing resources more efficiently.

fig. 36 Hub and classroom sections
source: https://ecosistemaurbano.com/malaga-university-campus/



2.1.6 Prato Urban Jungle

Project: **Prato Urban Jungle**
Architects: Stefano Boeri Architects, Pnat
Location: Prato, Italy
Year: 2019 - ongoing

The Prato Urban Jungle project aims to transform the marginal districts of Prato into high-density green areas that help reduce air pollution and promote well-being and social activities. The designing process includes participation of the citizens through digital platforms, in order to increase inclusiveness and promote sustainable development.
The two main objectives are: the repurposing of buildings and spaces to new, more innovative and sustainable uses in the regeneration of abandoned and deteriorating urban areas, and establishing community green hubs, with open spaces, social areas and cultural centres, producing the high-density green islands with the facilities for environmental, sport, cultural and social uses.
Urban Jungles represent high-densely green re-designed areas embedded in the urban fabric that amplify plants' ability to absorb pollutants while restoring underutilized soil and space to communal fulfilment, transforming marginal and decadent areas into green active hubs.
Urban Jungles are developed in four areas:

1. In a company-owned area - the ESTRA building and surroundings located in a complex area, overlooking the busiest thoroughfare.
2. A highly populated and social housing area, with social marginality - a complex building with 152 dwellings in-

habited by around 500 people
3. Macrolotto 0, a former industrial area with underutilized space - area close to the Macrolotto Creative District and the new metropolitan market.
4. Farm Park at Via delle Pleiadi

The design, development and maintenance of the Urban Jungles involves a participatory process from the community, by creating Green Hubs and innovative communities of stakeholders, citizens, businesses, civil society actors that mobilise the urban creativity and resources to nurture the Urban Jungles.

The project includes:

- the transformation of yards, roofs, buildings, walls, and barriers into green elements;
- the redevelopment of abandoned industrial grounds and surfaces into green gardens with greater permeable and green surfaces, enhanced soil fertility by increasing soil organic matter by de-sealing and the addition of biochar and microbial species;
- increased soil biodiversity and carbon sequestration through higher presence of vegetation, and pollution reduction through increased presence of leaves, branches;
- improved microclimatic wellness through shadowing, evaporative cooling and altering the radiative properties of the soil;
- a network of vegetable spots that ensure higher benefits to citizens and increased education towards green ownership, awareness and care, and the promotion of more environmental-friendly behaviours through gamification activities;
- an enhanced community ownership of gardens and urban green by citizens, enterprises, stakeholders, together with - a governance model for replicating urban jungles, green buildings and vertical forests.

1. Consiag-Estra headquarters, Stefano Boeri Architects, 2019

The redevelopment project of this area focuses on the existing elements - the four facades, the roof and outdoor parking. The construction of an Urban Forest mitigates the impact of the high-traffic avenue in front of the building.
In the external parking area the intervention includes a partial demineralization of the soil and creation of parking spaces dedicated to sustainable mobility. The vegetation on the facades differs based on their orientation and exposure to the sunlight. The chosen species are native, with the aim of removing air pollution and CO2 and attracting pollinating insects. The roof is divided into parts that host the species which attract the pollinating insects and provides a meeting space for the employees. The project promotes the use of leading-edge irrigation and rainwater collection systems.

fig. 37 Project render
source: https://www.stefanoboeriarchitetti.net/en/project/prato-urban-jungle/

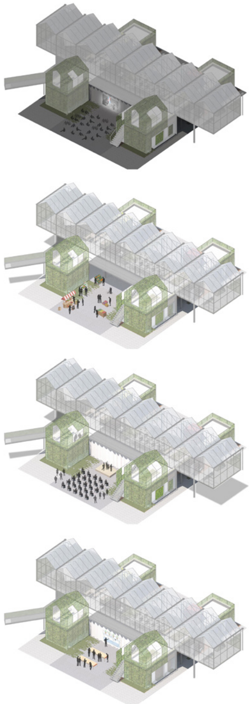
2. Via Turchia Urban Farming, Stefano Boeri Architects, Pnat, 2020

Stefano Boeri Architects designed the intervention on the building facades. The facade surfaces are covered in vegetation, supported by the steel cables which allow the growth of the climbing plants and the creation of the green sunscreen systems on the south-facing facades. This intervention helps mitigate the microclimate and improve the well-being of the residents. The vegetation is mainly irrigated with recovered rainwater.

fig. 38 Social housing render
source: https://www.pratourbanjungle.it/en/prato-urban-jungle/siti-pilota/quartiere-san-giusto/pagina2000.html

Between the buildings, Pnat architects designed an innovative greenhouse for growing vegetables, which generates both the local economy and community life. The greenhouse is easily accessible to the inhabitants, it is located in the square between the high-density buildings and provides spaces for community gathering, buying and selling vegetables and promoting sustainable agriculture. The design is based on hydroponics and rainwater reuse technologies in order to ensure the sustainable production of large quantities of vegetables.

fig. 39 Greenhouse render
source: https://www.pnat.net/works/prato-urban-jungle-via-turchia-urban-farming/



The management of the greenhouse should be the responsibility of the residents association, who would benefit from the training course, learning practices and technologies of cultivation. The marketing would provide the income for the workers and maintenance of the facilities.
The redeveloped courtyard with the greenhouse is a place for social interaction, enabling the neighbourhood to generate food, work, training and income for the community.

fig. 40 Multifunctional space
source: https://www.pnat.net/works/prato-urban-jungle-via-turchia-urban-farming/

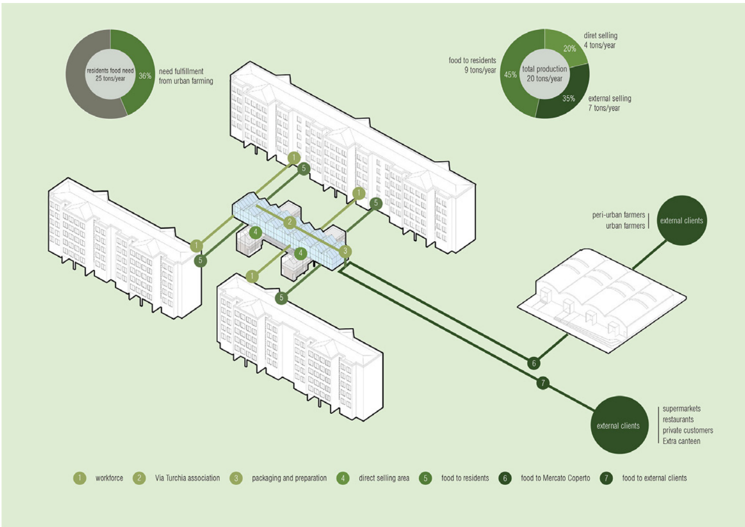


fig. 41 Food distribution scheme
source: https://www.pnat.net/works/prato-urban-jungle-via-turchia-urban-farming/

3. Macrolotto 0 Covered Market, Pnat, 2020

The architects transformed an industrial building into a covered market where the sale and consumption of local agricultural products would occur. The project includes a range of plant based solutions, which contribute to the microclimate regulation, temperature mitigation, air quality, thermal and acoustic insulation and rainwater regulation.
The proposal outside of the market building creates a relaxation and meeting space at the entrance square through the green facade and street furniture with dual function of seating and planting pots, with low-maintenance technologies. Aside from the market function, the interior space also hosts an indoor greenhouse for preparation and consumption of food.
The Indoor Jungle includes the construction of various botanical purification devices and systems with the combination of strategies that allow to remove and degrade most of the contaminants present within the space, through active and passive filtration. That allows the entire building to benefit from a healthy and comfortable nature-immersed environment.

fig. 42 Exterior market render
source: https://www.pnat.net/works/prato-urban-jungle-macrolotto-0-covered-market/

fig. 43 Concept diagram
source: https://www.pnat.net/works/prato-urban-jungle-macrolotto-0-covered-market/

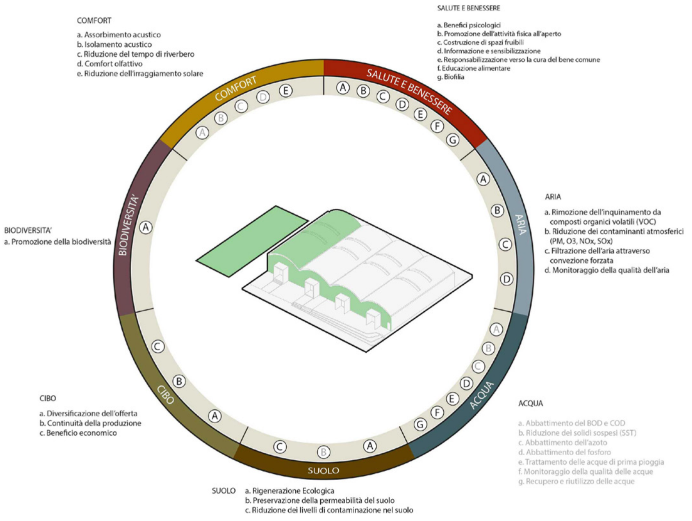


fig. 44 Market axonometry showing main elements
source: https://www.pnat.net/works/prato-urban-jungle-macrolotto-0-covered-market/

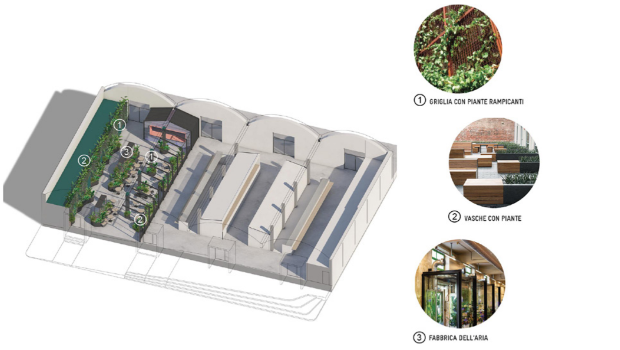
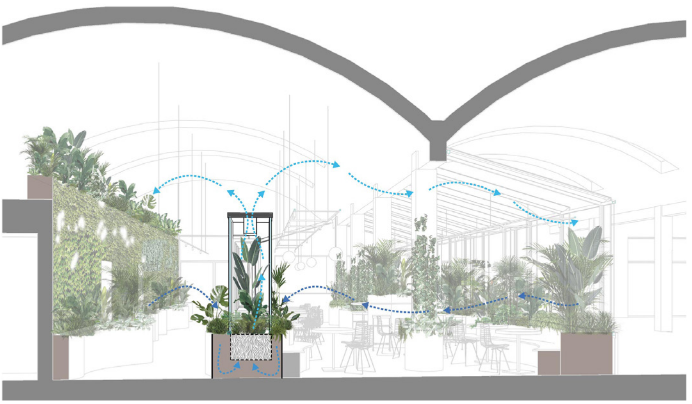


fig. 45 Section showing indoor air purification strategies
source: https://www.pnat.net/works/prato-urban-jungle-macrolotto-0-covered-market/



4. Farm Park, Pnat, 2021

The project consists of several parts: an urban greenhouse for the plant production, a vegetable garden with aromatic and floral plants that increase the presence of pollinators and the biodiversity, a refreshment area with industrial containers for the administration of locally produced food and drinks and an area for children.
The intervention includes the planting of a large number of plants and trees that help purify air and regulate the microclimate, which contributes to the environmental, visual and thermal comfort of the space. With the participation of the Municipality and the associations, the project should gradually involve the whole park. The project is aimed at generating local economy while promoting social interaction and the activities within the community.

fig. 46 Project axonometry
source: https://www.pnat.net/works/prato-urban-jungle-farm-park/

fig. 47 Schemes of the urban transformation and connectivity
source: https://www.pnat.net/works/prato-urban-jungle-farm-park/

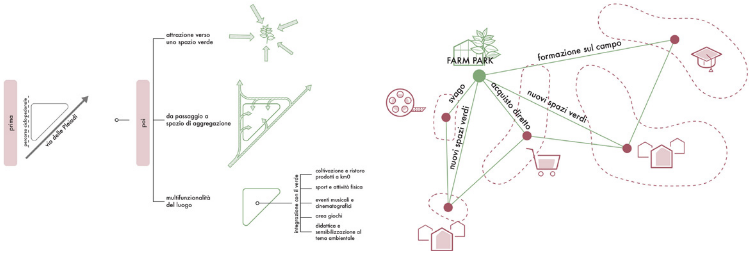
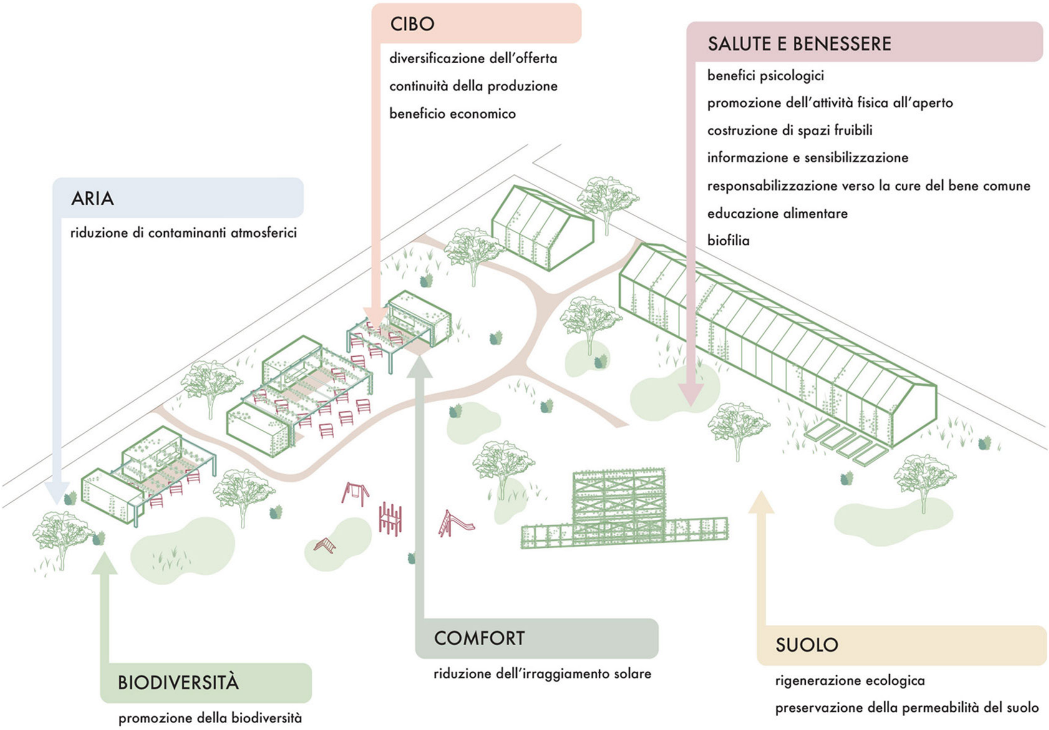


fig. 48 Functional scheme
source: https://www.pnat.net/works/prato-urban-jungle-farm-park/

The technologies of hydroponic cultivation and reuse of rainwater enable the sustainable production of large quantities of vegetables. The greenhouse also has an educational function, where the citizens could learn about the cultivation practices and technologies. The project therefore promotes the food education, sustainable agriculture and ecology.



Outcomes of the overall project Prato Urban Jungle:

- 65% of the municipal area of Prato covered from vegetation
- 29,151 registered trees, with a leaf area of about 388 hectares, generating economic benefits equivalent to 439,000 Euro per year
- 3.715 Kg per year of atmospheric pollutants removed by trees, equivalent to an economic benefit of Euro 224,500 per year
- 2.010 MWh of energy savings equivalent to an economic benefit of Euro 191,000 per year
- 7.900 m3 of meteoric water intercepted equivalent to an economic benefit of Euro 15,000 per year.

fig. 49 Ştreet view render in via Turchia
source: https://www.stefanoboeriarchitetti.net/en/project/prato-urban-jungle/

2.2 Research case studies

2.2.1 Courtyards in the Netherlands

Research paper: **Heat in courtyards: A validated and calibrated parametric study of heat mitigation strategies for urban courtyards in the Netherlands**
Authors: Mohammad Taleghani, Martin Tenpierik, Andy van den Dobbelsteen, David J. Sailor
Published in: Solar Energy, vol. 103
Year: 2014

The study examines the effect of different microclimate mitigation strategies in the urban courtyards of different shapes, dimensions and orientation through five phases.

Phase 1: Reference study
ENVI-met simulations for the hottest reference day in the Netherlands were performed on 18 courtyards of different orientations and dimensions, with the buildings' height of 9m. The models vary in length and width from 10 to 50m with steps of 10m and have four main orientations, N-S, E-W, NW-SE, NE-SW (fig x).
Phase 2: The climate of 2050
Three reference models were considered for the severest scenario for the Netherlands in 2050: +2°C, changed air circulation.
Air temperature has a low effect on the mean radiant temperature, therefore the MRT is only slightly higher in 2050. However, air temperature increases by 3°C in the 2050 climate scenario.

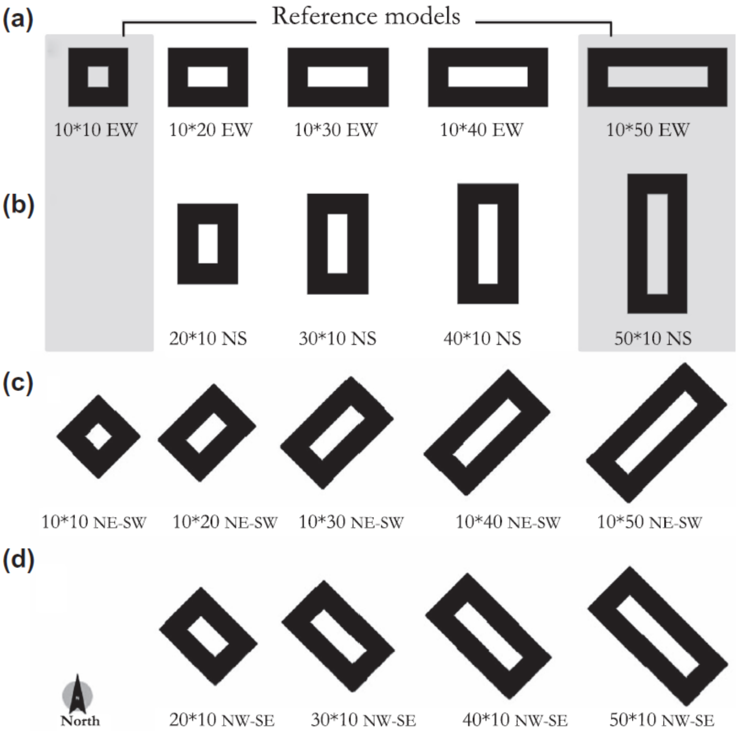


fig. 50 Overview of the basic models for the parametric study, with the reference models used in phases 2–5 highlighted in grey
source: Taleghani et al., 2014

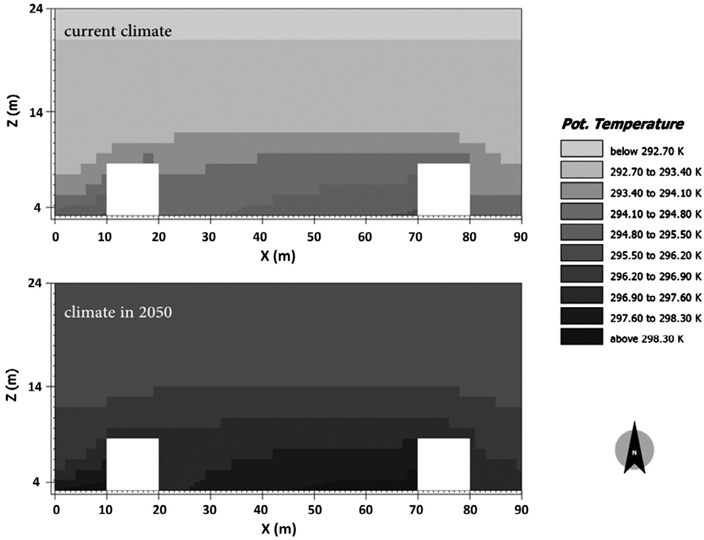


fig. 51 Comparison of air temperature (potential temperature) of the 10 * 50 m^2 EW model in the current climate and in 2050 (on 19 June at 16:00).
source: Taleghani et al., 2014

Phase 3: The albedo effect

In the first two phases, the albedo of the facades was 0.10 (dark brick), while in this phase, the albedo was changed to 0.55 (white marble) and 0.93 (highly reflective plaster). The MRT increased due to the reflections of the surfaces.

Phase 4: The effect of water

The water pool was embedded on the ground inside the courtyard, covering 65% of the area. MRT in this case was lower due to the position of the pools, which causes upwards reflectance, heat capacity of water and evaporation.

Phase 5: The effect of vegetation

In this phase, the ground of the courtyard and the roofs of the blocks were covered with grass. MRT was reduced due to the evapotranspiration as well as grass layer as a protection of the soil.

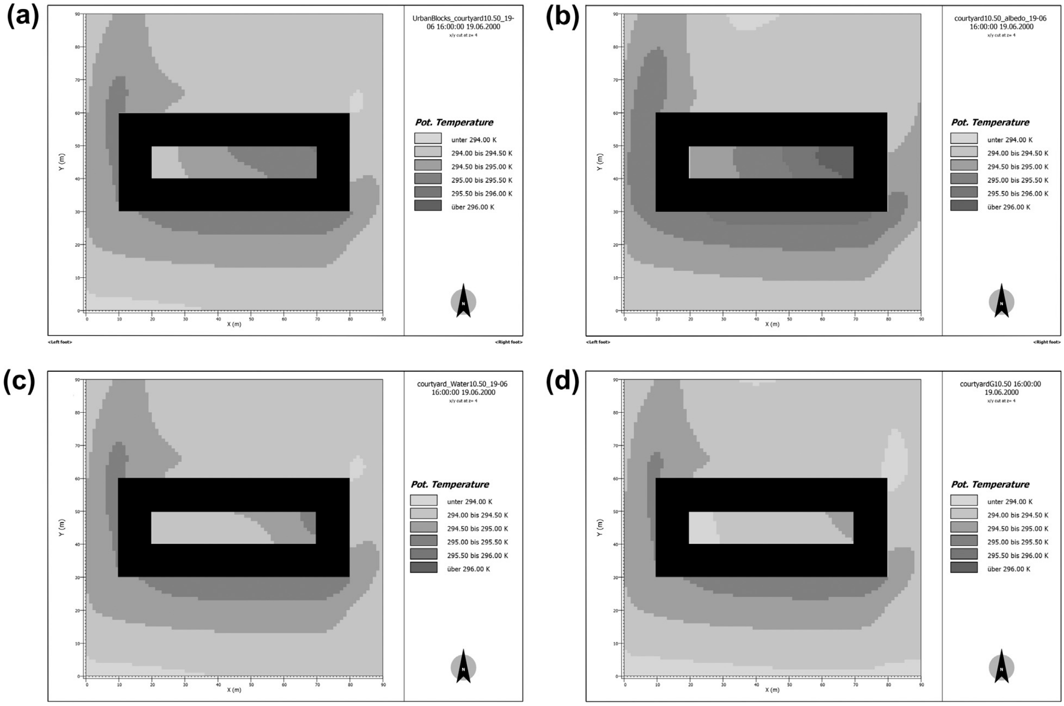


fig. 52 Air temperature of the 10 * 50 m^2 EW courtyard model in different phases of the study: (a) basic study, (b) using high albedo facades, (c) using water pool, and (d) using grass
source: Taleghani et al., 2014

Conclusions:
The courtyard orientation:

- N-S - suitable for hot climates
- E-W preferred in colder regions
- NW-SE - in areas with cold nights, where early morning sun is desired
- NE-SW - best forcold climates, spaces for afternoon activities

High albedo of the facades leads to a higher MRT due to multiple reflections. Water body inside the courtyard, as well as presence of vegetation, strongly reduces the MRT, which this research suggests as the most effective mitigation strategies for the microclimate of the courtyards in the Netherlands.

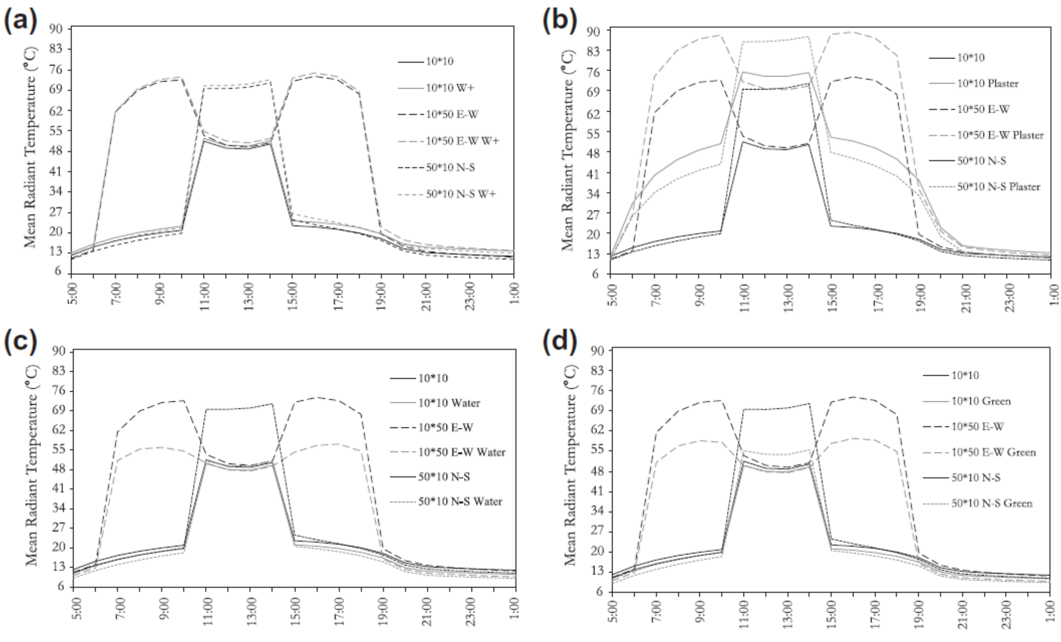


fig. 53 Mean radiant temperature of reference models in comparison with: (a) the 2050 climate scenario; (b) higher albedo of plaster; (c) courtyards with a water pool; and (d) courtyards with a green area
source: Taleghani et al., 2014

2.2.2 Ex Mercati Generalli in Rome

Research paper: **Thermal impact of a redeveloped area on localized urban microclimate: A case study in Rome**
Authors: Gabriele Battista, Emiliano Carnielo, Roberto De Lieto Vollaro
Published in: Energy and Buildings, vol. 133
Year: 2016

The aim of the case study is to examine the impact of the new built areas on the microclimate and possible mitigation measures for the area to be developed. It consists of two parts: monitoring campaign and numerical analysis.
In the monitoring campaign the measurements were conducted in order to collect the microclimate data from the site. The data is used for the validation of the micro-scale models used in the numerical analysis.
The numerical analysis consisted of three steps:

1. model based on the current conditions of the area, but the input parameters were changed in order to match the data from the monitoring campaign (ante-operam)
2. 3D model recreates the future redeveloped scenario (post-operam)
3. a new configuration - an alternative version of the previous model, cool materials and vegetation added (final-post-operam)

The site is located at "Ex Mercati Generalli", in the southern part of Rome. It is composed by 13 historical buildings with a height up to 8m. The area currently mainly consists of rubble, sandy soil and spontaneous vegetation. It is a residential

zone, surrounded with prevalent typology of high rise buildings. It is characterized by large urban voids, mainly covered in asphalt.
In the microclimatic measurement campaign four weather

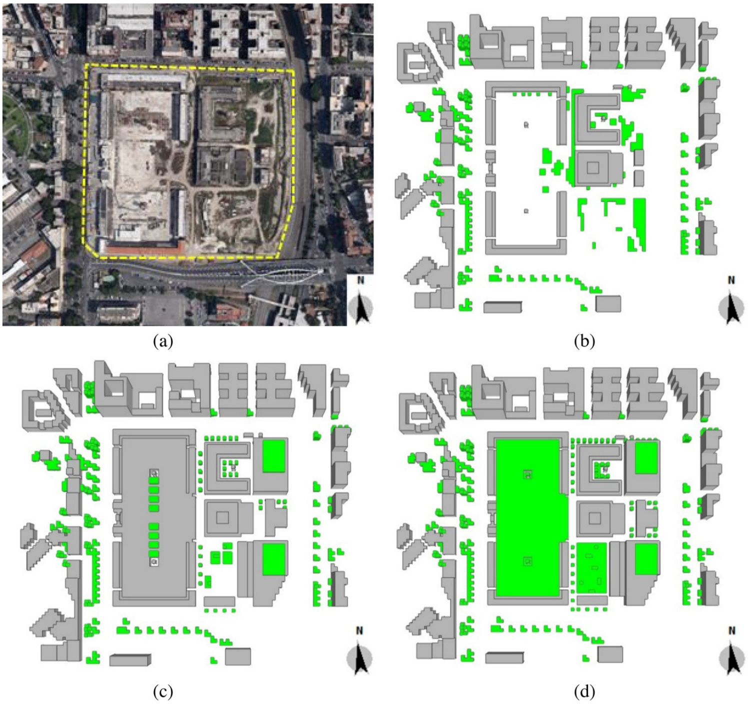


fig. 54 Micro-scale models: (a) "ex Mercati Generali" aerial view; (b) ante-operam; (c) post-operam; (d) final-post-operam
source: Battista et al., 2016

parameters were measured: outdoor temperature, wind velocity, relative humidity and intensity of solar radiation on the horizontal plane.
The ENVI-met analysis shows:

- the increase in the built surfaces can significantly raise the air temperature in the domain
- the use of cool materials on vertical and horizontal surfaces confirms to be an effective mitigation strategy
- despite the mitigation strategies, the ante-operam temperatures are still lower than the final-post-operam ones

In post-operam scenario maximum increase in temperatures

fig. 55 Thermal map of the area on July 16th at 12:00 AM 1.5 m height: (a) ante-operam model; (b) post-operam model; (c) final-post-operam model
source: Battista et al., 2016

is registered at low heights - under the canopy, close to the ground, which implies that the new structures worsen the conditions.

In the final-post-operam scenario decrease of temperature occurs mostly under the canopy, providing the greater benefits both under the canopy and over it.

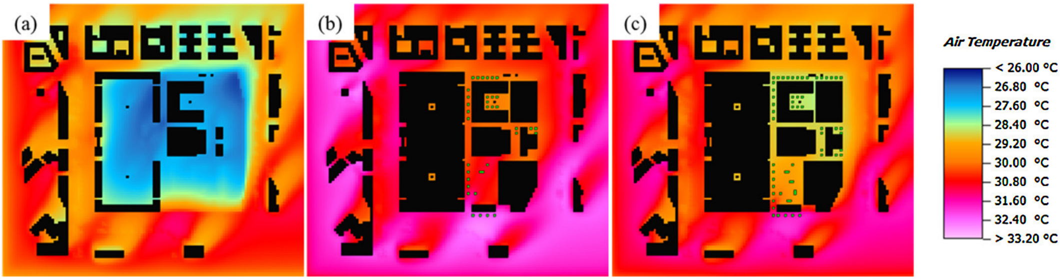
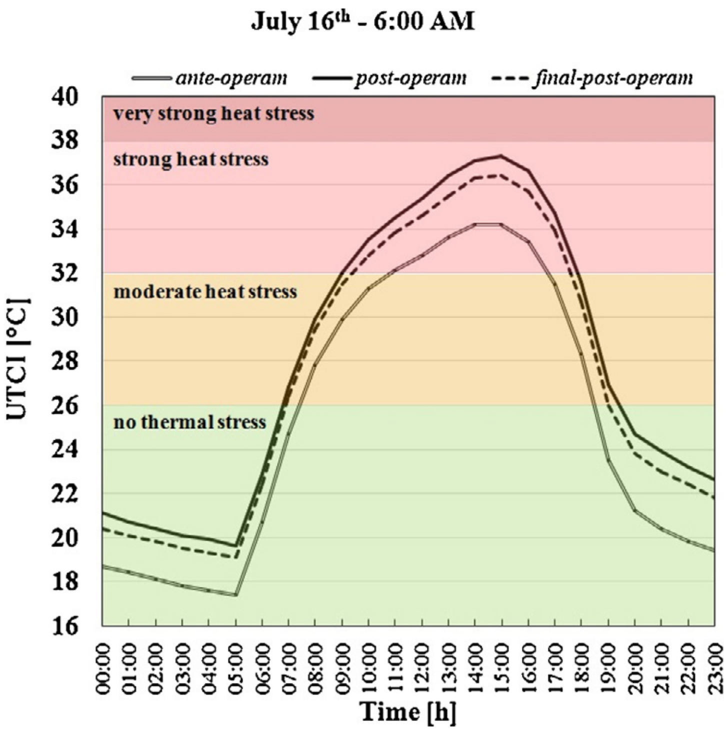


fig. 56 Universal Thermal Climate Index (UTCI) in the investigation point on July 16th
source: Battista et al., 2016



The outdoor thermal comfort was estimated using RayMan software. Thermal stress was assessed with a 10 point scale. The analysis was conducted for the same point as the vertical temperature. The UTCI permanence within the "no thermal stress" category is similar for all the models considered. The implementation of the mitigation strategies assessed in this case study shows a decrease of the UTCI value of about 1°C.

Conclusions:
The thermal analysis carried out with ENVI-met demonstrates the increase in temperature with the new built intervention by 3.5°C. The application of cool materials and vegetation as UHI mitigation measures leads to a decrease in temperature by 2°C in comparison with the post-operam scenario.
The increase in built surface mostly affects the microclimate conditions under the average height of buildings, but also affect the surrounding area.
The UTCI differences between the three models were more significant in the "strong heat stress" category, where the post-operam model is confined 3h more than the ante-operam one with a maximum increase of 3°C, while the UHI mitigation measures in the final-post-operam scenario reduce it for 1h and approximately 1°C.
The study shows that the use of cool materials and vegetation integrated in a building complex is recommended and leads to a decrease of the critical issues that contribute to the UHI effects in the surrounding area.

2.2.3 Public space in Granada

Research paper: **Microclimate design for micro-urban desing. A case study in Granada, Spain**
Authors: Matteo Trane, Matteo Giovanardi, Riccardo Pollo, Chiara Martoccia, 2021
Published in: SMC Magazine, n. 14
Year: 2021

The main goal of the paper is to identify site-specific strategies for the redevelopment of public space as methods of designing the microclimate while adapting cities in order to mitigate the effects of climate change.
The case study location is Santa Adela district in Granada, Spain. The climate is Mediterranean, characterized by hot summers. The project concerns the public housing district, Zaidin district, which is one of the most densely populated areas of the city. Asphalted surfaces prevail in the area, while the vegetation presence is minimal.
Various climatic parameters were evaluated to assess the impact of the redesign of the space between buildings, within which the most relevant are: Potential Air Temperature (PAT), Physiological Equivalent Temperature (PET) and Surface Temperatures (ST).
The analysis was carried out for the data of 22nd July 2019, the hottest day of the year detected by the weather station.
The design proposal includes three clusters of targets, with specific design strategies implemented for each of them:

- Pedestrianization - many of the interstitial areas were redesigned for the benefits of pedestrians, which includes freeing the public space from cars, implementing soft mobility through traffic calming strategies and by encouraging the use of sustainable public or private transport, as well as the conversion of the buildings' ground floors to meet the needs identified in the meta-design phase, providing flexible spaces for co-working and study rooms, temporary residences, commercial activities, services, and parking for bicycles.

- Densification - "urban void" was transformed into a common multi-storey car park, close to the pedestrianized areas; relocation of the ground floor resident spaces to the industrial lot to be redeveloped in compliance with the Urban Plan of Granada.
- Green and blue infrastructure - increase of the green horizontal and vertical infrastructure; installation of green roofs and walls; reduced road section for vehicles

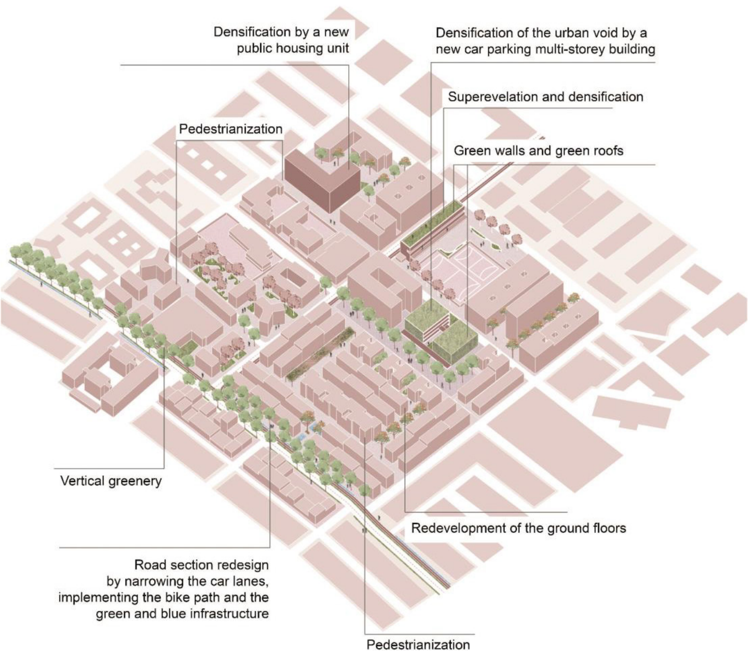


fig. 57 Site-specific redevelopment design strategies
source: Trane et al., 2021

to make space for the design of gardens, water ponds and cycle paths.

The design strategies at plot A include increasing the density of the urban fabric by creating a new multi-storey car park, designed on pilotis to favour the wind circulation, to be used mainly by the residents; allow redevelopment of the space between buildings in plots B and C; implementation of the green infrastructure, change of the paving materials and installation of green walls and roofs.

The simulation results show that the strategies improve the quality of microclimate at the site. Densification results in the decrease in the maximum PAT value in the central hours of the day from about 1°C to about 2°C. The PET index improves as well in the post-design scenario, the greatest impact showing at 18:00, when the maximum PET values are 12°C lower than the current condition. The ST were assessed in three points to quantify the benefits of the pavement change. The points analysed in the current urban void, whose new surfaces were provided in light concrete (Point 1) and meadow (Point 3), show a ST decrease of about 20°C in the central hours of the day (Point 3 at 3:00 PM).

The design proposal for plot B introduces the redevelopment

fig. 58 Design strategies in plot A
source: Trane et al., 2021

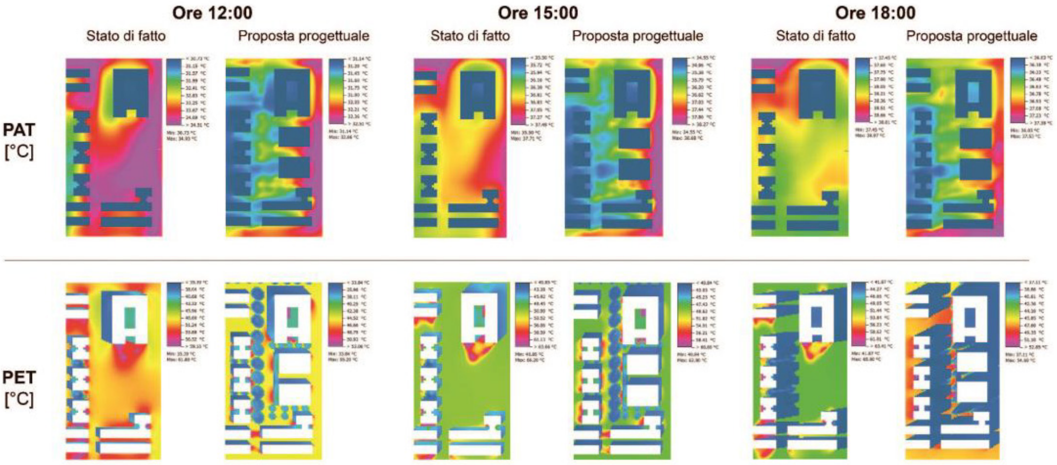


fig. 59 Plot A, PAT and PET outputs of the simulation at 12:00, 15:00 and 18:00
source: Trane et al., 2021

of the residential buildings' ground floors and the space between them by changing the pavement materials; addition of the water ponds and improvement of the green punctual infrastructure; installation of pergolas to provide shade from direct solar radiation.
The results of the analysis showed that the most evident PAT maximum value variations are recorded in the central hours of the day (approximately -4.5°C at 12:00 AM, -3.5°C at 3:00 PM), while variations of the minimum values are less evident (around -1°C between 12:00 AM and 3:00 PM). The change in pavement materials resulted in the decrease in ST, at the most in the points where the asphalt was replaced with the horizontal green.
The strategies in the Plot C concern the redesign of the roads (narrowing of the carriageway, insertion of a dual-lane cycle path, widening of the new light concrete sidewalks) and implementation of green and blue infrastructures.
The results show that the strategies show less impact in ST decrease than in the plots A and B, due to the smaller effect of the building shadows (in light of a wider road section than internal courtyards). More significant changes are observed

fig. 60 Design strategies in Plot B
source: Trane et al., 2021

in PAT values, where at 3:00 PM the maximum value in the design scenario is about 3.5°C lower than in the current state. The PET index does not vary significantly from the minimum values. However, it shows a widespread and general improvement in the whole area, net of the areas immediately adjacent to the south facades of the residential buildings, where the installation of green walls or new trees could be a solution. In this case, the design should provide a more

fig. 61 Design strategies in Plot C
source: Trane et al., 2021

effective system for shading from the direct solar radiation.

Conclusions:
Urban density and morphology of the buildings are determining factors in relation to the microclimate and comfort conditions for the specific context. Dense urban tissue has both direct and indirect effects on the microclimate in terms of shading the spaces between buildings as well as the mitigation of the vehicular traffic emissions which influences the main health determinants.
The implemented strategies led to the decrease of PAT and ST and improved the summer comfort index values.
The orientation of the urban canyon affects the thermal comfort as well. The simulations demonstrated that the internal courtyards oriented according to the north-south axis are affected by ST values which are 8-10°C lower than those oriented along the east-west axis, with a PET index range of 15°C in the most critical hours.
One of the key factors was the implementation of the green infrastructure, which is both an adaptation and mitigation measure. The increase in green infrastructure, combined with soil redefinition strategies (roadway redesign, de-waterproofing, de-paving, using surface materials with high albedo, installation of water blades and solar shading) implied the abatement of maximum PAT values of over 4°C in the most critical hours.

2.2.4 Open space redevelopment outside Università di Roma Tre

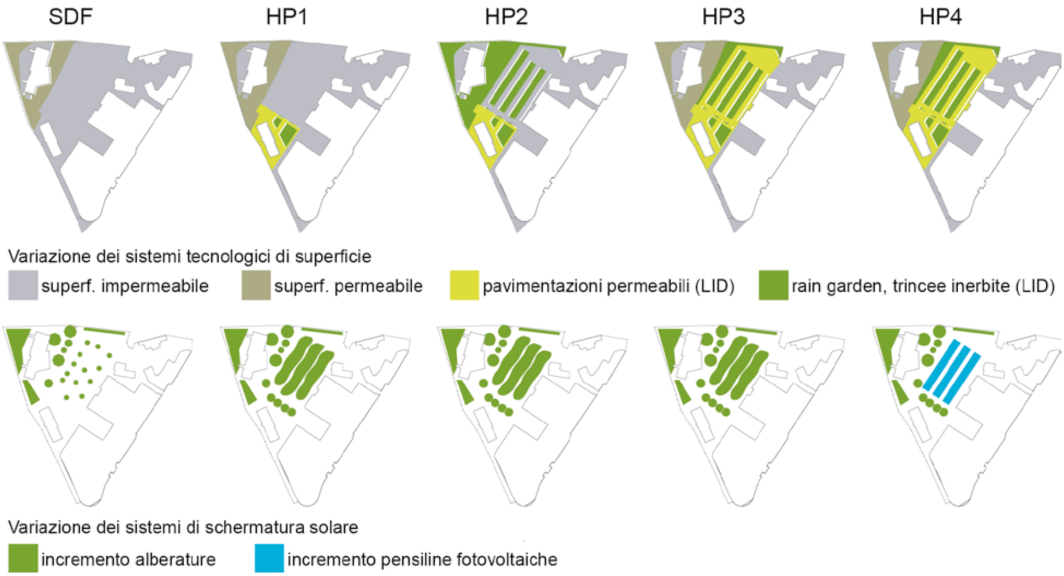
Research paper: **Resilience and open urban environments. Comparing adaptation and mitigation measures**
Authors: Paola Marrone, Federico Orsini
Published in: TECHNE, issue 15
Year: 2018

The paper analysed the effectiveness of adaptation and mitigation strategies for open space redevelopment in order to identify the resilience indicators with respect to urban heat island and hydrological risks related to the rainwater management. The research was conducted using two models: ENVI-met and SWMM.

The research area is the public space outside the Department of Humanities and Philosophy at the Università di Roma Tre. It was formerly the home of Alfa Romeo factories. The university establishment changed the use but preserved existing the spaces. The public space concerned is an asphalted parking area. The area is characterized with busy streets, a morphological system defined by different levels, almost total impermeability of the ground (88%), little vegetation, and the presence of large waterproof spaces.

Five scenarios were tested, an existing one and four including mitigation strategies:

1. SDF: current state;
2. HP1: intervention limited to the pedestrian area, increasing the permeable surface, adding a rain garden, planting trees;
3. HP2: HP1 + intervention on parking lot to increase the



permeable surface, add a rain garden, plant trees.
4. HP3: HP2 + total permeability of parking lot;
5. HP4: HP3 + addition of a photovoltaic canopy.

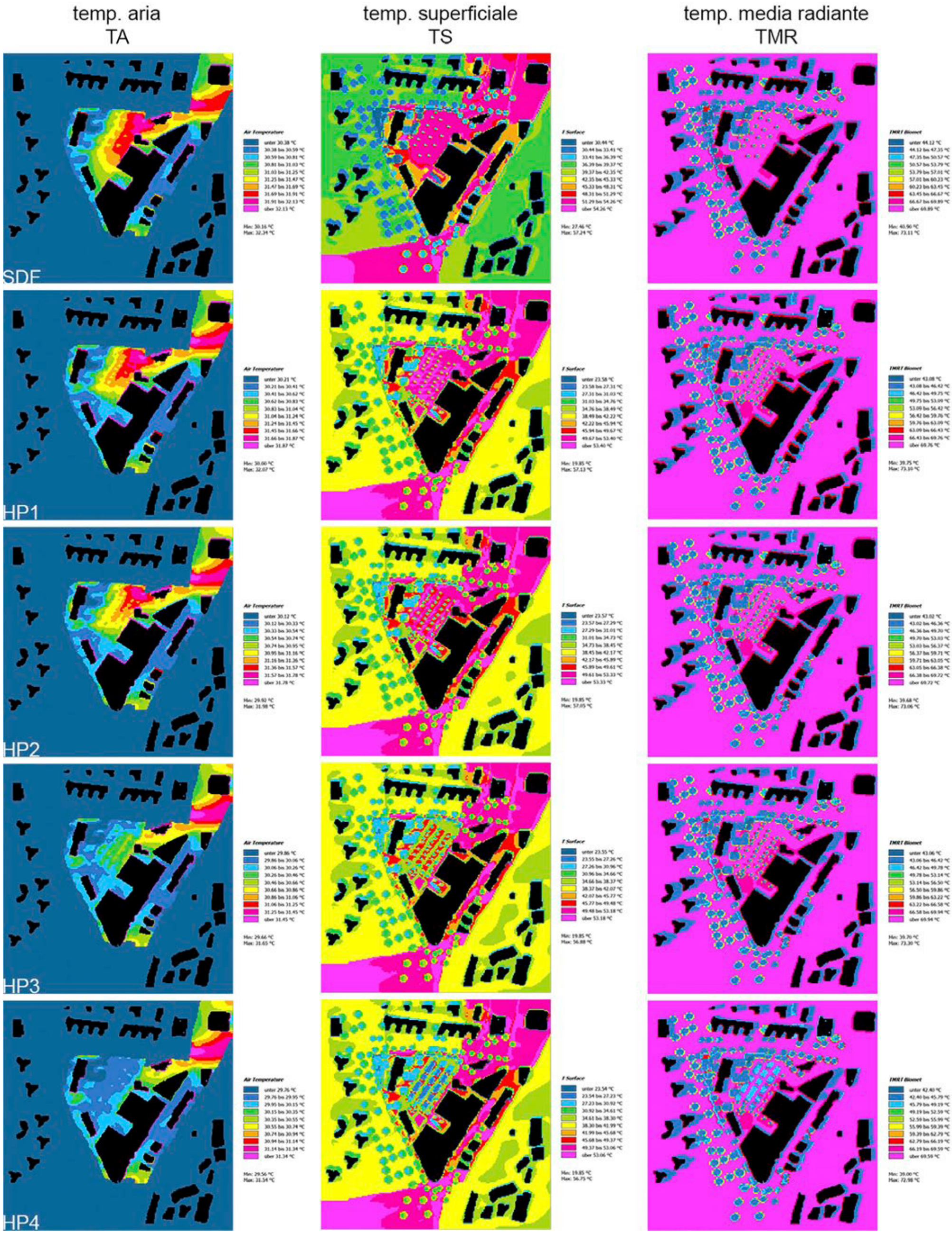
LID (Low Impact Development) surface technological systems were examined: permeable pavement composed of permeable interlocking paving, sand substrate, drainage layer, grassy trenches, raingarden.

The ST value varies with the direct or screened irradiance conditions (RS) and the type of material (its albedo and thermal conductivity). With respect to the SDF, the design scenarios showed a decrease of ST and mitigation of the UHI by 10-12°C for the pedestrian area in all the scenarios. The decrease for the parking area differs depending on the strategy implemented, with a maximum decrease for HP 4.

The AT value is strongly influenced by RS and ST. The design scenarios reduce the existing AT, improving user thermal comfort and mitigating the effects of the UHI

fig. 62 Variation of the technological systems of the improvement scenarios (HP1-4) compared to the current state
source: Marrone and Orsini, 2018

fig. 63 The impact of technological systems on AT, ST and MRT
source: Marrone and Orsini, 2018


temp. aria
TA
temp. superficiale
TS
temp. media radiante
TMR
SDF
HP1
HP2
HP3
HP4

by 1°C (HP 2), 1-2°C (HP 3), and 2-3°C (HP 4).
The MRT value is strongly influenced by RS, ST and AT. By adding cool pavement and increasing the number of trees, the proposed design scenarios mitigate the SDF scenario's critical value. In particular, MRT is decreased by 5-7°C and 20-24°C, respectively.

Conclusions:
The proposed scenarios contribute to the mitigation of UHI and WR effects.
Changing the pavement type (from asphalt to light-coloured, highly porous interlocking slabs) decreases average surface temperature by 12-15%, and planting trees by 38-40% due to different albedo values of asphalt, concrete and vegetation.
Replacing asphalt with permeable pavement (HP3-4) increases the permeability of the pedestrian area by 10% and that of the parking lot totally. Along with this total increase (close to 400% compared to SDF), the final storm water flow rate decreases by about 10%.
Some general recommendations that can be drawn from the study, but have to be verified on a case-by-case basis would be:

- permeable systems and renaturation strategies have a strong impact on UHI and hydrological risks
- trees or photovoltaic canopies offer major benefits in reducing ST and ART with respect to changing the type of pavement
- LID systems are effective for smoothing the flood wave and for decreasing the volume of incoming water, though it is important to remember that their effectiveness depends to a considerable extent on the technological solutions adopted (material permeability, thickness, etc.)

2.2.5 Piazza dei Mirti in Rome

Research paper: **Assessment of urban overheating mitigation strategies in a square in Rome, Italy**
Authors: Gabriele Battista, Roberto de Lieto Vollaroa, Michele Zinzib
Published in: Solar Energy, vol. 180
Year: 2019

The aim of this study was to investigate the impact of different UHI mitigation strategies on the thermal comfort of the citizens of a densely populated area in Rome.
The study location is Piazza dei Mirti in Rome. The area consists of wide asphalt zones used for pavements and sidewalks, concrete structures used for the subway. The vegetation is scarce, consisting of few bushes and small trees which provide insufficient shading.
Mitigation scenarios that were assessed are:

- Standard - real condition of the square
- Cool - introduction of cool materials, the value 0.15 or 0.30 shows the reflectance of the used material
- Lawn - the application of lawn in the middle of the square
- T1 - substitution of the 8 trees of the square in an average height of 4m (named T3) with other of 10m average height
- T2 - substitution of trees of an average height of 6 m
- Num T1 - addition of 26 trees of T1 type and the substitution of the actual 8 T3 trees with others of T1 type
- Num T2 - addition of 26 trees of T2 type and the sub-

stitution of the actual 8 T3 trees of the square with T2 type trees

- Num T3 - addition of 26 T3 trees, the same of the ones already in the square.
- Water - addition of a water stretch in the middle of the square
- Canopy - a roof
- Multiple - union of the techniques Cool 0.3, Water, Canopy and Num T1

Air temperature doesn't change significantly in relation to the mitigation techniques in the morning. The only variations are about the case Num T1, Canopy, Water and Multiple.

In the hottest hours of the day air, temperature variations can be found at 12 o'clock. Considerable decrease of temperature is noted in cases T1, Cool 0.30, Water and Canopy, listed from the lowest to the highest decrease value.

The same considerations from the 12 o'clock results can be observed at 6 pm.

The more effective techniques considering the average difference in the entire simulated day are the canopy (-0.84 °C), the water stretch (-0.48 °C), the cool material 0.3 (-0.19 °C), the T1 trees (-0.12 °C) and the increase of them (-0.37 °C).

Considering the maximum difference value, the biggest variation is due to the canopy which makes the air temperature decrease of 1.18 °C. The lawn, as well as the cool materials 0.15, the 6m high trees (T2 type), the increase of trees numbers of type T3 and T2, doesn't lead to a significant variation of the air temperature despite the standard case. The canopy and the T1 trees, which are 2.5 times higher than the ones in the square, lead to a bigger shadow and to a less overheating of the path surface reducing the air temperature in the centre of the Mirti square during the solar radiation. The union of the mitigation techniques in the Multiple case leads to a reduction of the air temperature of a maximum of 1.86 °C

and an average of 1.39 °C.
The UTCI analysis allows to distinguish the best mitigation technique that induces a significant increase of the thermal

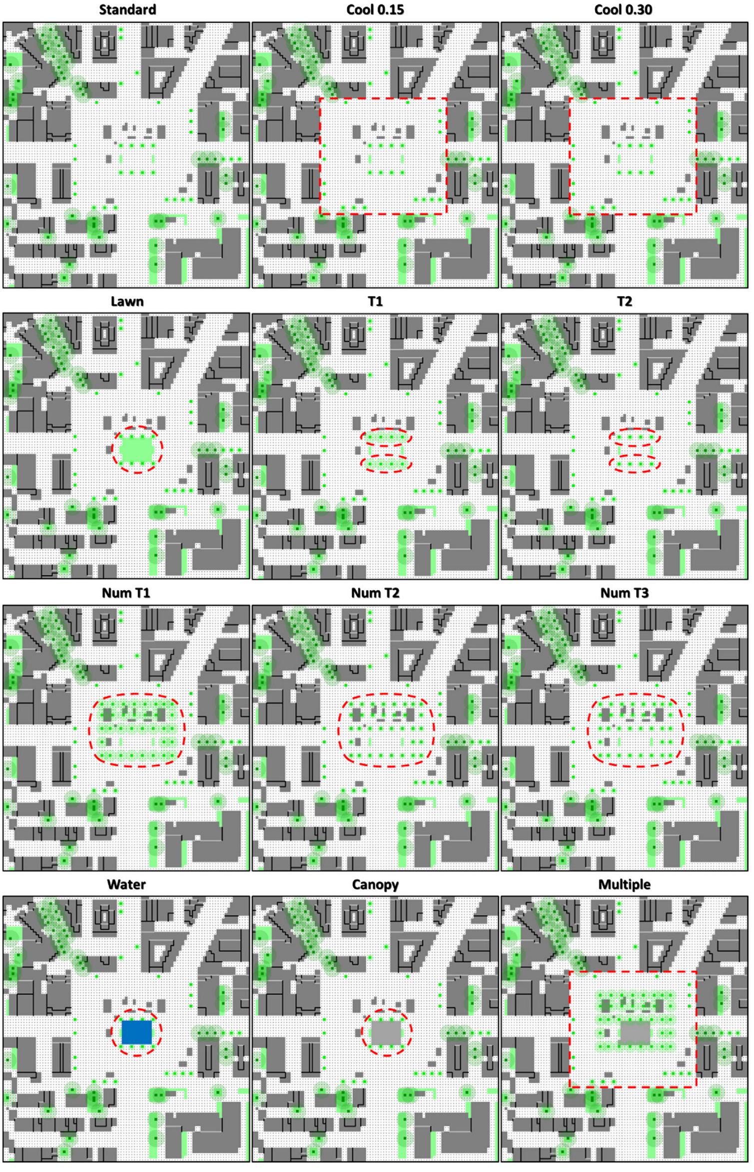


fig. 64 Used models of mitigation with the interested area inside the dotted red line
source: Battista et al., 2019

comfort. The results lead to the consideration that shadow effects are more relevant compared to the other technologies. The Canopy and Multiple are the cases which contribute most to the better UTCI values.

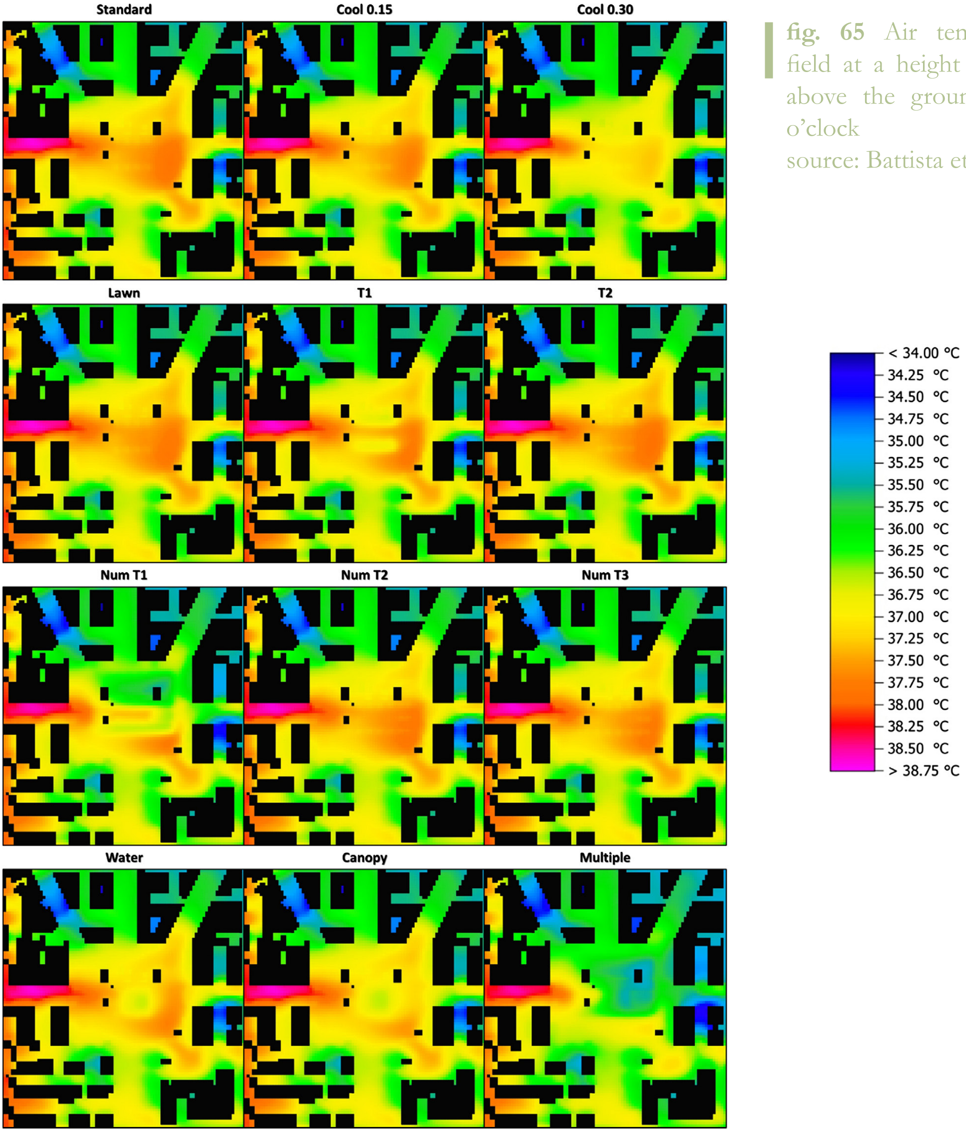
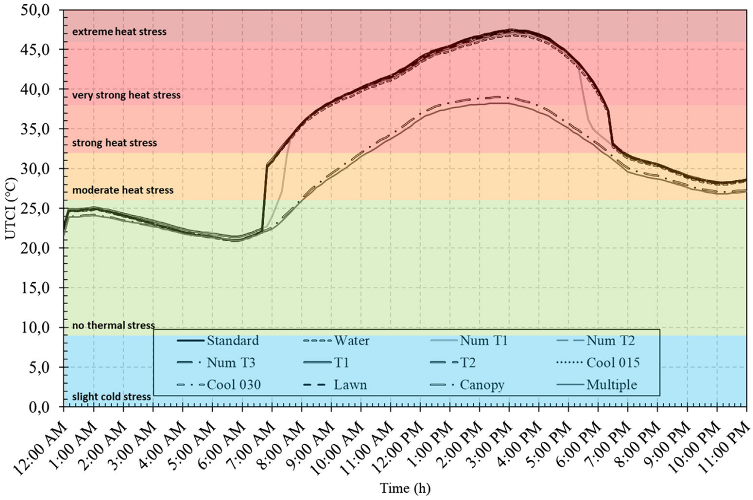


fig. 65 Air temperature field at a height of 1.8m above the ground at 12 o'clock
source: Battista et al., 2019

fig. 66 Comparison of the UTCI among the different mitigation techniques
source: Battista et al., 2019



Conclusions:
yThe research confirmed that the examined mitigation strategies lead to the air temperature reduction. The most efficient single solution was the case Canopy with 1.18 °C air temperature peak reduction, followed by water stretch with 0.90 °C, the increase of tallest trees numbers with 0.54 °C and the introduction of cool material with albedo 0.30 that lead to 0.44 °C. Best results were achieved thanks to the combination of solutions with 1.86 °C air temperature peak reduction. These results are relevant to mitigate the thermal response in the built environment, affected by overheating and high cooling uses in the summer. Thermal comfort improvement, on the contrary, is less sensitive to the implemented solutions than the air temperature analysis. The results demonstrated that the most effective strategy to improve thermal comfort was the Canopy. The UTCI index decreases from about 47 °C in the current situation to about 38 °C.

3
Modelling and simulations

3.1 Research

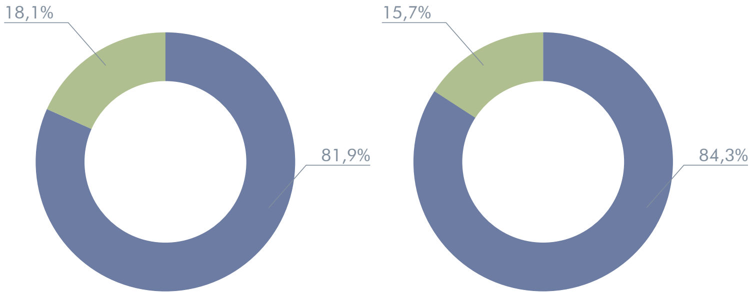
3.1.1 Controviali

The urban matrix of Turin is characterized by wide tree-lined avenues with narrow roads on their right and left side, called "controviali". This format of the streets is unique to Turin and it dates back to the 19th century. The architect Carlo Promis designed the avenues based on the "allées" which had originated in the 18th century and the Napoleonic period (Sciolla, 1982). The project for the avenues was executed between 1851 and 1853, starting from the part of Corso Vittorio Emanuele II from Corso Re Umberto to Piazza Carlo Felice (Sciolla, 1982). However, Bergeron (1989) argues that it was actually Edoardo Pecco who designed the plan of Turin in order to loosen the urban tissue. In this plan the avenues where trees were planted, the minimum distance between the building facades and the row of trees was 12 metres. This allowed for wide avenues with plenty of vegetation, creating a new urban concept. Analogous solutions emerged soon in the other European cities, such as Haussman's boulevards in Paris, between 1853 and 1871, and Ring of Vienna in 1858-1859 (Sciolla, 1982).

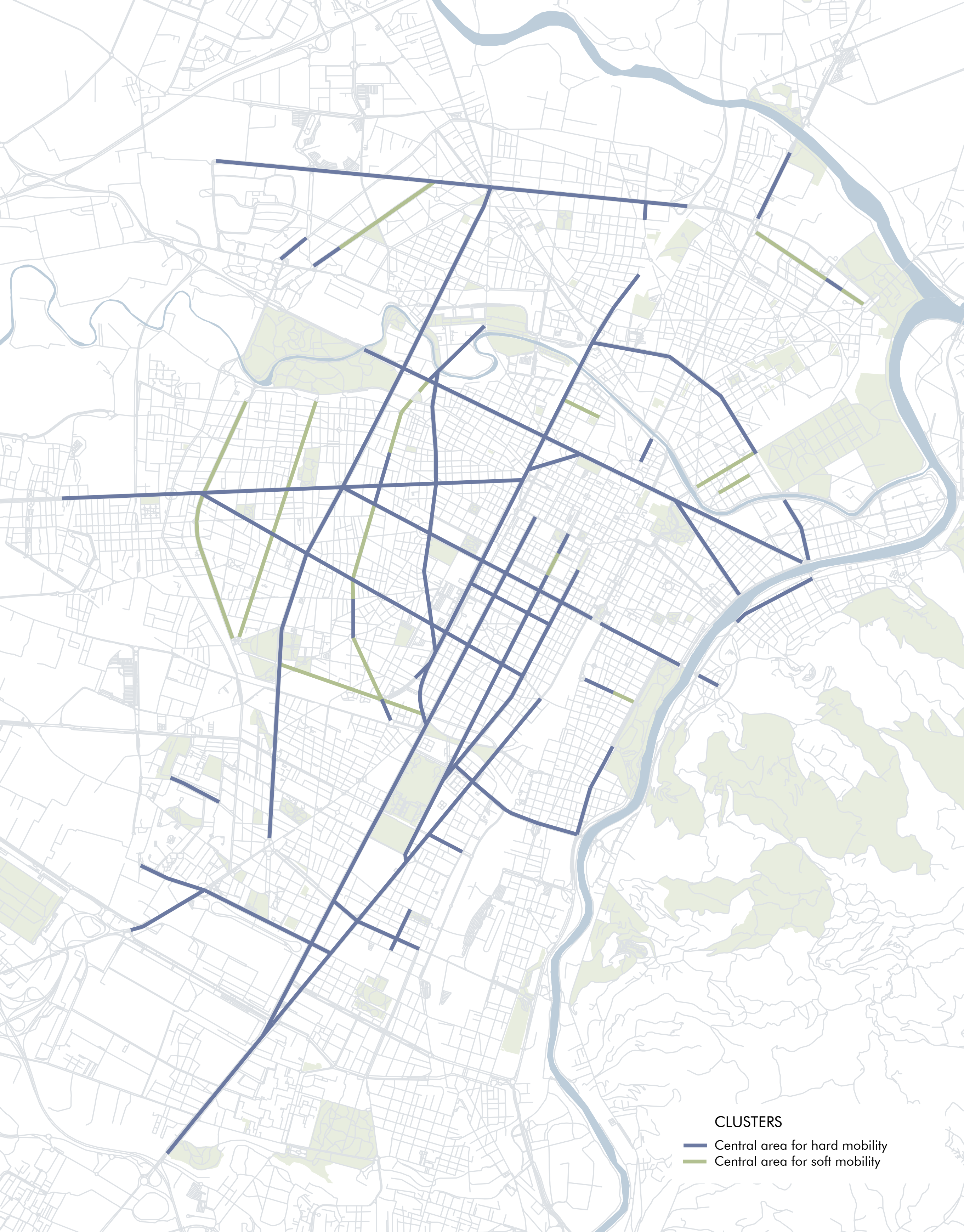
3.1.2 Clustering I: type of mobility

At present, majority of the avenues with controviali are used mainly for car traffic. Controviali are mostly used for turning at the intersections and parking, while the central part is predominantly used for traffic continuing in the straight line. Detailed analysis and mapping of the avenues and streets containing controviali indicates that there are two main clusters: one where the central area is dedicated to hard mobility and the one with the soft mobility in the central area.
There are 62 streets containing controviali in Turin and they are divided into 171 segments based on their structure. Therefore, the segments do not have the same length or area. All the comparisons are made on two bases, the number of segments and the overall length. Total length of all the streets with controviali is 86159,5 m.
The analysis demonstrates that the majority of the avenues are used for the hard mobility, precisely 81,9% of the segments or 84,3% of the overall length of all the streets containing controviali (fig. 67). Map 1 shows the layout of two clusters in the urban area of Turin.

fig. 67 Comparison of the two clusters based on the segment number (left) and their length (right)



Hard mobility-centred
Soft mobility-centred


CLUSTERS
Central area for hard mobility
Central area for soft mobility

map 1 Clusters of hard mobility and soft mobility centred streets with controviali

The elements concerning microclimate conditions, such as street orientation, aspect ratio, surfaces, type of mobility were analysed.

The two dominant orientations of the controviali streets, just like the urban matrix of Turin, are NE-SW and NW-SE (fig. 68). These orientations offer certain exposure to the sun in winter and allow easier solar control in the summer, providing better outdoor thermal comfort (Ali-Toudert and Mayer, 2006).

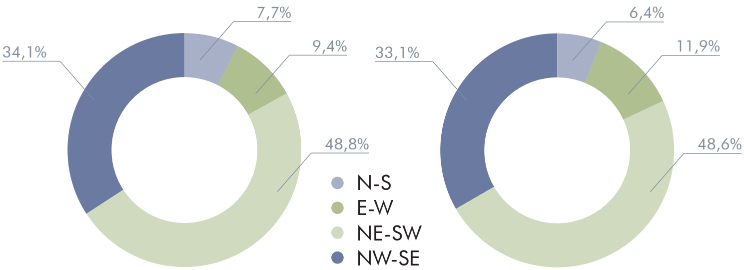


fig. 68 Comparison of the street orientation based on the segment number (left) and their length (right)

Due to the great width of the streets and relatively short buildings (mainly up to 10 floors), the urban canyons are dominantly shallow. Majority of the streets have aspect ratio between 0,2 and 0,6 (fig. 69, map 2).

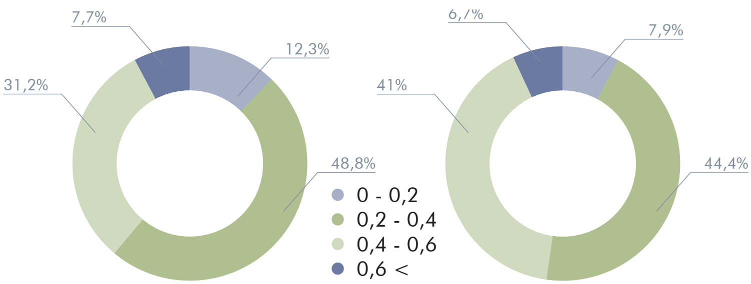


fig. 69 Comparison of the aspect ratio based on the segment number (left) and their length (right)


H/W RATIO
0 (no buildings)
< 0,2
0,2 - 0,4
0,4 - 0,6
0,6 <
One-sided canyon

map 2 Aspect ratio of the streets with controviali

Four main constituents of the street surfaces are asphalt, permeable surfaces, walking paths and cycling paths. Asphalt is a dominant component (map 3), accounting for 73,2% of all the surfaces of the streets with controviali, while the permeable surfaces cover 23,4% (fig. 70, map 4).

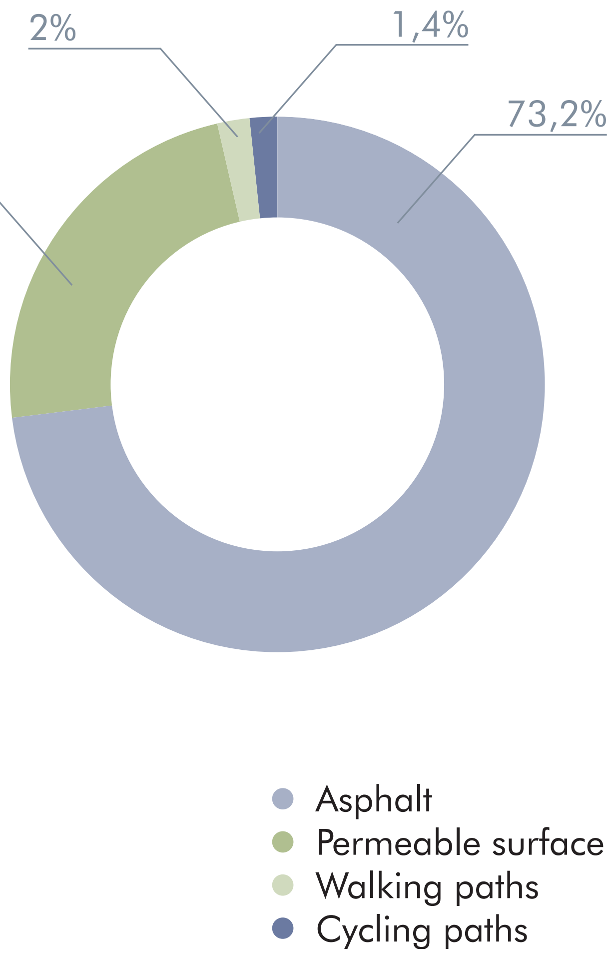
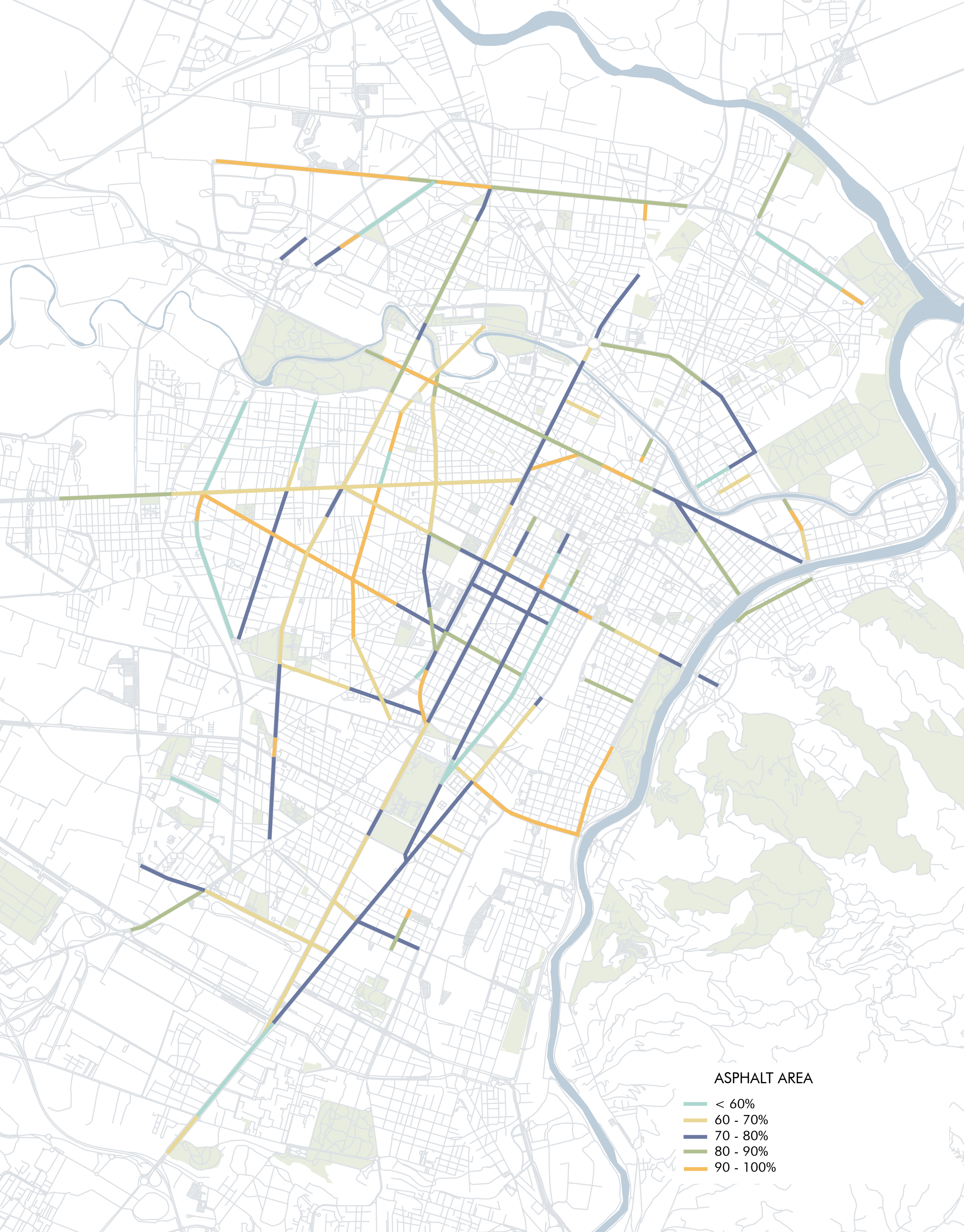


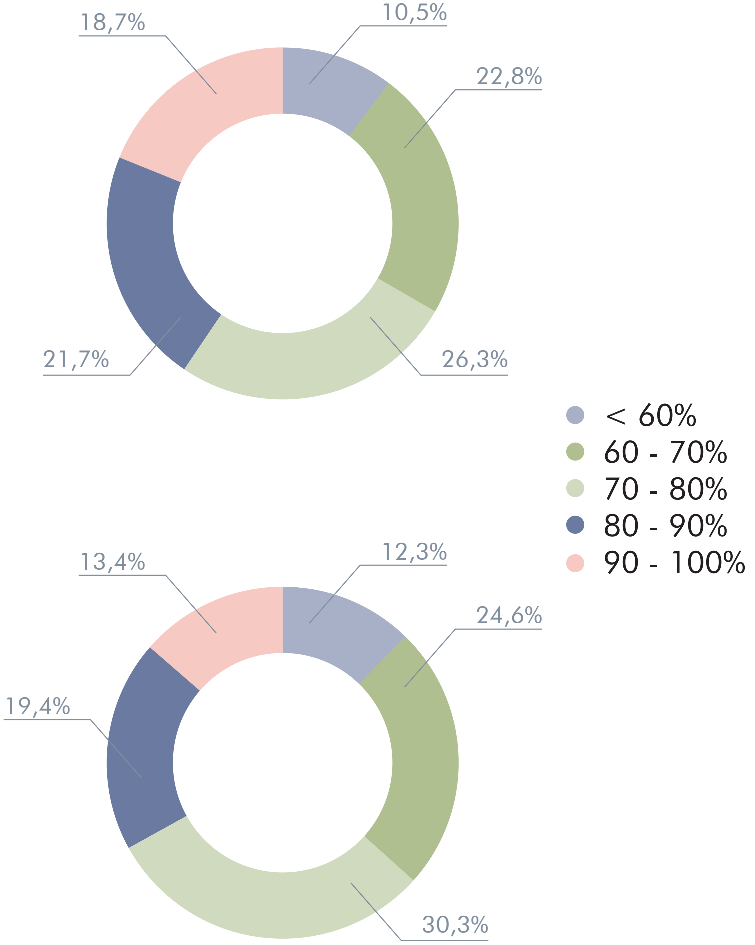
fig. 70 Total area components

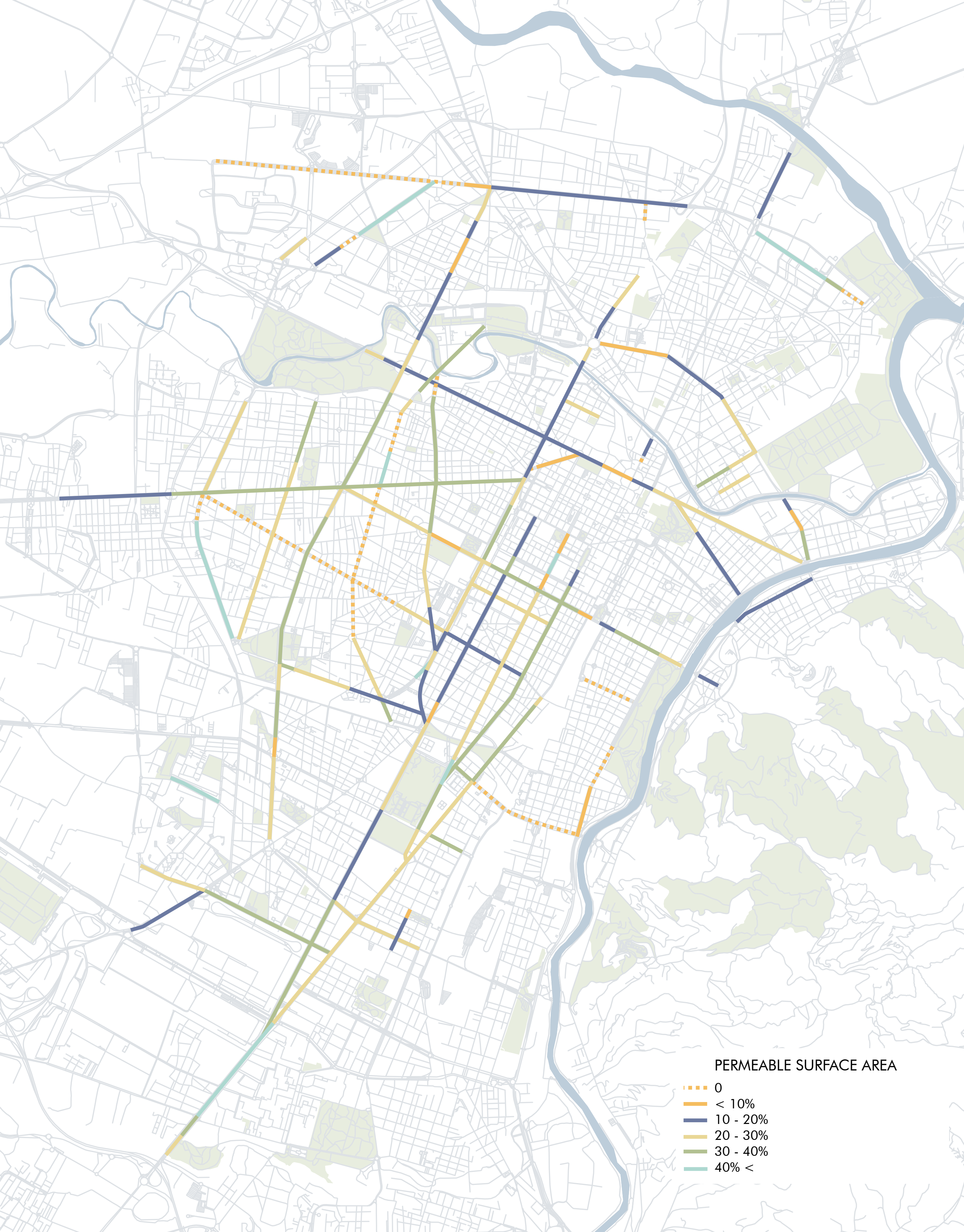

ASPHALT AREA
< 60%
60 - 70%
70 - 80%
80 - 90%
90 - 100%

map 3 Asphalt area of the streets with controviali

Asphalt is one of the most common surfaces in urban areas, especially the ones used for traffic. However, due to its low albedo, it is a major contributor to the UHI effect.
The research shows that only 10,5 % of the segments or 12,3% of the overall length of the streets with controviali have less than 60% of the area covered in asphalt., while 11,7% of the segments or 9,6% of the overall length of the streets are fully covered in asphalt (fig. 71).

fig. 71 Percentage of the streets surface covered in asphalt based on the segment number (top) and their length (bottom)




PERMEABLE SURFACE AREA
0
< 10%
10 - 20%
20 - 30%
30 - 40%
40% <

map 4 Permeable area of the streets with controviali

fig. 72 Percentage of the streets containing permeable surfaces based on the segment number (left) and their length (right)

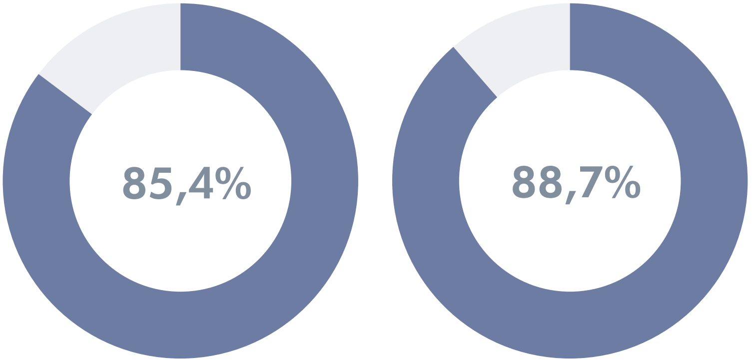
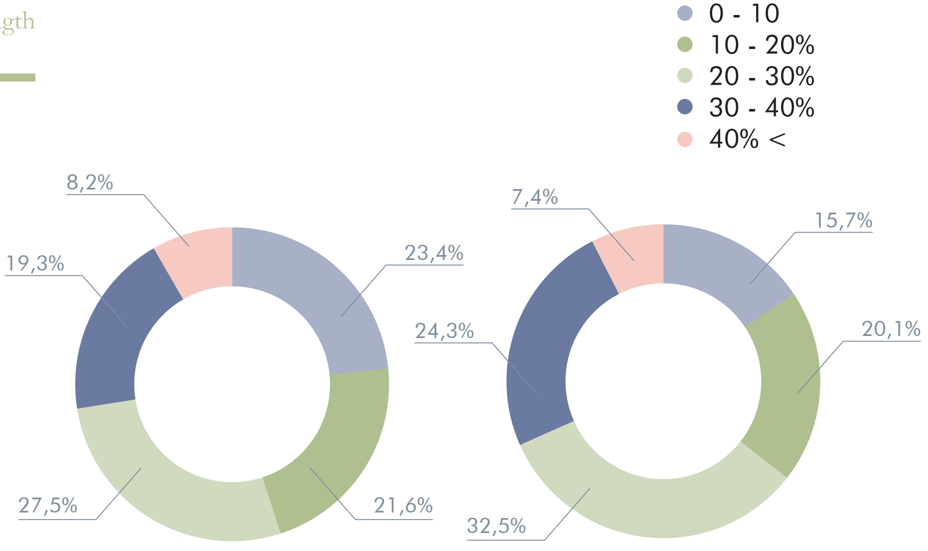


fig. 73 Percentage of the streets surface covered in permeable surfaces based on the segment number (left) and their length (right)

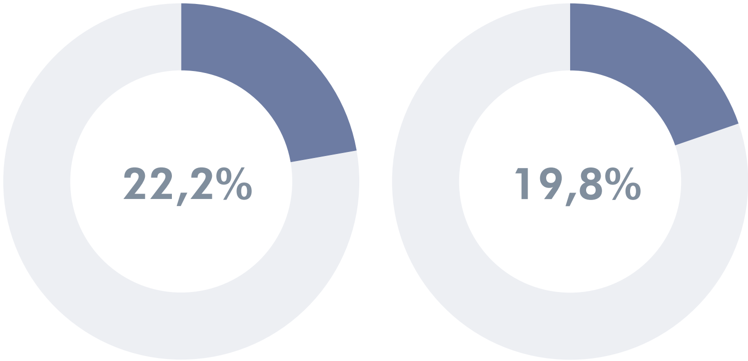
Green areas and vegetation are important elements of the microclimate. Majority of the streets with controviali are characterized with rows of high trees and a certain amount of permeable surfaces, which positively contributes to the microclimatic conditions. Only 14,6% of the segments or 11,3% of the overall street length have no permeable surfaces (fig. 72).




WALKING AND CYCLING PATHS
Walking path
Cycling path along the street
Cycling path along the sidewalk

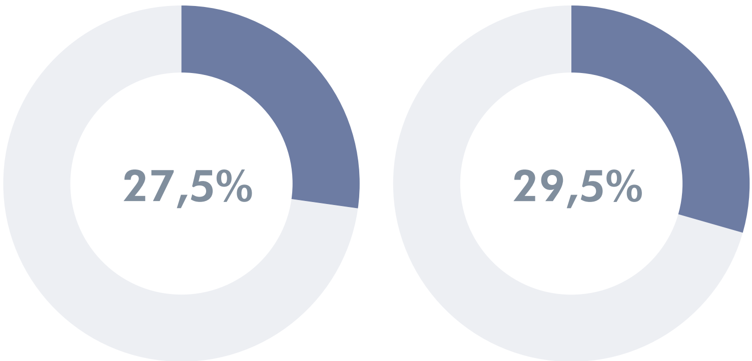
map 5 Walking and cycling paths along the streets with controviali

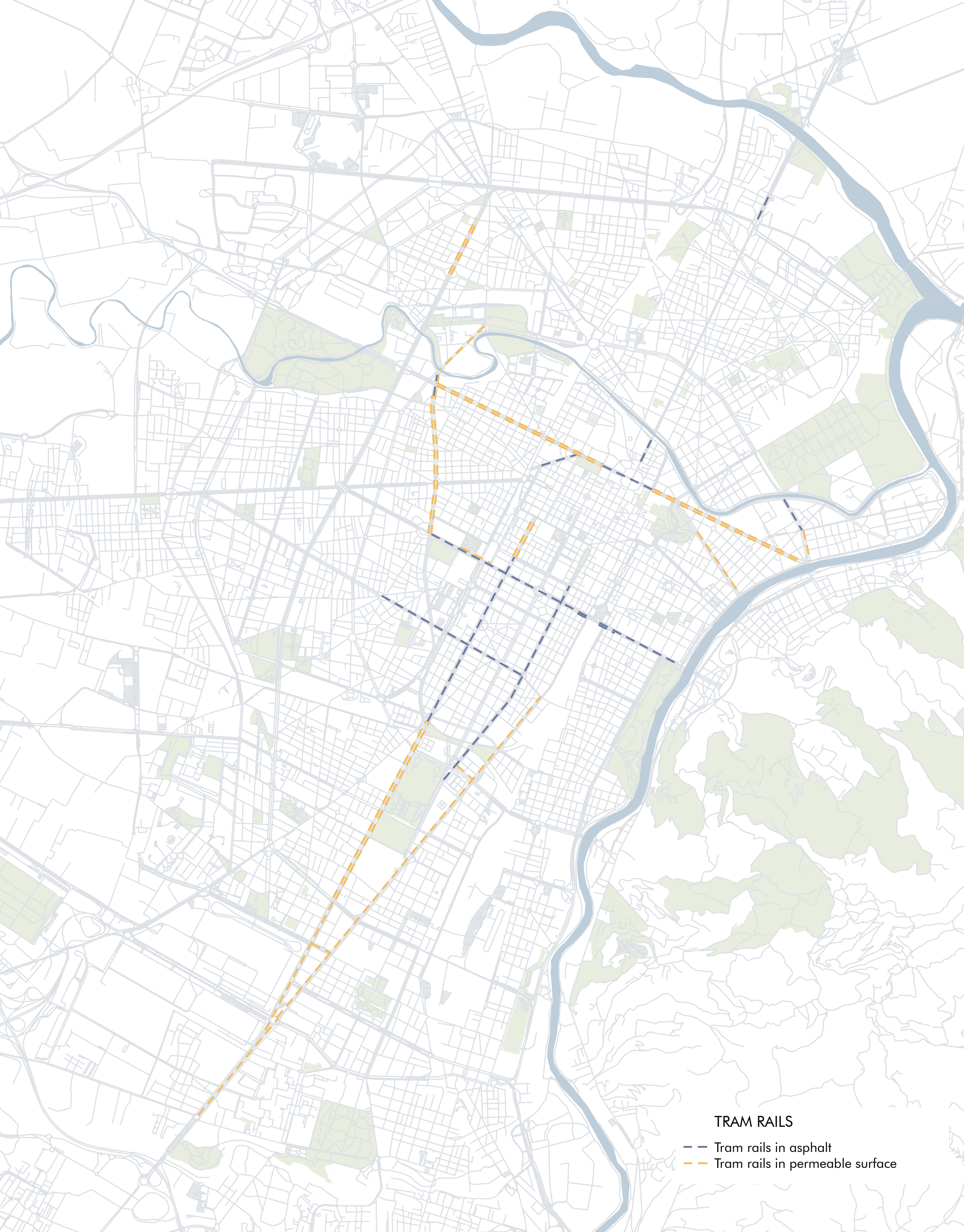
fig. 74 Percentage of the streets containing walking paths based on the segment number (left) and their length (right)



The sustainable urban development places people in the centre instead of the cars, and therefore, outdoor thermal comfort and areas for soft mobility are extremely important for the future development.
However, in Turin, apart from the sidewalks, only around one fifth of the streets with controviali have walking paths among them (fig. 74), while a little less than one third have cycling paths (fig. 75).

fig. 75 Percentage of the streets containing cycling paths based on the segment number (left) and their length (right)




TRAM RAILS
Tram rails in asphalt
Tram rails in permeable surface

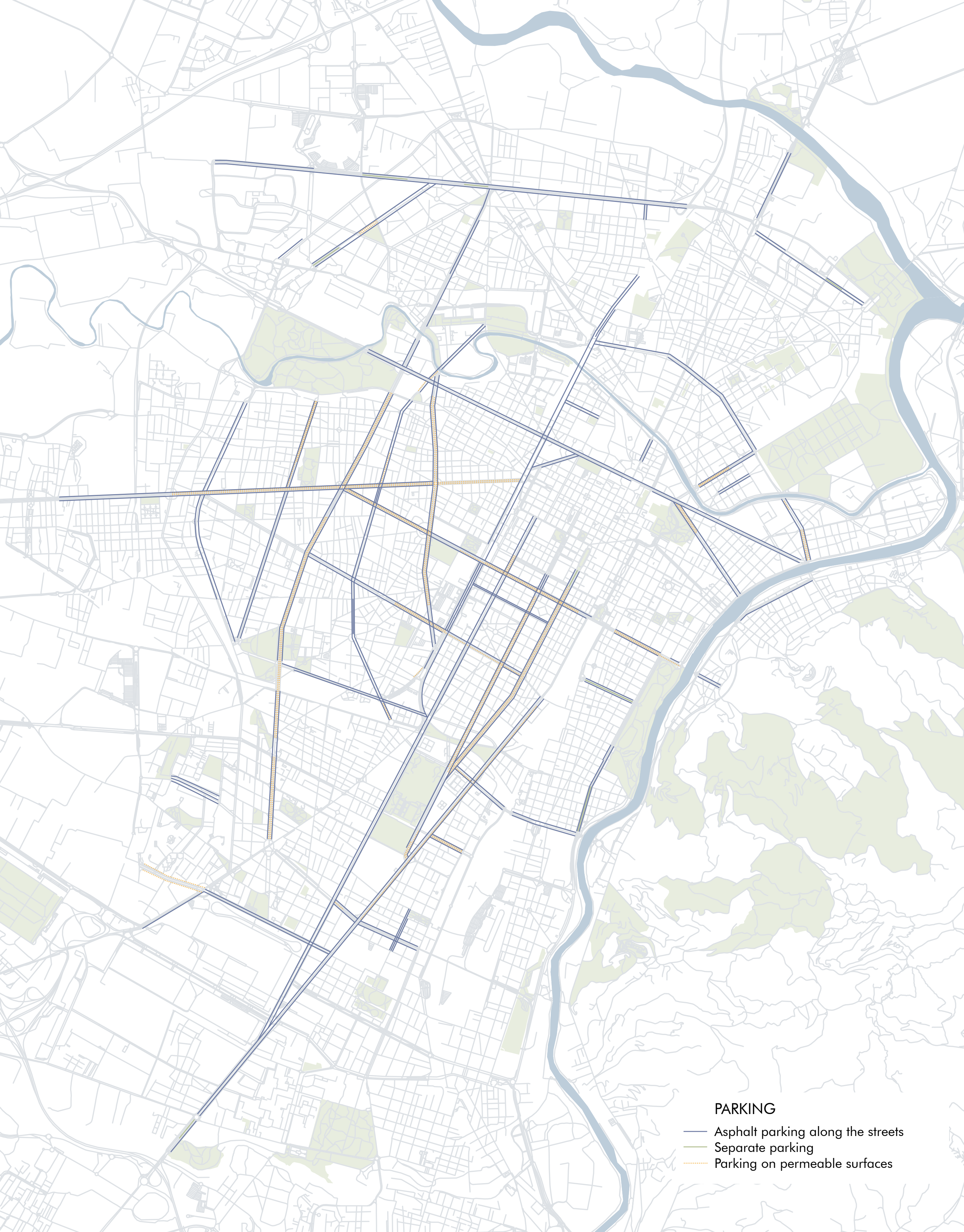
map 6 Tram rails along the streets with controviali

The avenues with controviali are dominant traffic routes, including public transportation. Precisely, 28,1% of the segments and 32,6% of the overall length of the streets contain tram rails among them (fig. 78). Tram rails are either positioned on the asphalt among the cars or in the green area between central lanes and controviali.

fig. 76 Percentage of the streets containing tram rails within asphalt based on the segment number (left) and their length (right)

fig. 77 Percentage of the streets containing tram rails within permeable surfaces based on the segment number (left) and their length (right)

fig. 78 Percentage of the streets containing tram rails based on the segment number (left) and their length (right)


PARKING
Asphalt parking along the streets
Separate parking
Parking on permeable surfaces

map 7 Parking areas along the streets with controviali

One of the most common elements of the controviali is parking. The research shows that 87% of the segments and 81,3% of the overall controviali length have parking within both controviali, while only 2,3% of the streets or 3,5% of the length have no parking within controviali (fig. 80).
A number of streets have a central parking area, precisely 11,7% of the segments or 7,7% of the overall length. Only 2,3% of the segments and 1% of the overall length have no parking at all. This shows that the vast majority of the streets is made for cars, both in fast and slow traffic.

fig. 79 Percentage of the streets containing parking on permeable surfaces based on the segment number (left) and their length (right)

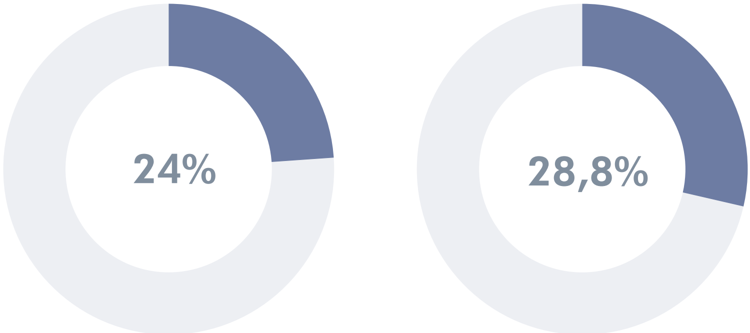
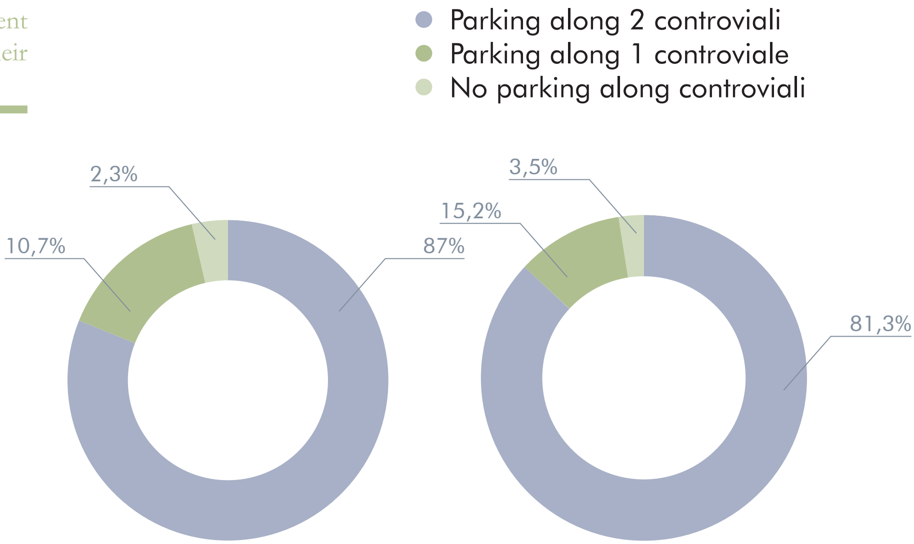


fig. 80 Percentage of parking areas within controviali based on the segment number (left) and their length (right)



3.1.3 Clustering II: street section features

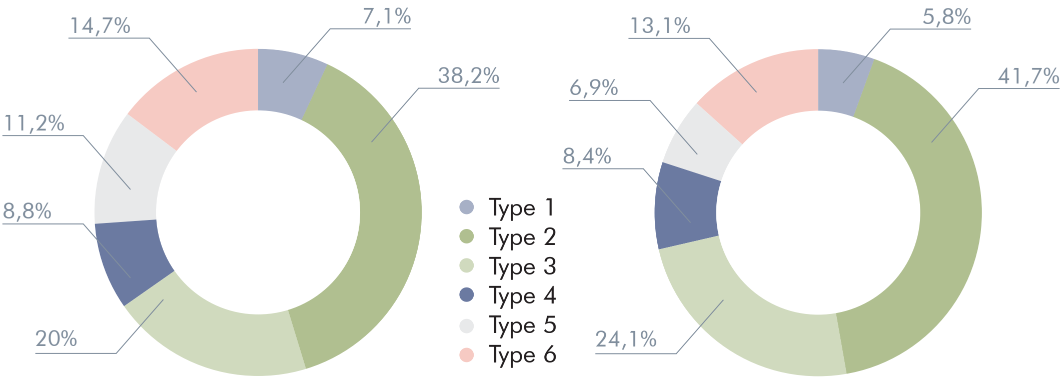
In the analysis, six types of the street section were recognized, based on the mobility type, surfaces and layout (fig. 82):

Type 1. Street with controviale on one side only
Type 2. Street with controviali on both sides, with only car lanes in the central area
Type 3. Street with controviali on both sides, with tram rails within car lanes in the central area
Type 4. Street with controviali on both sides, with tram rails within the green areas
Type 5. Street with controviali on both sides, with asphalt areas for parking or soft mobility between them
Type 6. Street with controviali on both sides, with green areas between them.

The most common one, accounting for more than one third of the streets is Type 2, while Type 3 takes up around one fifth or one fourth of the streets (fig 81, map 8).

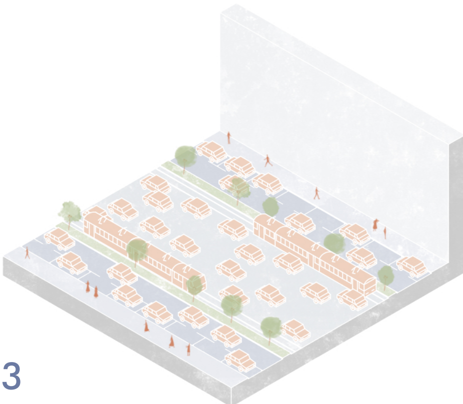
fig. 82 Scheme of the street section typologies

fig. 81 Percentage of each street section typology based on the segment number (left) and their length (right)

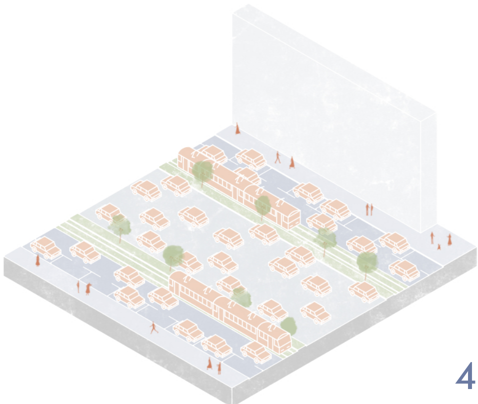


1

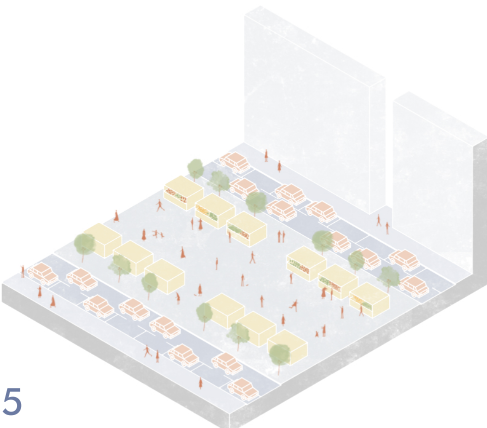
2



3

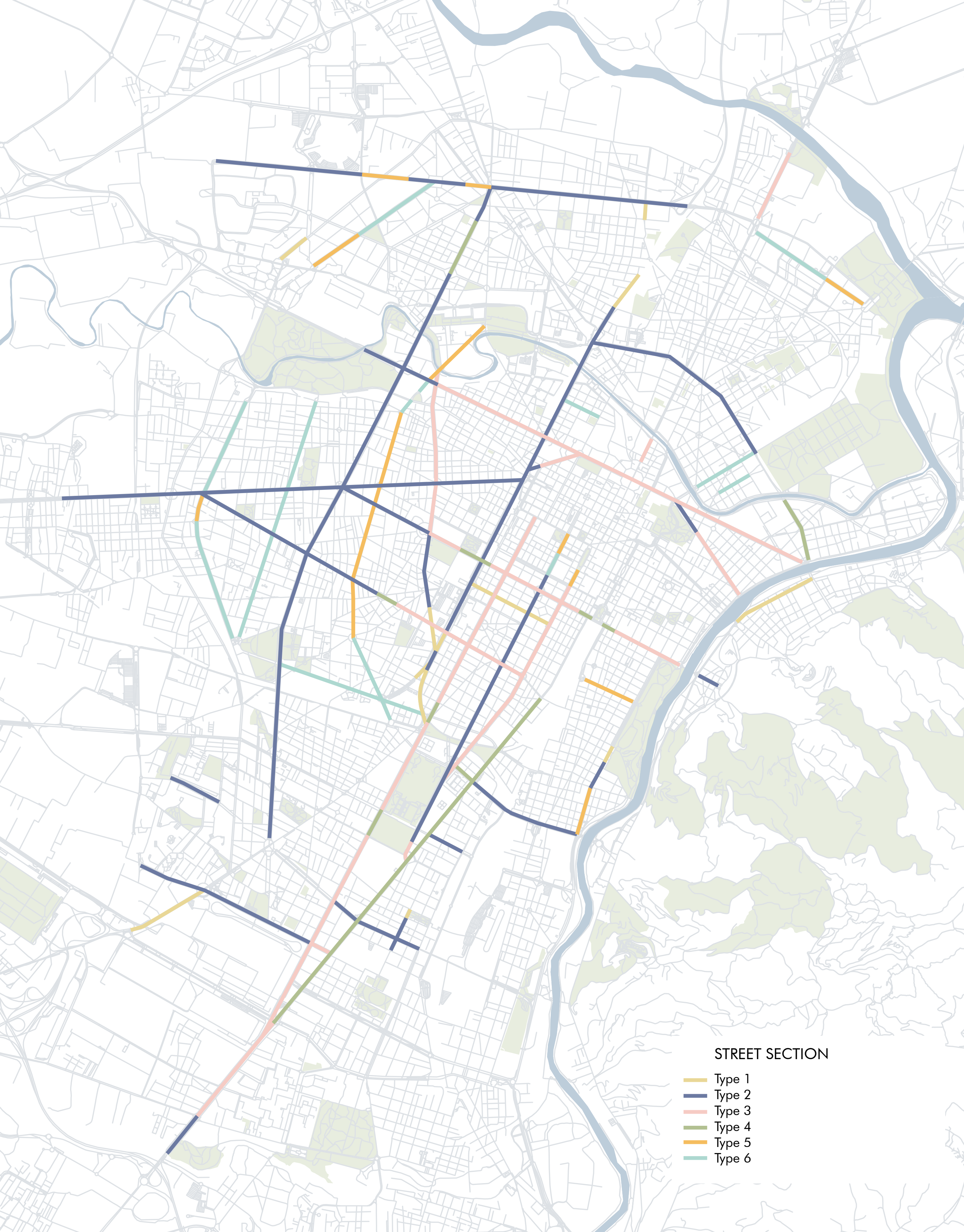


4



5

6

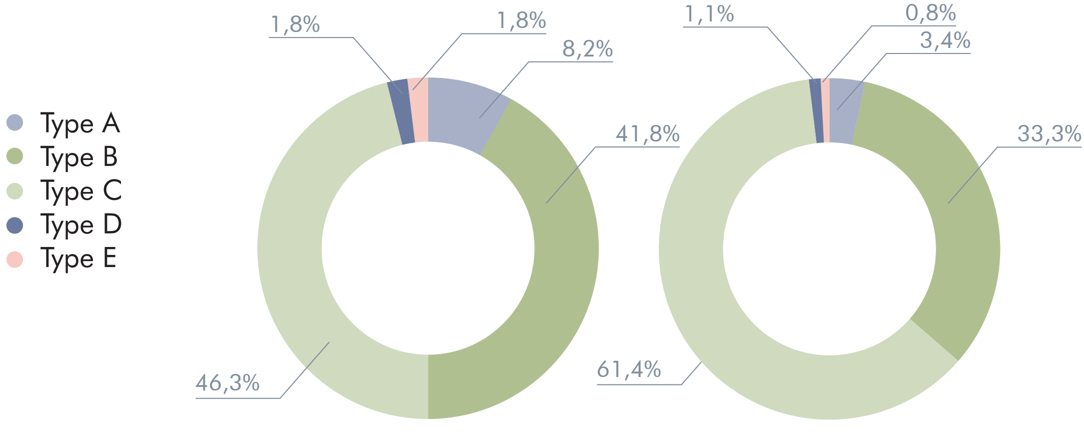

STREET SECTION
Type 1
Type 2
Type 3
Type 4
Type 5
Type 6

map 8 Different typology of the streets with controviali based on the street section

Types 1, 2, 3 and 4 belong to the cluster with central area for hard mobility. Type 5 belongs to both clusters, depending on whether the central area is used for parking or soft mobility. And finally, Type 6 belongs to the cluster with central aea for soft mobility.

Along the streets, different types of the controviali were distinguished as well. The five types were determined mainly based on different functions (fig. 84):
Type A. Only car lanes
Type B. Car lanes and one parking lane
Type C. Car lanes and two parking lanes
Type D. Car lanes and cycling lanes
Type E. Car lanes and two different functions (tram rails, cycling path, bus lane, parking).
The most common types are C, accounting for 46,3% of the segments or 61,4% of the overall length, and B, which makes 41,8% of the segments or 33,3 % of the overall length (fig. 83, map 9). This shows that the dominant use of the controviali is hard mobility, while the controviali containing cycling paths amount to only 1,8% of the segments or 1,1% of the overall length.

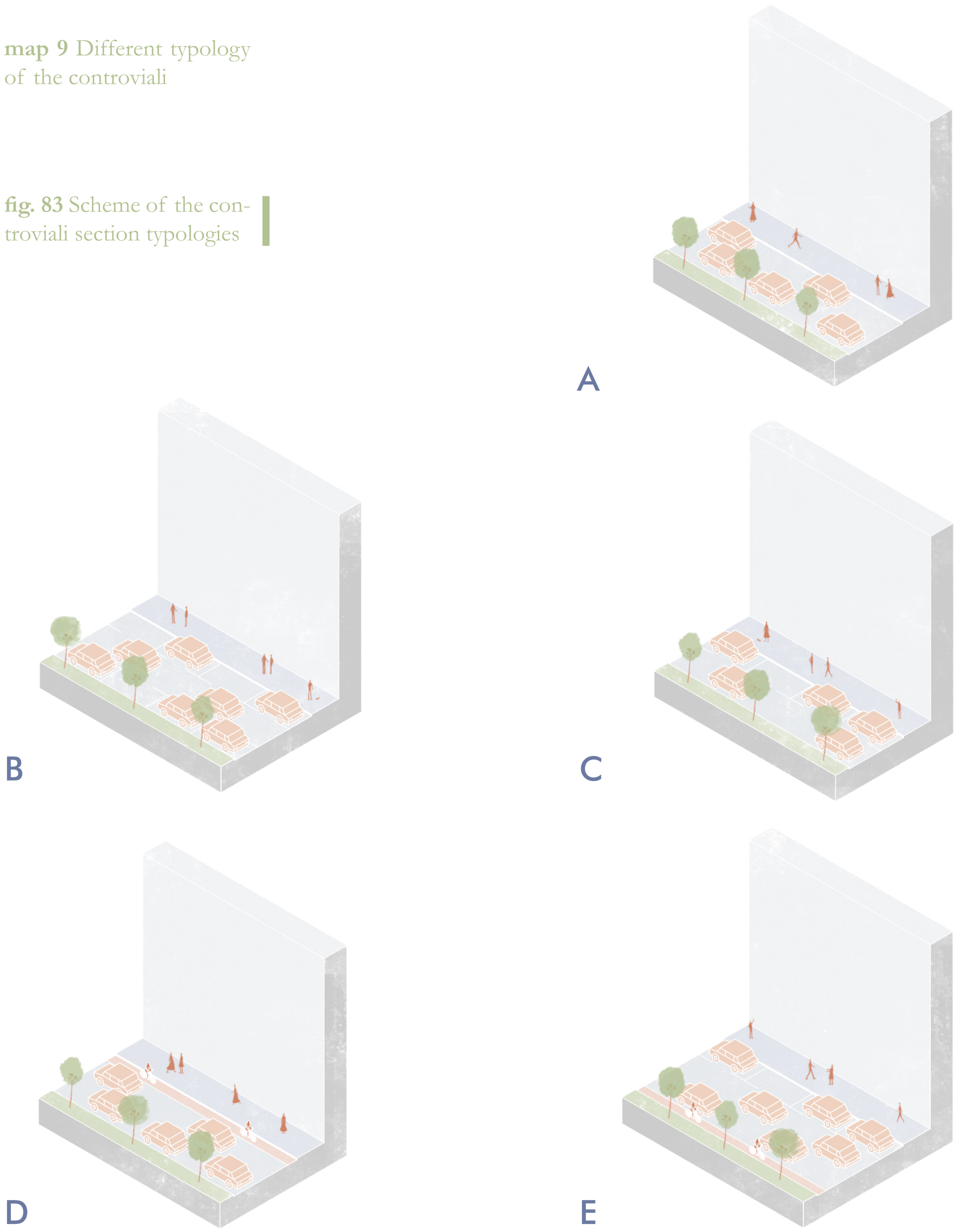
fig. 83 Percentage of each controviali section typology based on the segment number (left) and their length (right)




CONTROVIALE SECTION
Type A
Type B
Type C
Type D
Type E

map 9 Different typology of the controviali

fig. 83 Scheme of the controviali section typologies



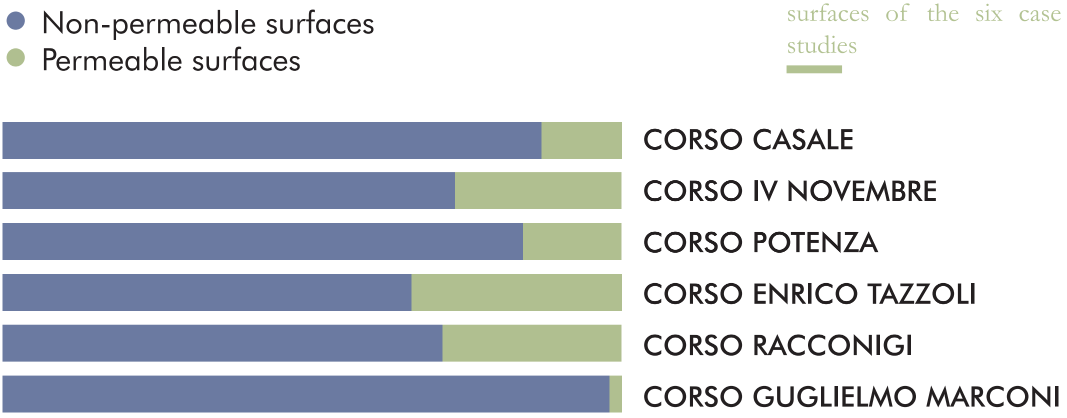
3.2 Case studies

In order to examine the microclimatic conditions of the avenues in Turin, six case studies were selected (map 10) based on the street section typology, different surface coverage, aspect ratio, orientation, mobility type. Each case study belongs to different type of street section.

The case studies have different ratio of permeable and non-permeable surfaces in their sections (fig 85). Corso Enrico Tazzoli has the biggest permeable area or 34%, while Corso Marconi has almost none and is covered entirely with asphalt.

map 10 Case studies

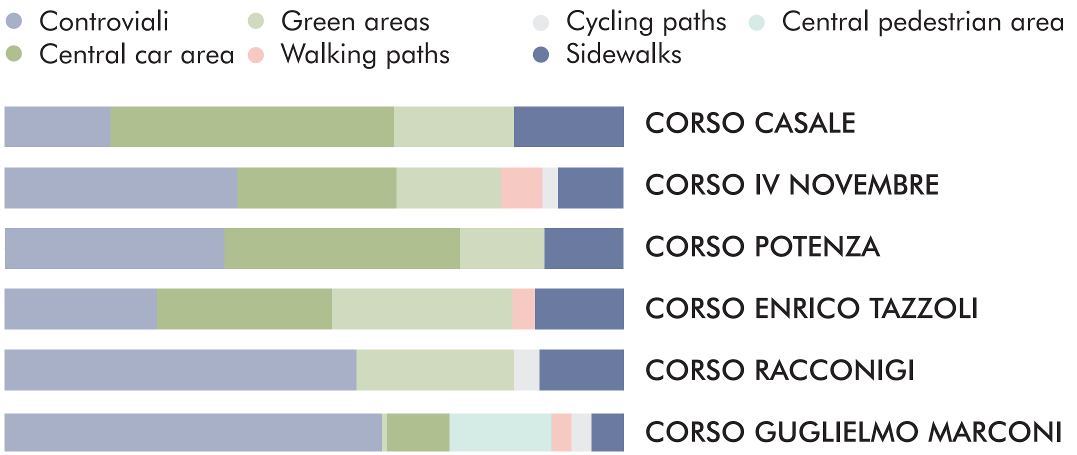
fig. 85 Ratio of permeable and non-permeable surfaces of the six case studies




CASE STUDIES
Corso Casale
Corso Enrico Tazzoli
Corso Potenza
Corso IV Novembre
Corso Marconi
Corso Racconigi

The case studies have different composition each (fig. 86), but the most common elements are controviali, central car area and green areas.
Half of the case studies have walking paths: Corso IV Novembre, Corso Enrico Tazzoli and Corso Guglielmo Marconi (fig. 90). Similarly, cycling paths are present in Corso IV Novembre, Corso Racconigi and Corso Guglielmo Marconi (fig. 91).
In Corso Racconigi, the central area is green, with cycling paths along it.
Corso Marconi in one part has parking, walking and cycling area in the centre, while in the other it was transformed into a pedestrian are covered in asphalt.

fig. 86 Composition of the case studies



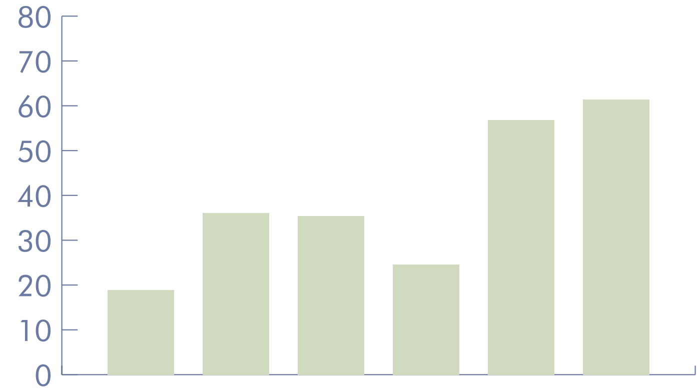


fig. 87 Percentage of controviali in the street section

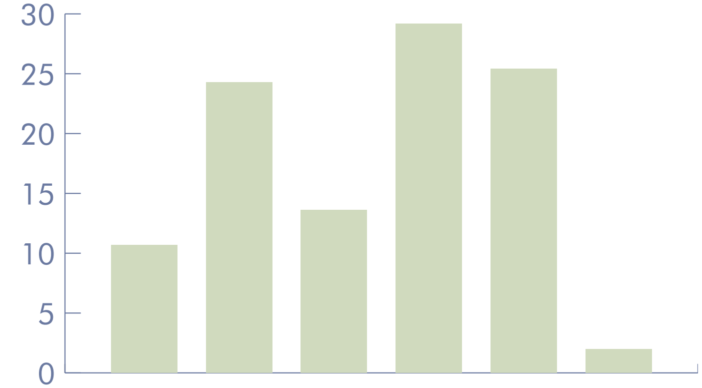


fig. 88 Percentage of green areas in the street section

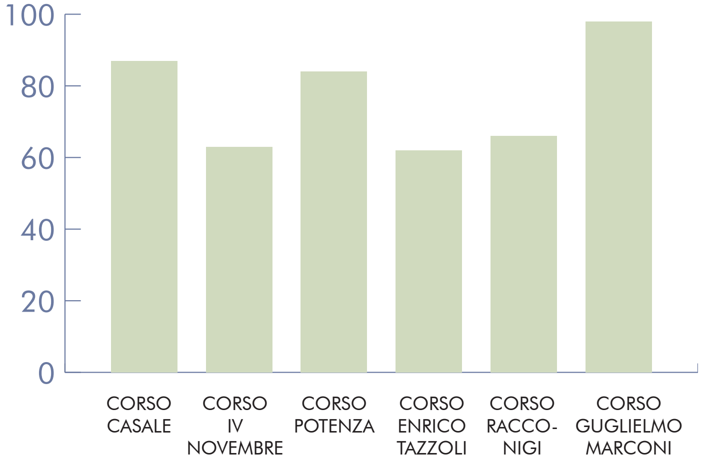


fig. 89 Percentage of asphalt in the street section

Three urban canyons are one sided: Corso Casale, Corso IV Novembre and Corso Enrico Tazzoli. The canyons are rather shallow, the deepest one being Corso Racconigi, with aspect ratio of 0,54 (fig. 92).

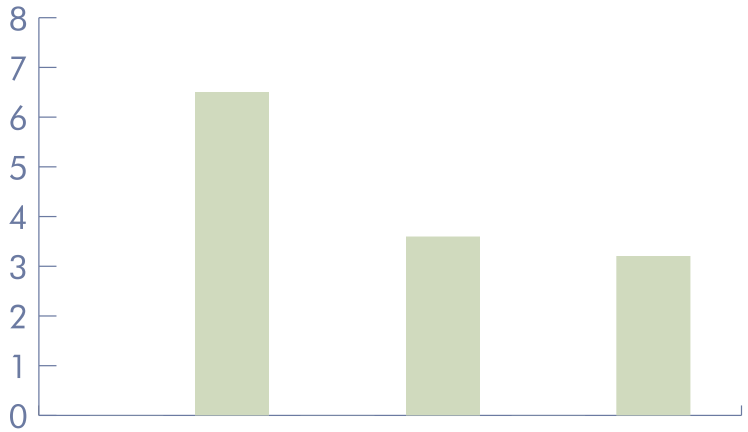


fig. 90 Percentage of walking paths in the street section

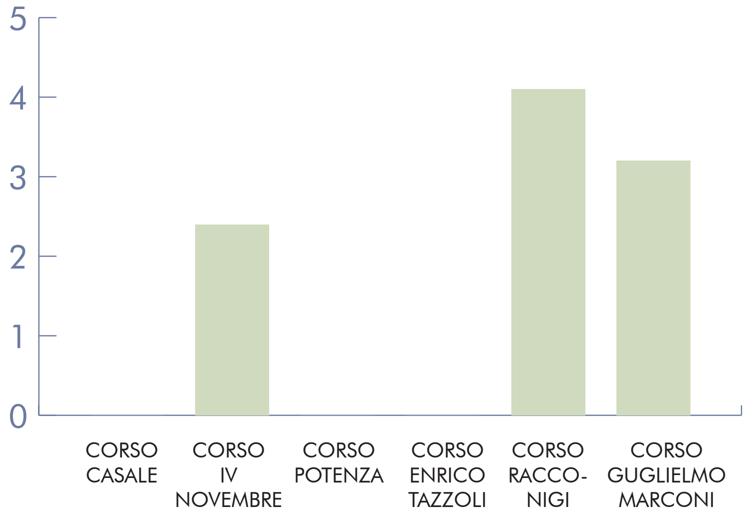


fig. 91 Percentage of cycling paths in the street section

fig. 92 Urban canyons with aspect ratio

The case studies have different orientation (fig. 93) in order to assess the importance of this factor in the microclimate conditions. The main orientations are NE-SW and NW-SE, but they all have a different angle.
Aspect ratio and orientation are important elements of the urban geometry that affect the microclimate and cannot be assessed separately.

fig. 93 Orientation of the case studies

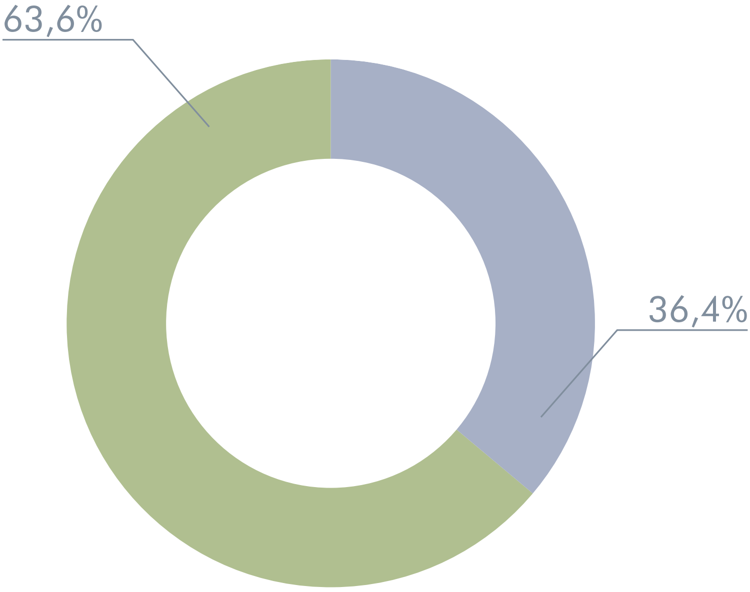
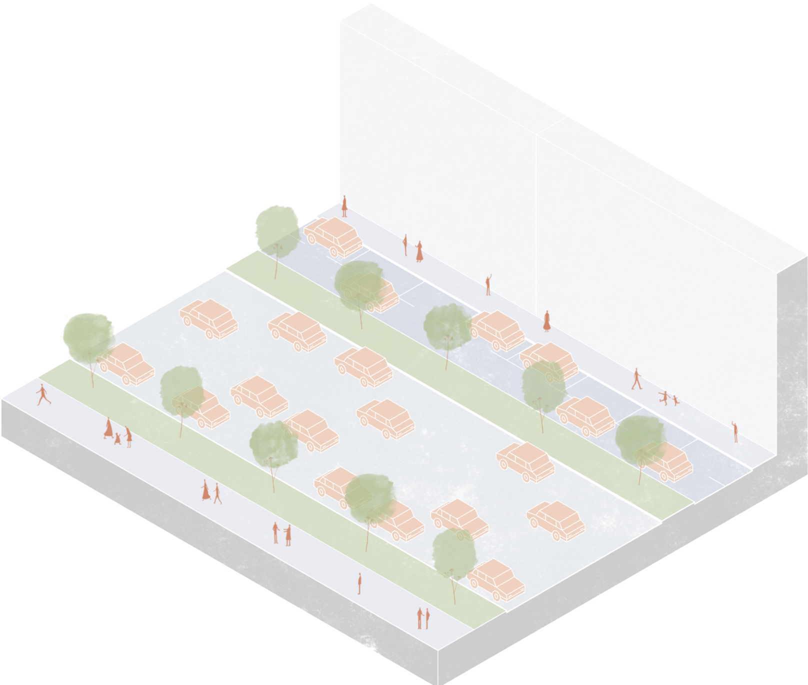


fig. 94 Controviali types in the case studies

The case studies have only two type of controviali, Type B and Type C (fig. 94), which are the most common types.
Corso IV Novembre has both types of controviali, one on each side. Corso Marconi, Corso Enrico Tazzoli and Corso Racconigi have controviali Type C, with parking on both sides. Corso Casale and Corso Potenza have parking only on one side, therefore their controviali belong to Type B.



CORSO CASALE

3.2.1 Corso Casale

fig. 95 Corso Casale orientation

Corso Casale belongs to Type 1, which means that it has controviale on one side only. It is located along the river Po and a green area, which are important elements of the microclimate. The part of Corso Casale which was assessed is located between Piazza Gran Madre di Dio and Ponte Regina Margherita.
Corso Casale is oriented NE-SW (fig. 95). The aspect ratio of this urban canyon is 0,46 (fig. 96). It is one sided canyon, with average building height of 14,4 m. Total street width, including sidewalks, is 31 m.
Majority of the surface of the street area (considering the space between the two sidewalks) is covered in asphalt. Precisely, 87% of the area is covered in asphalt, while the remaining 13% is covered with permeable surface (fig 97).

fig. 96 Corso Casale urban canyon with aspect ratio

fig. 97 Corso Casale surfaces

fig. 98 Corso Casale orto photo with simulation area


Simulated area
100 m

Most of the area is dedicated to hard mobility, with the central area accounting for 45,8% and controviale 17,1% of the overall surface (fig. 99).

Total street width: 31 m
Controviale width: 5,3 m
Central car area width: 14,2 m
Green area width: 3 m
Green area along sidewalks width: 3 m
Sidewalks width: 5,5 m

Another important characteristic of Corso Casale is presence of chestnut trees along the whole street. They provide shade both for the cars and the pedestrians.
The controviale in Corso Casale is type B, it has parking only on the right side, while the left one is a driving lane.

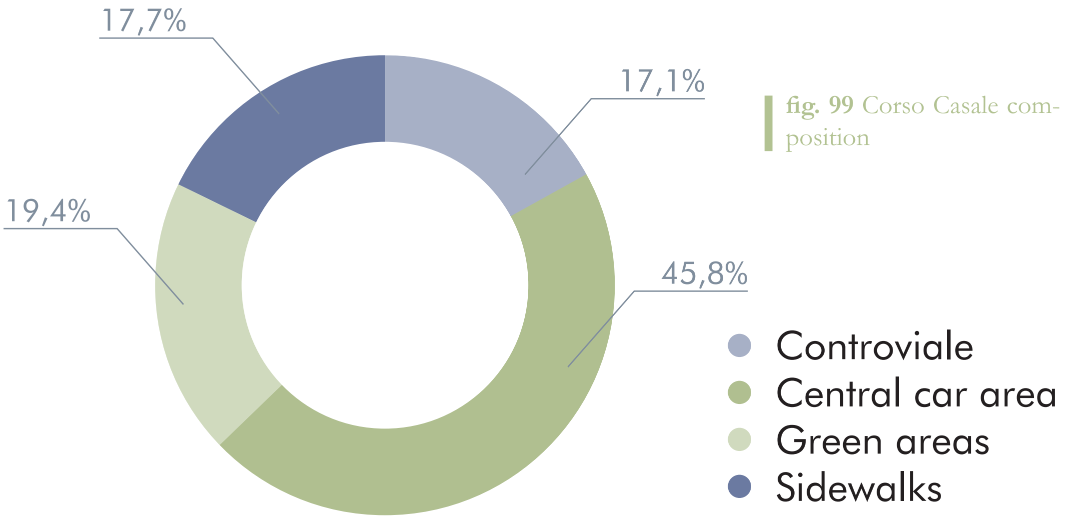
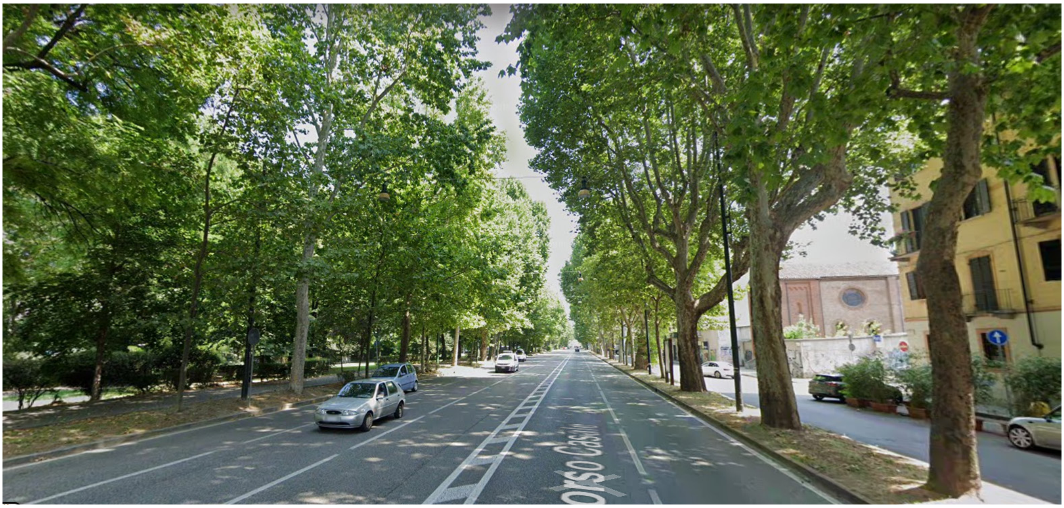
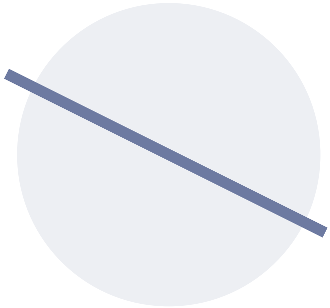


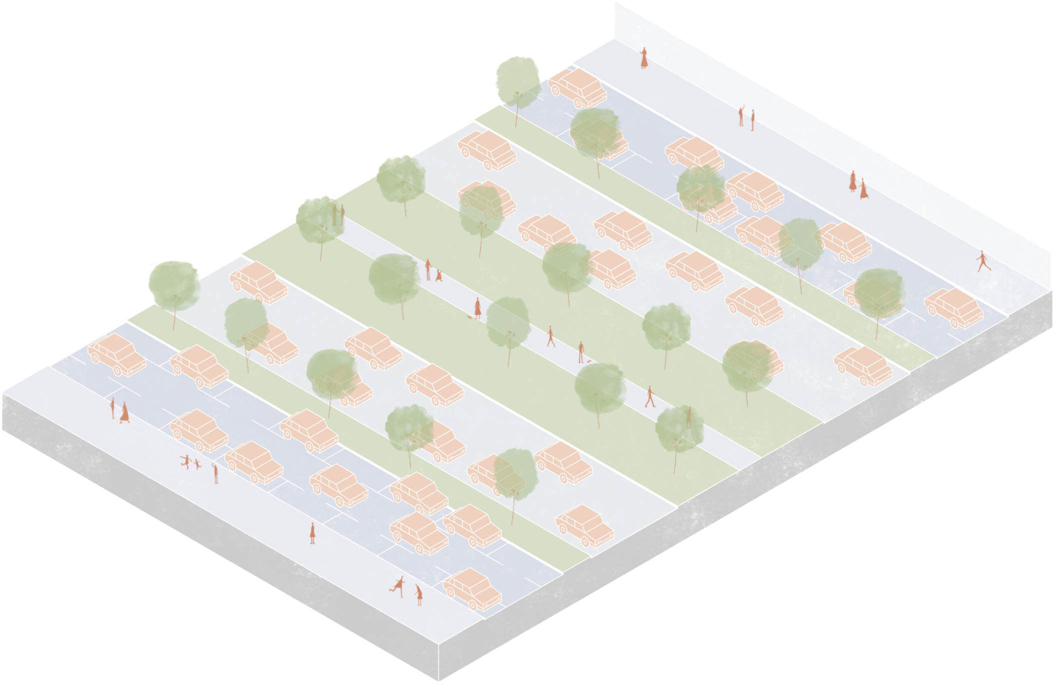
fig. 99 Corso Casale composition

fig. 100 Corso Casale street view
source: google earth

fig. 101 Corso Casale street view
source: google maps







CORSO ENRICO TAZZOLI

3.2.2 Corso Enrico Tazzoli

fig. 102 Corso Enrico Tazzoli orientation

Corso Enrico Tazzoli has street section Type 2, with central area dedicated to cars and controviali on both sides. It is located at the south part of Turin, at the periphery. The examined section is positioned between Corso Orbassano and Corso Siracusa.

Corso Tazzoli is oriented NW-SE (fig. 102). The aspect ratio of the urban canyon is 0,05 (fig. 103). It is one sided canyon, bounded only one side with a solid fence with a height of 3 m. Total street width, including sidewalks, is 56,1 m.

The surface of the street area (considering the space between the two sidewalks) is covered asphalt, greenery and pavement. Precisely, 62% of the area is covered in asphalt, 34% is covered with permeable surface while 4% is covered in pedestrian paths (fig. 104).

fig. 103 Corso Enrico Tazzoli urban canyon with aspect ratio

fig. 104 Corso Enrico Tazzoli surfaces

fig. 105 Corso Enrico Tazzoli orto photo with simulation area


Simulated area
100 m

One of the characteristics of this street is a wide central area between the car lanes, containing greenery and walking path. Due to this aspect, there is more balanced ratio of permeable and non-permeable surfaces than in the other case studies. Non-permeable surfaces cover 66% of the area, while the remaining 34% of the area is covered with permeable surfaces.

Total street width: 56,1 m
Controviali width: 7,2 m and 6,6 m
Central car area width: 15,8 m
Green areas width: 16,4 m
Walking path width: 2 m
Sidewalks width: 8,1 m

Both controviali in Corso Tazzoli are type C, with a central driving lane and two parking lanes, one on each side.

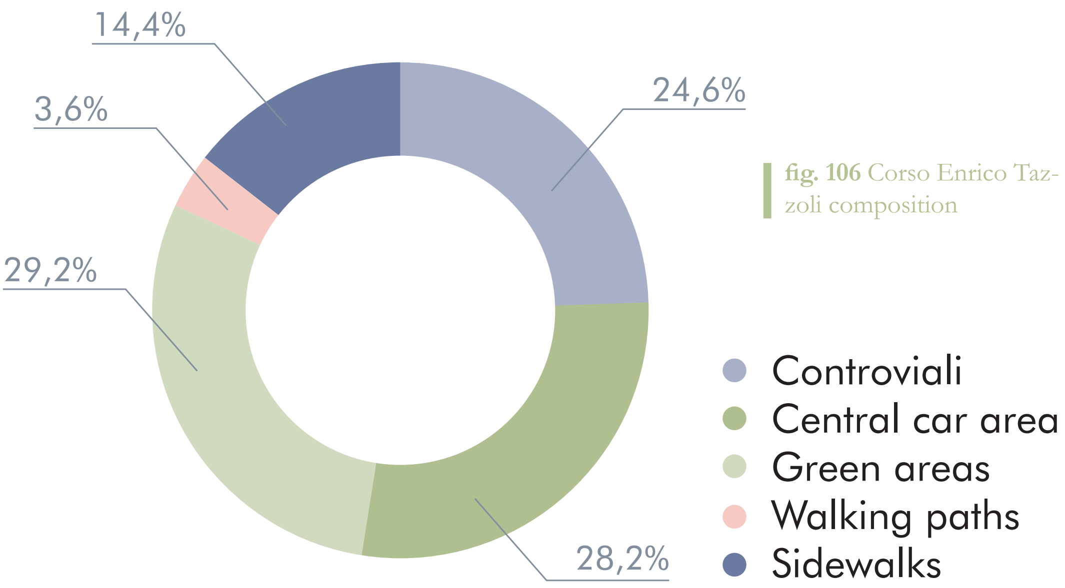
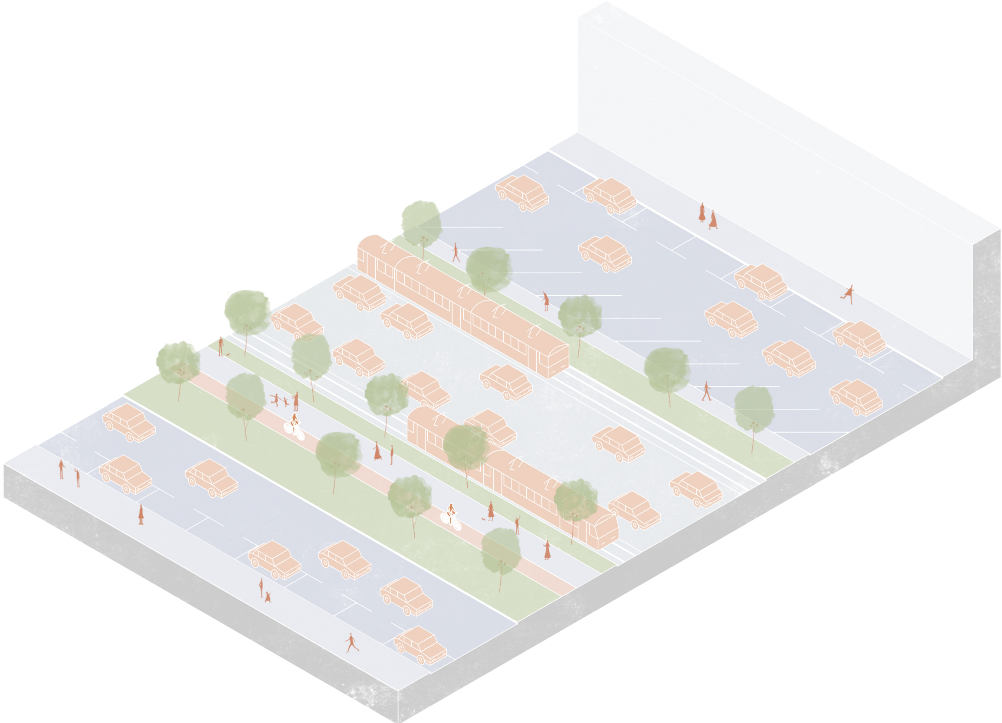


fig. 106 Corso Enrico Tazzoli composition

fig. 107 Corso Enrico Tazzoli street view
source: google maps

fig. 108 Corso Enrico Tazzoli street view
source: google maps



CORSO IV NOVEMBRE

3.2.3 Corso IV Novembre

fig. 109 Corso IV Novembre orientation

Corso IV Novembre belongs to street section Type 3, with central area dedicated to cars, with tram rails in the asphalt and controviali on both sides. The examined section is positioned between Corso Sebastopoli and via Caprera.
Corso IV Novembre is oriented NE-SW (fig. 109). The aspect ratio of the urban canyon is 0,14 (fig. 110). It is one sided canyon, with average building height 10,1 m. Total street width, including sidewalks, is 59,2 m.
The surface of the street area (considering the space between the two sidewalks) is covered asphalt, greenery, walking and cycling pavement. Precisely, 63% of the area is covered in asphalt, 23% is covered with permeable surface, 7% is covered in pedestrian paths and 3 % in cycling paths (fig. 111).

fig. 110 Corso IV Novembre urban canyon with aspect ratio

fig. 111 Corso IV Novembre surfaces

fig. 112 Corso IV Novembre orto photo with simulation area

Simulated area
100 m

Corso IV Novembre is located along the park and therefore there is a lot of greenery present on one side of the street. The street itself contains rows of high chestnut trees along its whole length.

Total street width: 59,2 m
Controviali width: 13,5 m and 8,8 m
Central car area width: 15,1 m
Tram rails along car area: 5 m
Green areas width: 10 m
Walking path width: 4 m
Sidewalks width: 1,5 m

Corso IV Novembre has two types of controviali. Controviale on the west side is type C, with a central driving lane and two parking lanes, one on each side. Controviale on the east side is type B, with one driving lane and one parking lane.

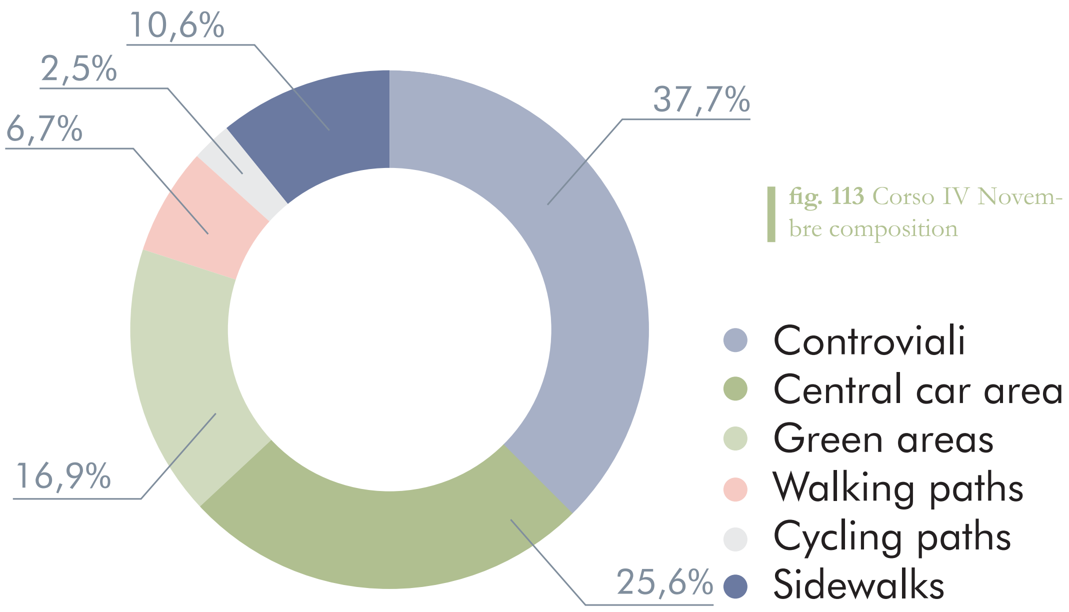
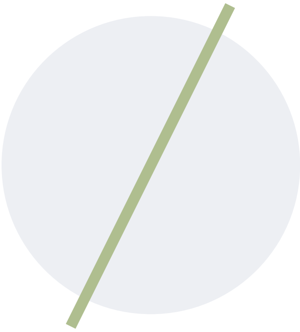
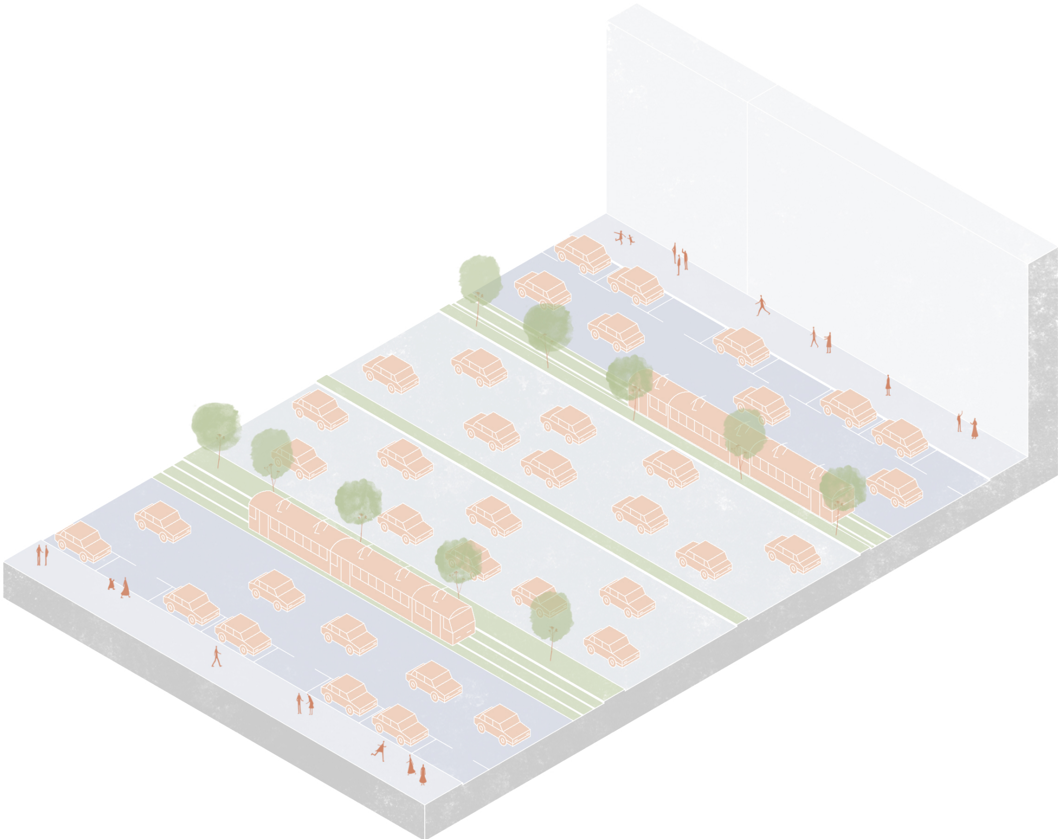


fig. 113 Corso IV Novembre composition

fig. 114 Corso IV Novembre street view
source: google maps

fig. 115 Corso IV Novembre street view
source: google earth





CORSO POTENZA

3.2.4 Corso Potenza

fig. 116 Corso Potenza orientation

Corso Potenza is located at the northern part of Turin. It belongs to street section Type 4, with controviali on both sides, and central car area and tram rails at its edges, within green areas. The examined section is located between via Domenico Morelli and via Terni.
Corso Potenza is oriented NE-SW (fig. 116). The aspect ratio of the urban canyon is 0,28 (fig. 117), with the average building height 15,7 m. Total street width, including sidewalks, is 55,7 m.
The surface of the street area (considering the space between the two sidewalks) is covered asphalt and greenery. Precisely, 84% of the area is covered in asphalt, while only 16% is covered with permeable surface (fig. 118).

fig. 117 Corso Potenza urban canyon with aspect ratio

fig. 118 Corso Potenza surfaces

fig. 119 Corso Potenza orto photo with simulation area

Simulated area
100 m

Corso Potenza is characterized with two rows of high chestnut trees which provide a lot of shade to the cars and pedestrians.

Total street width: 55,7 m
Controviali width: 9,2 m and 10,5 m
Central car area width: 21,2 m
Green areas width: 7,6 m
Tram rails within green areas: 5 m
Sidewalks width: 7,2 m

Both controviali in Corso Potenza are type B, with a driving lane and one parking lane next to the sidewalk.

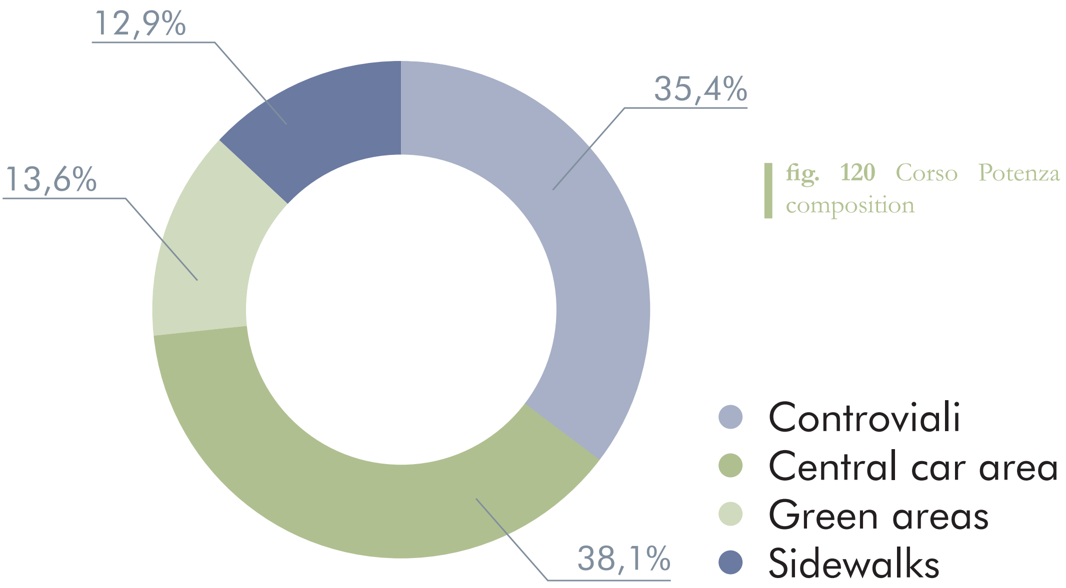
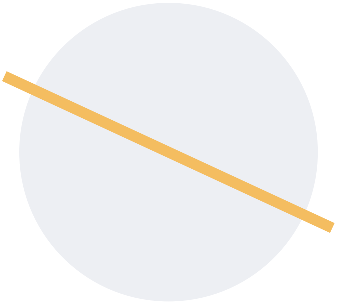
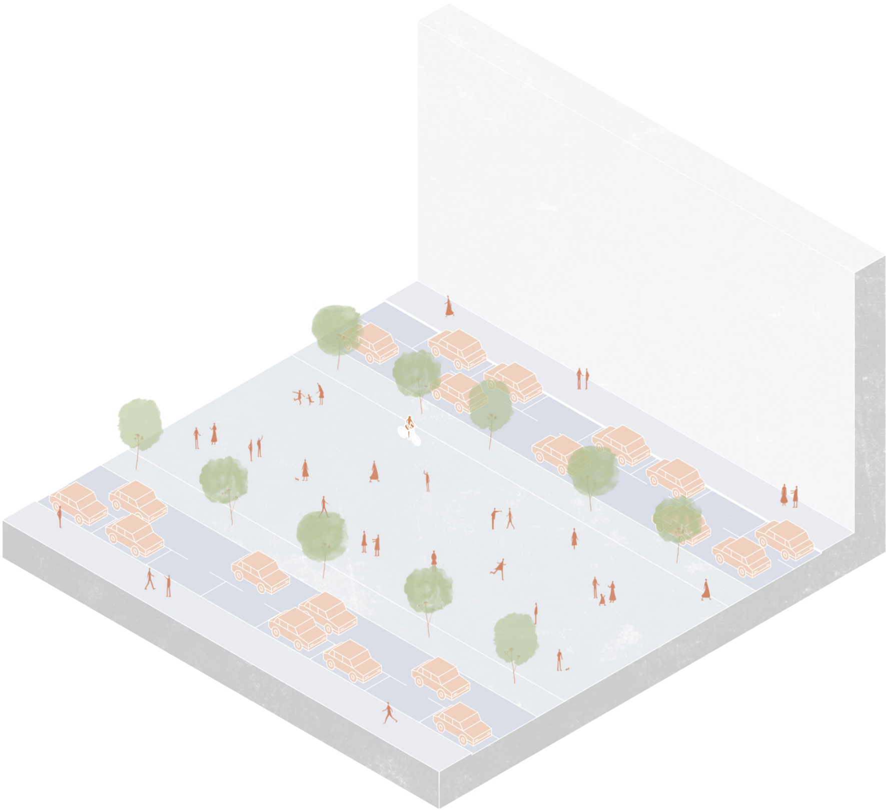


fig. 120 Corso Potenza composition

fig. 121 Corso Potenza street view
source: google maps

fig. 122 Corso Potenza street view
source: google earth





CORSO GUGLIELMO MACONI

3.2.5 Corso Guglielmo Marconi

fig. 123 Corso Guglielmo Marconi orientation

Corso Marconi is located close to the centre of Turin, in an urban area of San Salvario neighbourhood. It belongs to street section Type 5, with controviali on both sides, and asphalt areas for parking or soft mobility between them. The simulation was done for the whole street.
Corso Marconi is oriented NW-SE (fig. 123). The aspect ratio of the urban canyon is 0,50 (fig. 124). It is one of the two deepest canyons examined, with the average building height 20,6 m. Total street width, including sidewalks, is 41,2 m.
The surface of the street area (considering the space between the two sidewalks) is almost completely covered in asphalt, permeable surface exists only in a small area around the trees (fig. 125). It consists of two parts that differ only in the central area. In the east part, until via Madama Cristina, central area consists of a parking, cycling and walking paths. In the west part, close to Valentino park, the central area has recently been transformed into a pedestrian area, closed for cars.

fig. 124 Corso Marconi urban canyon with aspect ratio

fig. 125 Corso Marconi surfaces

fig. 126 Corso Guglielmo Marconi orto photo with simulation area

Simulated area
100 m

Although there street is almost entirely covered in asphalt, the vegetation is present within Corso Marconi. There are two rows of high chestnut trees along the whole street, between the controviali and the central area.

Total street width: 41,2 m
Controviali width: 12,1 m and 11,9 m
Walking path width: 2,5 m
Cycling path width: 2,5 m
Central parking width: 8 m
Central pedestrian area width:13 m
Sidewalks width: 4,2 m

Both controviali in Corso Marconi are type C, with a central driving lane and two parking lanes, one on each side.

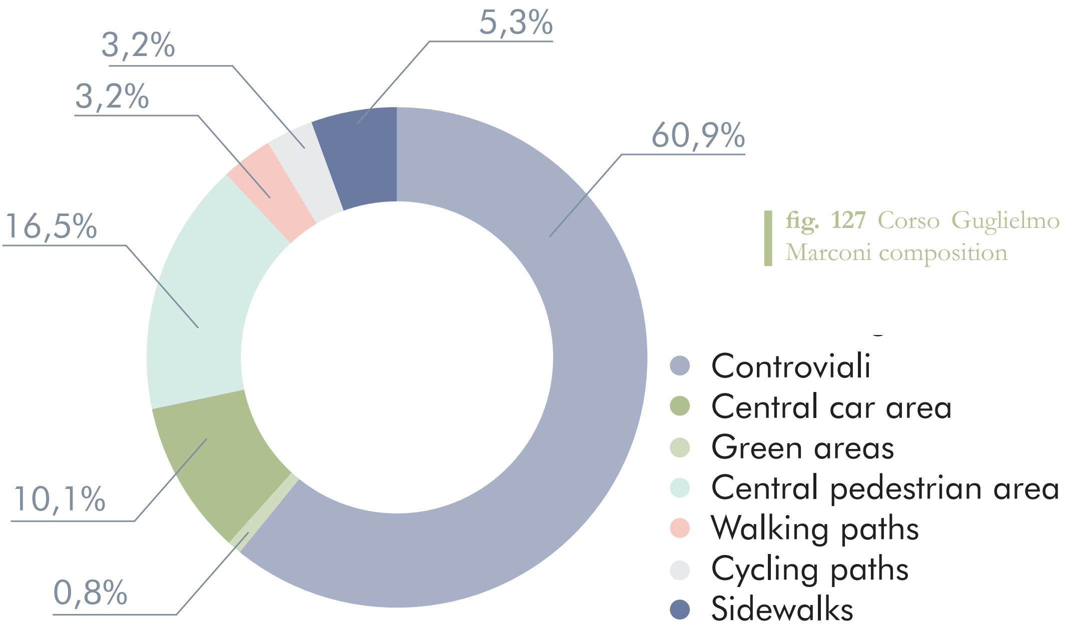
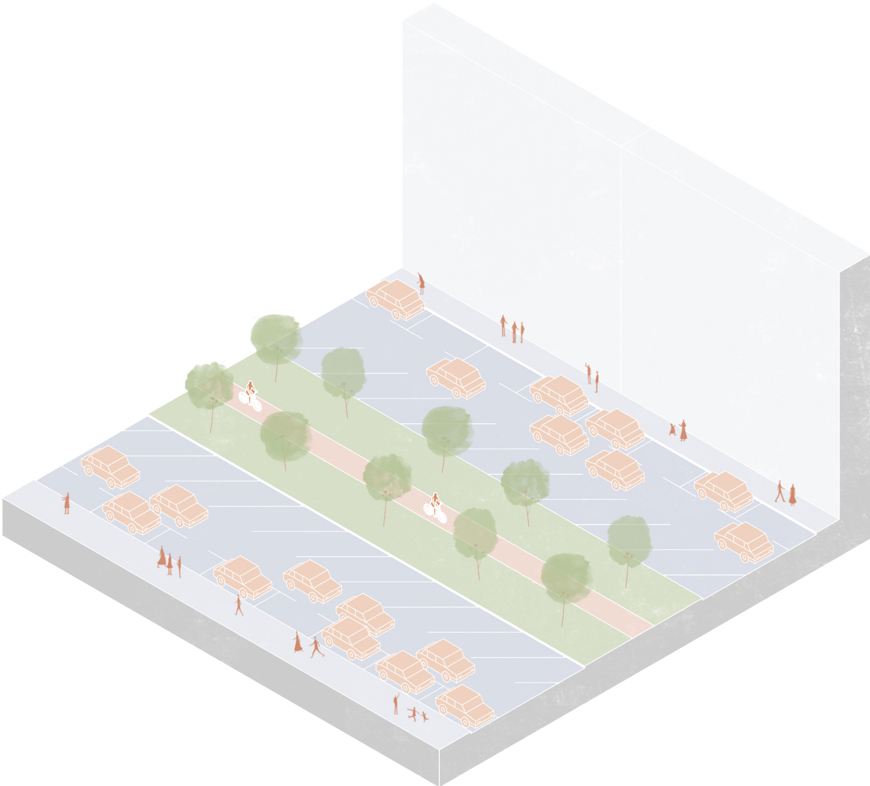


fig. 127 Corso Guglielmo Marconi composition

fig. 128 Corso Marconi street view
source: google maps

fig. 129 Corso Marconi
source: photo by the author



CORSO RACCONIGI

3.2.6 Corso Racconigi

fig. 130 Corso Racconigi orientation

Corso Racconigi belongs to street section Type 6, with controviali on both sides and green areas between them. The simulation was done for the segment between Piazza Marmolada and Piazza di Robilant Carlo Generale.
Corso Racconigi is oriented NW-SE (fig. 130). The aspect ratio of the urban canyon is 0,54 (fig. 131). It is the deepest canyon examined, with the average building height 19,6 m. Total street width, including sidewalks, is 36,6 m.
The surface of the street area (considering the space between the two sidewalks) is covered in asphalt, permeable surface and cycling path (fig. 132). Asphalt covers 66% of the area, cycling paths cover 5%, while the remaining 29% are covered in permeable surfaces.

fig. 131 Corso Racconigi urban canyon with aspect ratio

fig. 132 Corso Racconigi surfaces

fig. 133 Corso Racconigi orto photo with simulation area


Simulated area
100 m

Corso Racconigi differs from the other types due to the surface of the central area. It is covered in grass and a cycling path, placing pedestrians and cyclists in the middle of the street. In the function aspect, it is similar to Corso Marconi, but however, they differ in the surface cover of the central area.

Total street width: 36,6 m
Controviali width: 10,4 m and 10,4 m
Cycling paths width: 1,5 m
Green areas width: 9,3 m
Sidewalks width: 5 m

Both controviali in Corso Racconigi are type C, with a central driving lane and two parking lanes, one on each side.

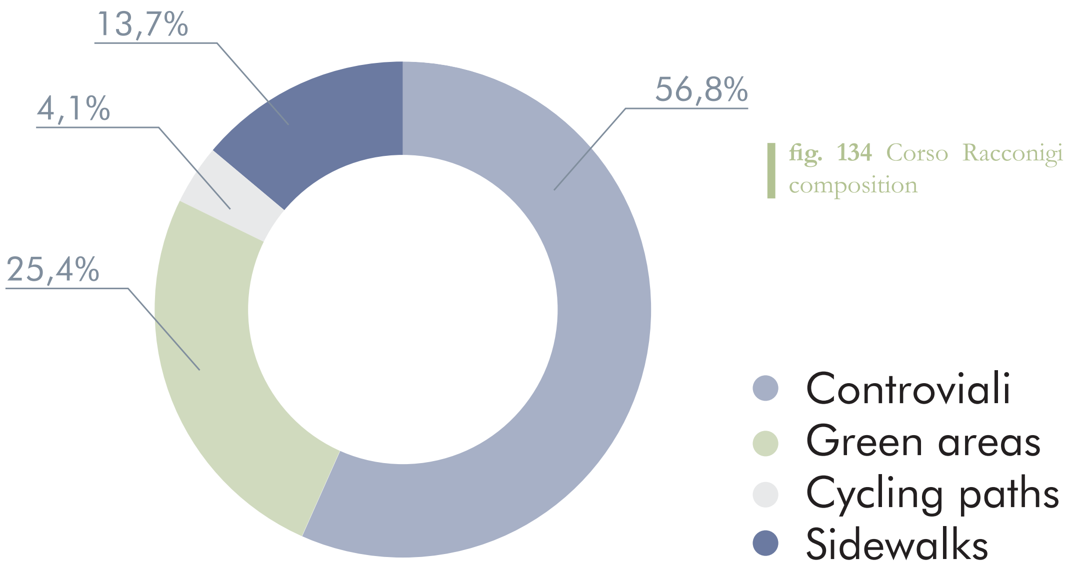


fig. 134 Corso Racconigi composition

fig. 135 Corso Racconigi street view
source: google earth

fig. 136 Corso Racconigi street view
source: google earth

3.3 Microclimate modelling

3.3.1 ENVI-met

As explained in the chapter 1.3.4, ENVI-met is a CFD 3D microclimate modelling software based on the laws of fluid dynamics and thermodynamics. The software simulates the climatological interactions between surfaces, plants and the atmosphere. It analyses the effects of planning measures on the urban climate as well.

ENVI-met is able to calculate and simulate (ENVI-met, 2022):

- Short and long wave radiation fluxes
- Surfaces and wall temperatures
- Water and heat exchange
- Dispersion of gases and particles
- Evapotranspiration and sensible heat fluxes
- Façade and roof greening
- Various biometeorological metrics

The software is grid-based and has high temporal and spatial resolution. Horizontal resolution typically varies from 1-10 m, with simulation period between 1 and 5 days. The model area size is commonly between 50x50 and 500x500 grid cells horizontally and 20-50 cells vertically.

The software is comprised of six modules or programs:

1. Monde
2. Spaces
3. ENVI-guide
4. ENVI-core
5. BIO-met
6. Leonardo

fig. 137 Monde

fig. 138 Spaces

fig. 139 ENVI-guide

fig. 140 ENVI-core

fig. 141 BIO-met

fig. 142 Leonardo

In the simulations of the case studies, ENVI-met version 5.0.2 was used. Almost all of the modules were used in the simulation process. Spaces (fig. 138) was used to model the areas. Due to difference in the size of the areas, simulation complexity and time, the first case study, Corso Casale, was modelled with a resolution 5x5x2 m, while all the rest were modelled in 4x4x2 m. Sizes of the simulated areas vary, the smallest ones being Corso Potenza and Corso IV Novembre, with the dimensions 400x500 m. The biggest simulated area is Corso Casale, with the dimensions 800x500 m. The vertical dimension is typically twice the hight of the highest building in the area.
ENVI-met has four additional modules or programs: Projects/Workspaces, Database Manager, Albero and TreePass (available from 2022), which had impact on the modelling phase. Projects/Workspaces was used to set up individual settings for each case study. Database manager allowed to create and modify database of surfaces and their setup. Albero was used to modify and create vegetation.
ENVI-guide (fig. 139) module was used to set up the simulation input data. All the simulations were made for 48h hours, but only the results of the last 24h were considered in order to avoid errors.
ENVI-core (fig. 140) was used to run the simulation. The average time of the simulations was 5 days per simulation, due to the complexity of the processes. The support was gained from SDG 11 Lab at Politecnico di Torino for running the simulations. Part of the simulations was done on the computers in the Lab.
BIO-met (fig. 141) was used to calculate PET index. Leonardo (fig. 142) was used to analyse model results and graphically represent the results such as maps and sections.

3.3.2 Input data

In the module Spaces, the input data for each case study was the same except for the dimensions and resolution. The location is Turin, with latitude 45.07 and longitude 7.69, time zone Central European Standard Time and reference longitude 15.00. All of the areas had the same number of nesting grids, 4. Nesting grids are placed at the borders of the area in order to avoid edge errors in the simulations. Wall material was set as Default Wall - moderate insulation, while roof material was Roofing: Tile. Dominant surfaces are asphalt, vegetation, light concrete (mainly in the courtyards) and grey concrete (for the sidewalks and walking paths).

Corso Casale is the only case study with a height difference of the ground, due to the slope along the river. The height difference is 7 m.
Dimensions: 800x500 m
Resolution: 5x5x2 m
Number of grids: 160x100x29

Corso Enrico Tazzoli
Dimensions: 700x400 m
Resolution: 4x4x2 m
Number of grids: 175x100x35

Corso IV Novembre
Dimensions: 400x500 m
Resolution: 4x4x2 m

Number of grids: 100x125x30

Corso Potenza
Dimensions: 400x500m
Resolution: 4x4x2 m
Number of grids: 100x125x35

Corso Guglielmo Marconi
Dimensions: 700x400 m
Resolution: 4x4x2 m
Number of grids: 175x100x35

Corso Racconigi
Dimensions: 500x700 m
Resolution: 4x4x2 m
Number of grids: 125x175x35

Simulation parameters were set in ENVI-guide module. They were the same for all the case studies. The simulation date was set as 19.07.2020, at 00:00 h. This date was chosen as the hottest of the year. The simulation time was set to 48 h. All the avaliable CPU cores were used for the simulations.
The software needs some information about the surrounding meteorology and based on the available information one og the two different metorological boundary conditions can be used to provide information to the model: simple forcing and full forcing. Simple forcing was used for all the case studies. Input parameters, which include air temperature, relative humidity, wind speed and direction for every hour of the day (tab. x) were obtained from Arpa Piemonte website. It is the data taken from the closest meteorological station.
The simulation was run through ENVI-core module. Each simulation lasted approximately 5 days, due to the size of the areas, resolution and complexity of the processes.

Hour	T air °C	R.H. %	Wind speed (m/s)	Wind direction
00:00:00	22,5	76	1,5	67
01:00:00	21,6	81	1,8	61
02:00:00	20,5	85	1,2	45
03:00:00	19,9	90	1,2	0
04:00:00	19,1	92	1,4	197
05:00:00	19,1	89	1,6	216
06:00:00	21,4	80	1,1	101
07:00:00	23,8	62	1,9	74
08:00:00	25,9	52	1,3	69
09:00:00	27,9	46	1	328
10:00:00	29,9	48	1,2	49
11:00:00	31	39	2,3	93
12:00:00	31,8	38	1,7	72
13:00:00	32,8	34	2,8	53
14:00:00	33,1	38	1,9	48
15:00:00	33	37	2,5	66
16:00:00	32,7	42	2,4	82
17:00:00	30,9	55	1,6	177
18:00:00	27,5	56	1,8	217
19:00:00	25,7	60	2	53
20:00:00	24,1	69	1,6	51
21:00:00	24,6	68	2	223
22:00:00	23,8	72	1,6	190
23:00:00	23,4	72	2,4	207

tab. 4 Input values
source: http://www.arpa.piemonte.it/dati-ambientali/richiesta-dati-orari-meteorologici

3.4 Results

Simulation results are viewed and analysed in Leonardo module. It allows to create 2D and 3D maps to visualise the results.
Four parameters were analysed: potential air temperature, surface temperature, wind speed and PET. The Physiologal Equivalent Temperature (PET) is a thermal comfort index that is based on a prognostic model of the human energy balance that computes the skin temperature, the body core temperature, the sweat rate and, as an auxiliary variable, the clothing temperature (ENVI-met, 2022). PET is obtained through BIO-met module and then analysed and visualised in Leonardo.
The most "critical" hour of the day, the one with the highest air temperature, is 14:00 h. The results were taken for three representative hours of the day: 10:00 h, 14:00 h and 18:00 h. All the data, except for the surface temperature, was taken for the height 1,8 m, which is an average height of a human. For each parameter, the legends were adjusted to show the same data for every map in the same hour, in order to make them easier to compare. Tables on the following pages contain information on minimum and maximum values for each parameter and hour, along with the step size used to synchronize the legends.
Due to the plentiful amount of the results produced, only the results for the most critical hour will be demonstrated in this chapter, while the remaining results can be found in the Appendix.

Potential air temperature (°C)	Corso Casale	Corso Enrico Tazzoli	Corso IV Novembre	Corso Potenza	Corso Guglielmo Marconi	Corso Racconigi	Max and min values	Step size
Min 10:00	26,24	27,54	27,18	27,35	26,99	**24,88**	24,88	0,58
Max 10:00	28,46	**30,41**	29,27	29,99	29,92	30,29	30,41	
Min 14:00	**29,20**	31,43	30,80	30,96	30,47	29,38	29,20	0,51
Max 14:00	32,36	34,00	33,78	34,38	34,32	**34,62**	34,62	
Min 18:00	27,26	28,83	28,50	28,76	28,20	**26,46**	26,46	0,58
Max 18:00	29,06	**32,18**	31,21	31,01	30,81	31,06	32,18	

tab. 5 Potential air temperature legend harmonization, extracted from ENVI-met data

Surface temperature (°C)	Corso Casale	Corso Enrico Tazzoli	Corso IV Novembre	Corso Potenza	Corso Guglielmo Marconi	Corso Racconigi	Max and min values	Step size
Min 10:00	19,84	19,85	19,85	19,85	19,41	**16,02**	16,02	3,01
Max 10:00	37,97	**47,13**	45,77	45,85	45,24	46,91	47,13	
Min 14:00	19,85	19,85	19,85	19,85	19,85	19,85	19,85	3,58
Max 14:00	47,62	55,98	55,73	**56,08**	54,80	55,61	56,08	
Min 18:00	19,85	19,85	19,85	19,85	19,85	19,85	19,85	2,40
Max 18:00	37,50	**45,39**	44,30	44,54	44,33	44,63	45,39	

tab. 6 Surface temperature legend harmonization, extracted from ENVI-met data

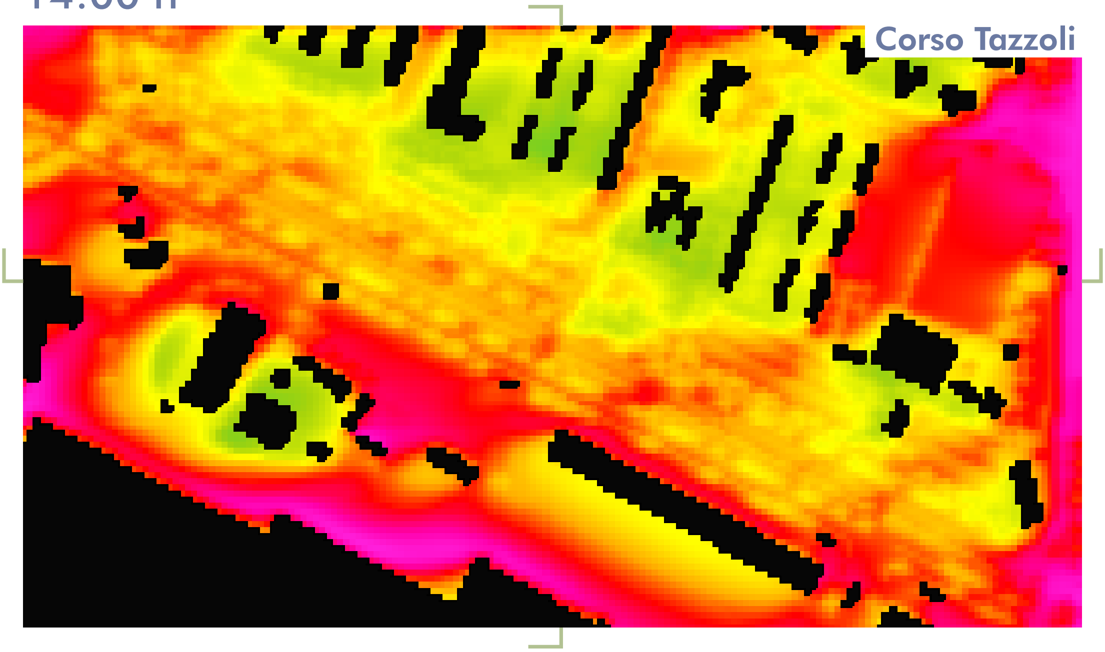
Wind speed (m/s)	Corso Casale	Corso Enrico Tazzoli	Corso IV Novembre	Corso Potenza	Corso Guglielmo Marconi	Corso Racconigi	Max and min values	Step size
Min 10:00	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,23
Max 10:00	**2,57**	1,39	1,63	1,62	1,25	1,65	2,57	
Min 14:00	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,21
Max 14:00	**2,54**	1,36	1,58	1,56	1,20	1,61	2,54	
Min 18:00	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,22
Max 18:00	**2,55**	1,37	1,58	1,56	1,21	1,66	2,55	

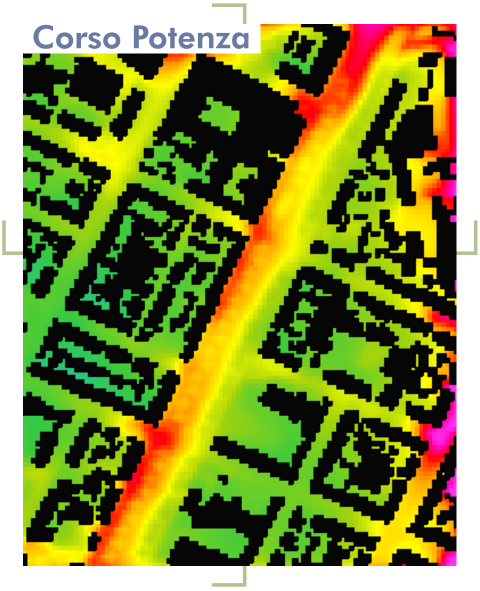
tab. 7 Wind speed legend harmonization, extracted from ENVI-met data

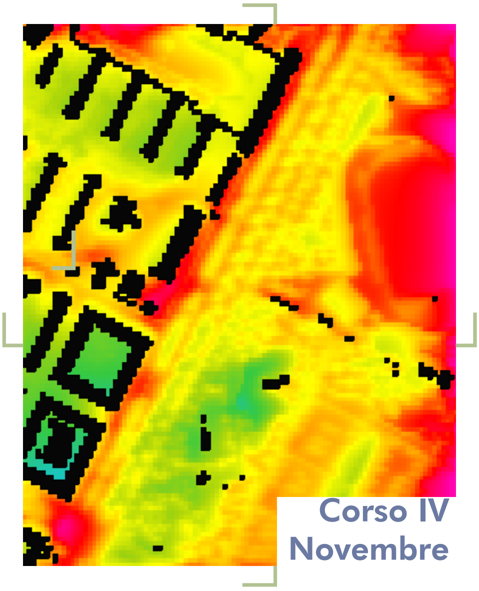
PET (°C)	Corso Casale	Corso Enrico Tazzoli	Corso IV Novembre	Corso Potenza	Corso Guglielmo Marconi	Corso Racconigi	Max and min values	Step size
Min 10:00	22,40	24,67	23,01	23,89	22,16	**20,27**	20,27	4,39
Max 10:00	65,63	59,72	64,92	65,34	66,25	**66,81**	66,81	
Min 14:00	26,39	28,16	27,41	28,14	25,81	**24,63**	24,63	4,85
Max 14:00	70,98	66,95	69,94	71,75	**75,01**	72,48	75,01	
Min 18:00	**21,80**	24,81	23,51	25,05	23,70	22,63	21,80	3,76
Max 18:00	57,07	53,89	54,85	58,36	59,99	**61,65**	61,65	

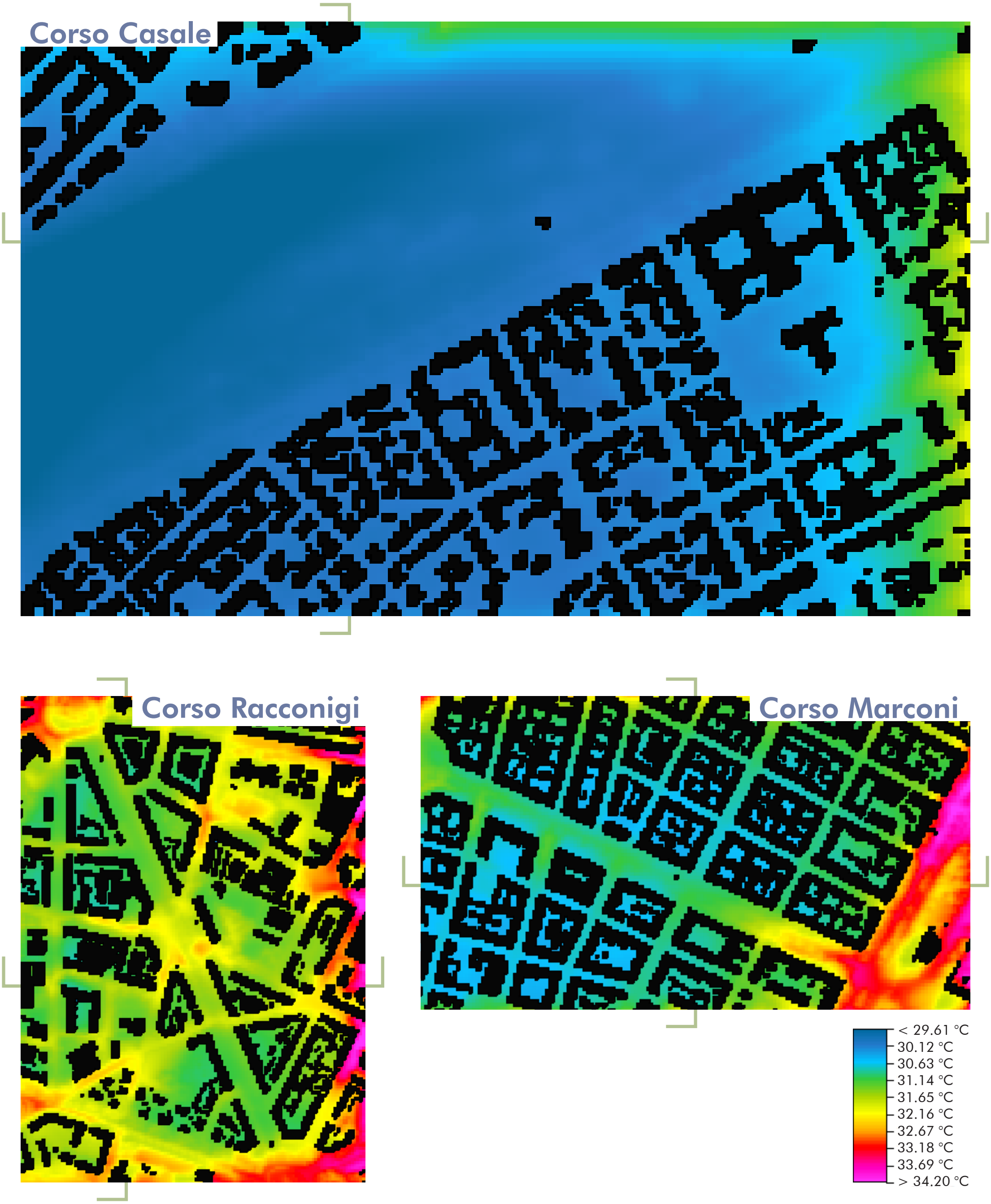
tab. 8 PET legend harmonization, extracted from ENVI-met data

3.4.1 Potential Air Temperature at 14:00 h



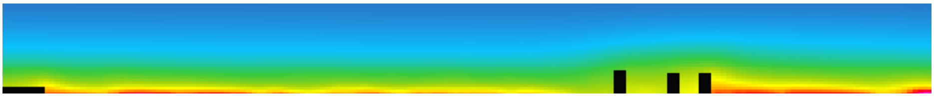




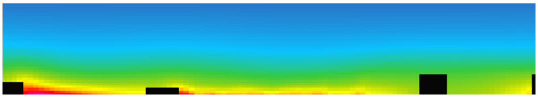

Corso Casale
Corso Racconigi
Corso Marconi
< 29.61 °C
30.12 °C
30.63 °C
31.14 °C
31.65 °C
32.16 °C
32.67 °C
33.18 °C
33.69 °C
> 34.20 °C

3.4.2 Potential Air Temperature urban sections at 14:00 h

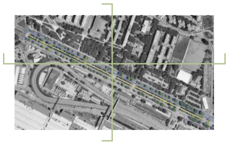
Corso Tazzoli

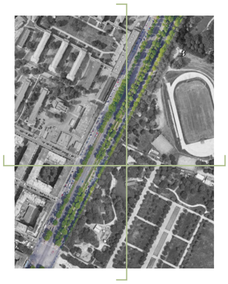


section x/z, y=230 m

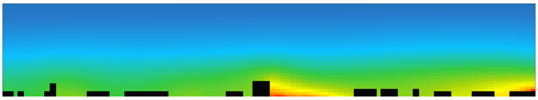


section y/z, x=358 m

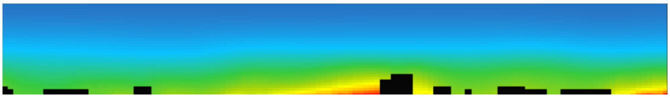




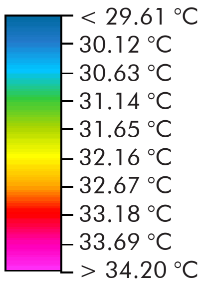
Corso Potenza



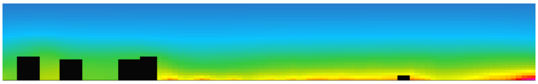
section x/z, y=290 m



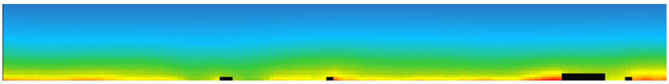
section y/z, x=198 m



Corso IV Novembre



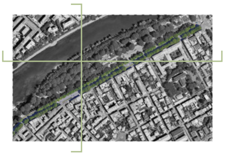
section x/z, y=210 m



section y/z, x=230 m

Corso Casale

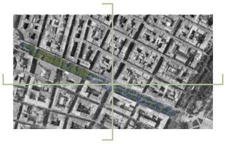
section x/z, y=302,5 m



section y/z, x=302,5 m

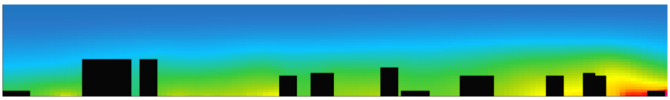
Corso Marconi

section x/z, y=162 m

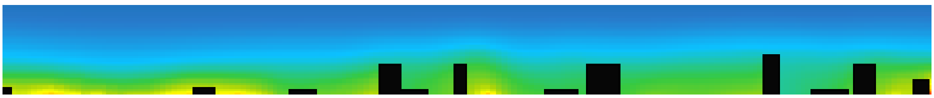


section y/z, x=354 m

Corso Racconigi

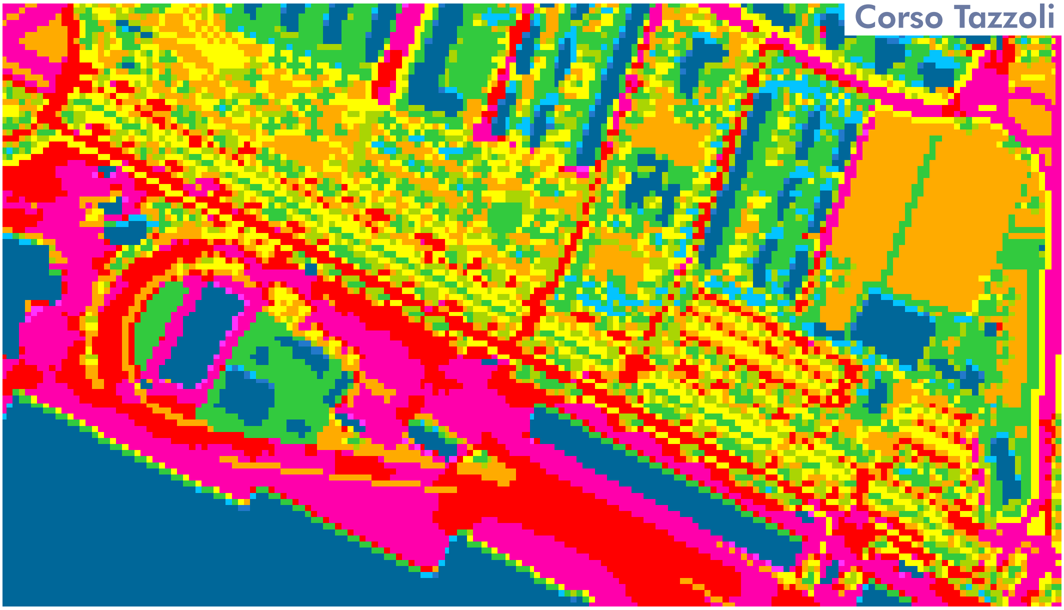


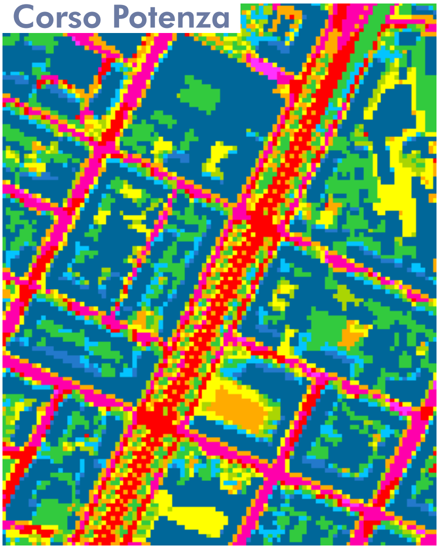
section x/z, y=274 m

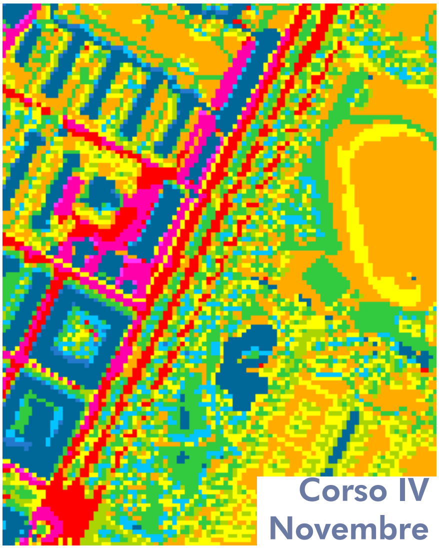


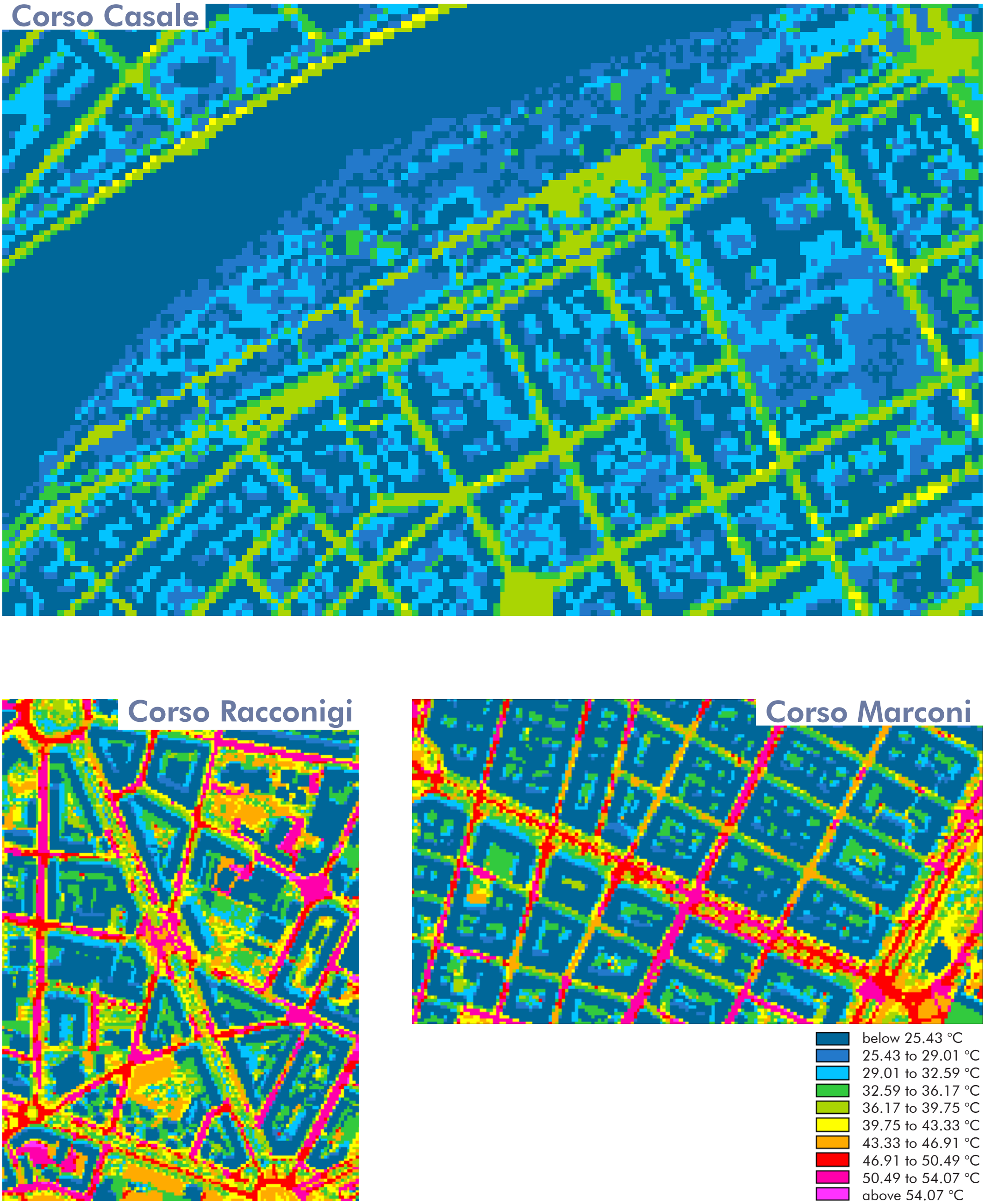
section y/z, x=158 m

3.4.3 Surface Temperature at 14:00 h

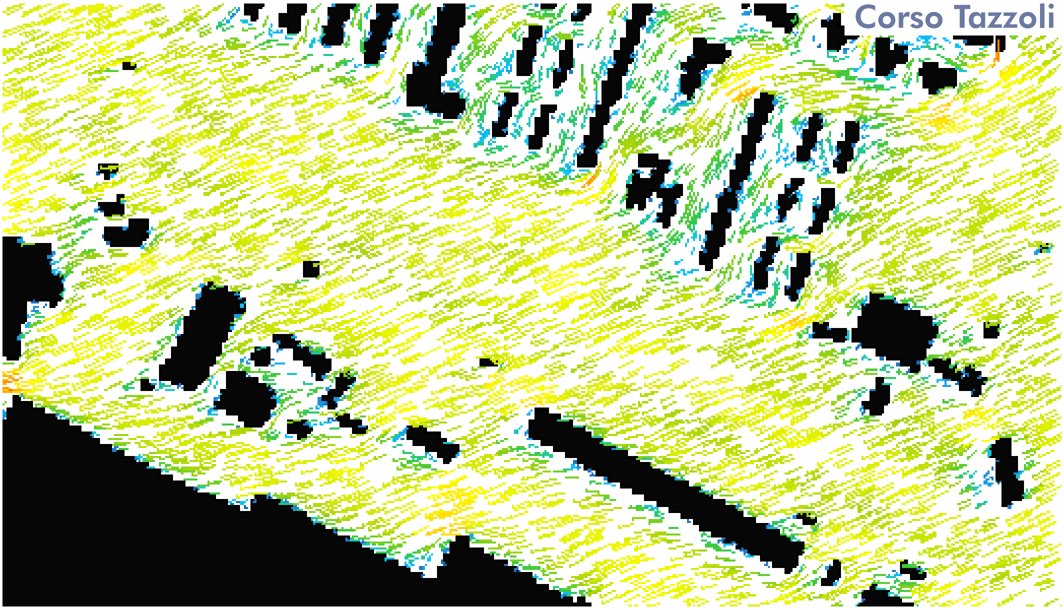


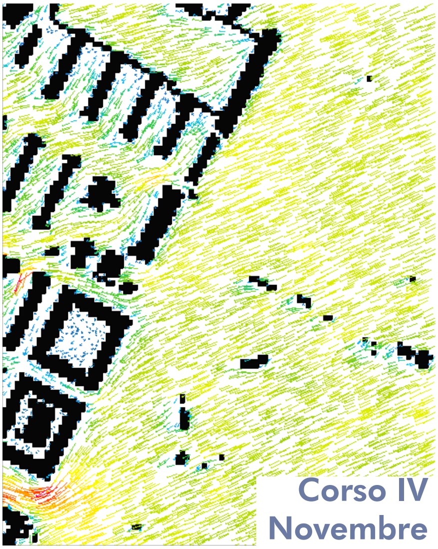


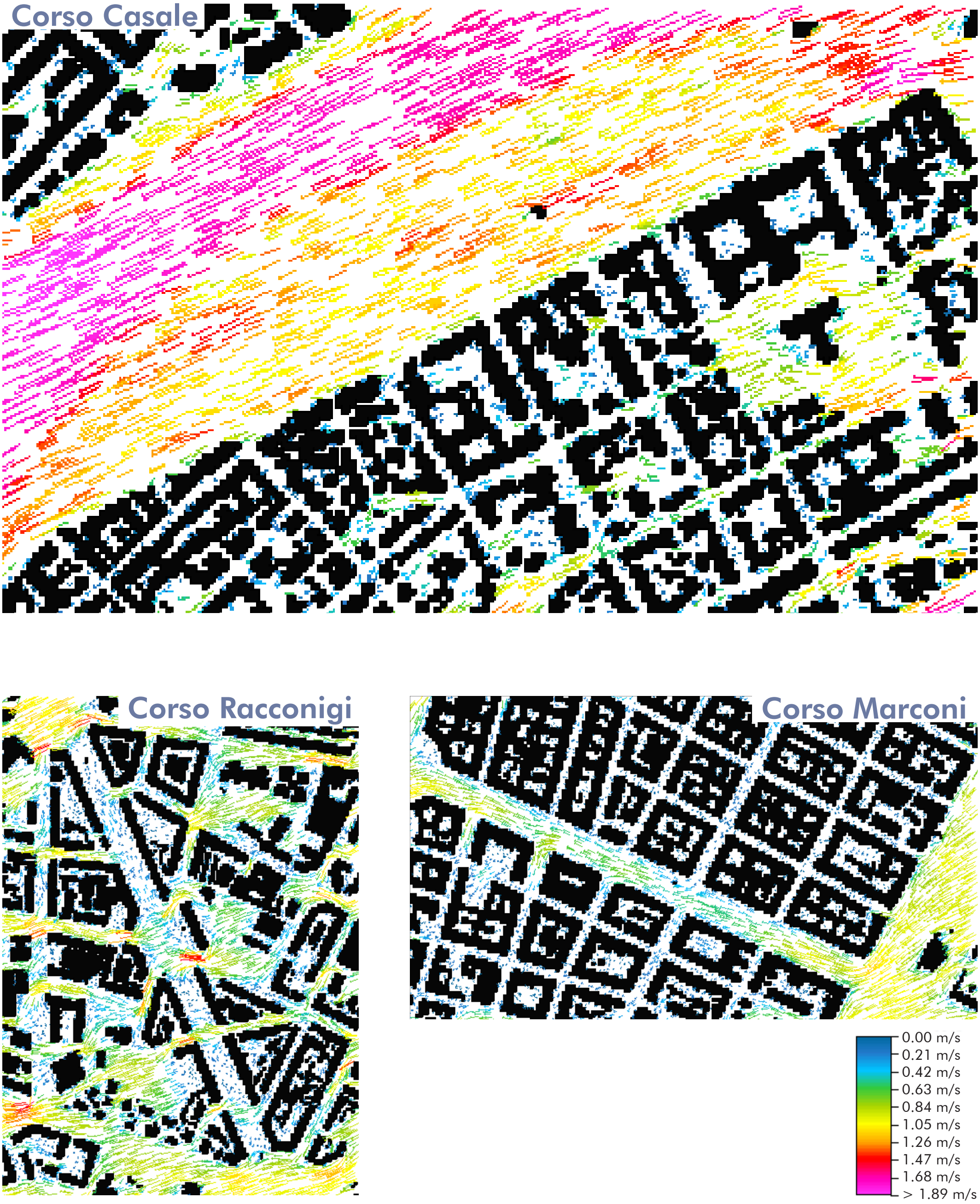



Corso Casale
Corso Racconigi
Corso Marconi
below 25.43 °C
25.43 to 29.01 °C
29.01 to 32.59 °C
32.59 to 36.17 °C
36.17 to 39.75 °C
39.75 to 43.33 °C
43.33 to 46.91 °C
46.91 to 50.49 °C
50.49 to 54.07 °C
above 54.07 °C

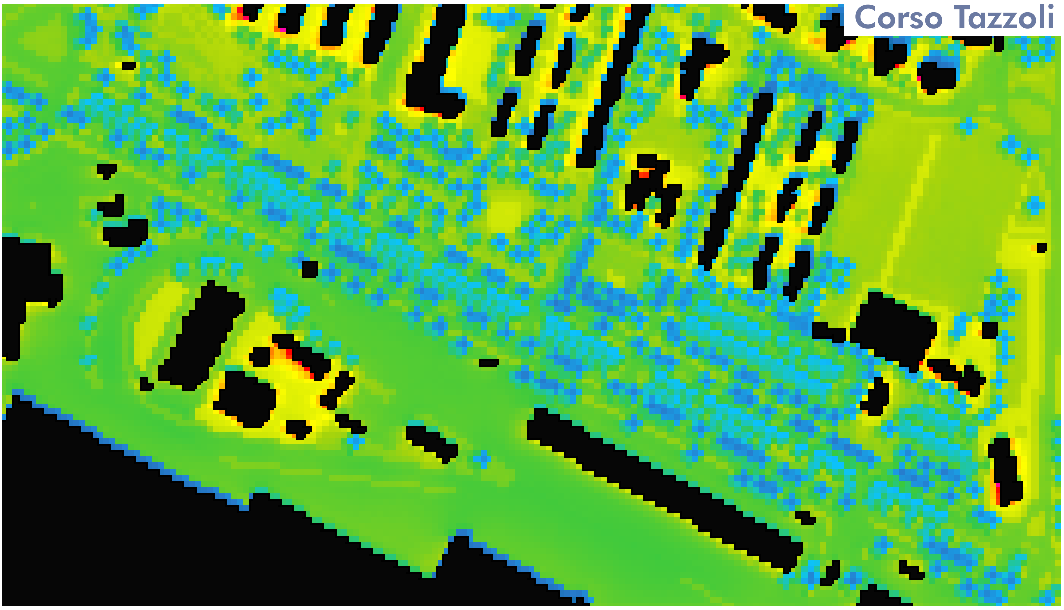
3.4.4 Wind Speed at 14:00 h

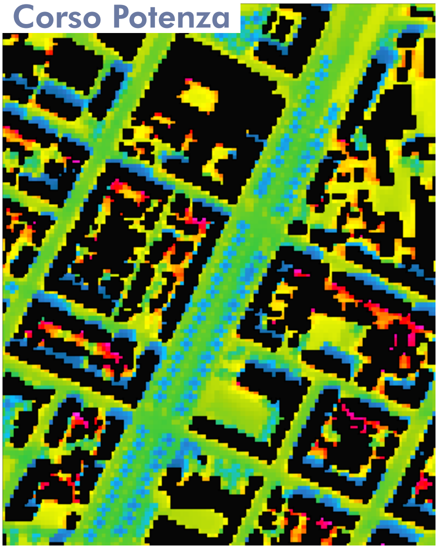


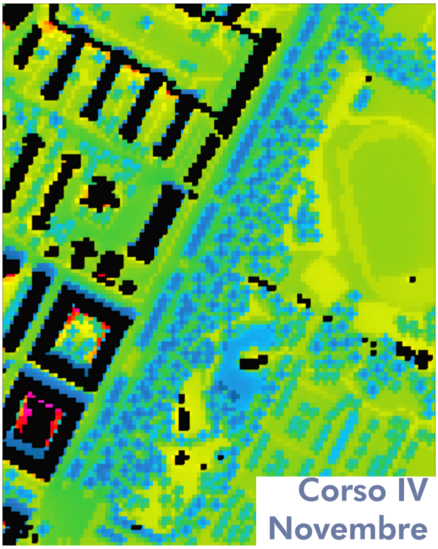


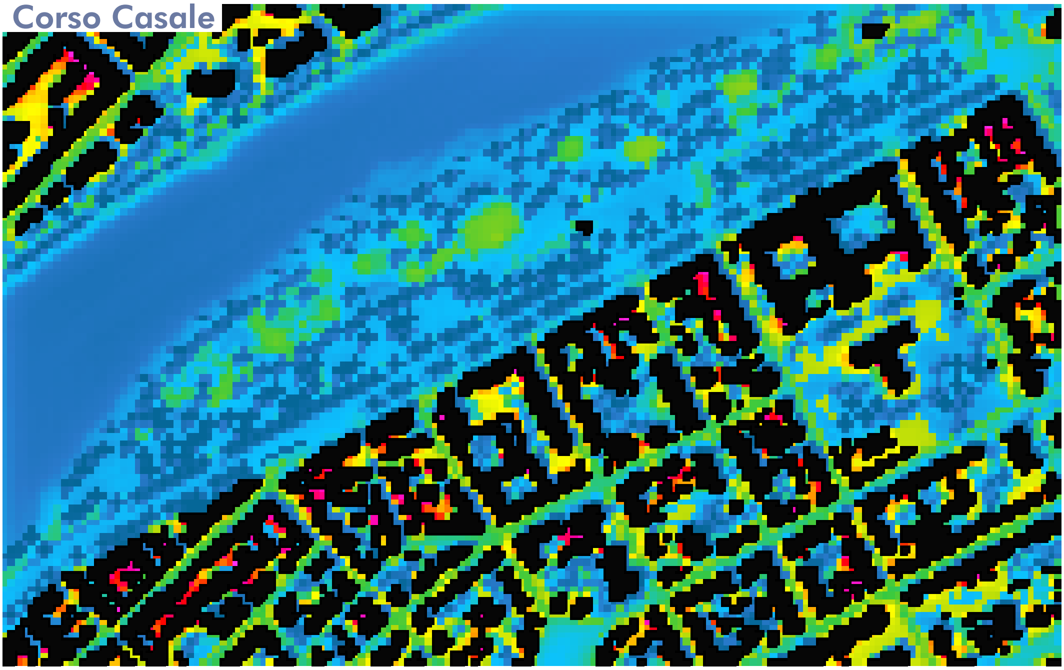

Corso Casale
Corso Racconigi
Corso Marconi
0.00 m/s
0.21 m/s
0.42 m/s
0.63 m/s
0.84 m/s
1.05 m/s
1.26 m/s
1.47 m/s
1.68 m/s
> 1.89 m/s

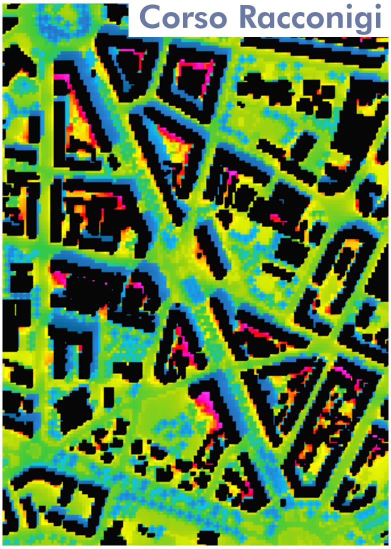
3.4.5 PET at 14:00 h

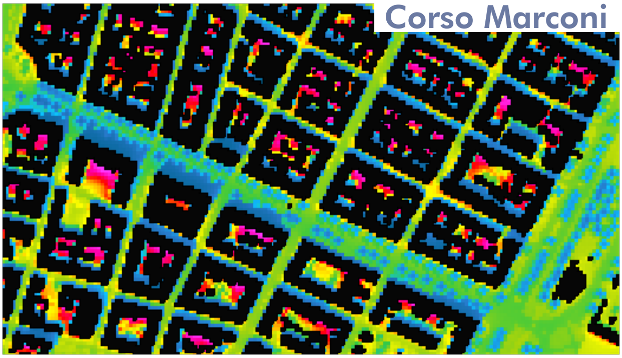


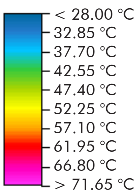





Corso Casale


Corso Racconigi


Corso Marconi


< 28.00 °C
32.85 °C
37.70 °C
42.55 °C
47.40 °C
52.25 °C
57.10 °C
61.95 °C
66.80 °C
> 71.65 °C

3.5 Discussion

3.5.1 Urban morphology

Urban canyon

Urban morphology is proved by numerous scientific papers (Lobaccaro et al., 2019; Perini and Magliocco, 2014; Trane et al., 2021) to be an important element which affects climate conditions at the micro-scale. Urban canyon, its orientation and the surrounding area have great impact on the micro-climate. In order to assess the effect and importance of the urban canyon in the microclimate conditions, different urban canyons were chosen for the case studies. Three of them are one sided. All the urban canyons have different aspect ratio, width and building height.

In the one sided canyons of Corso IV Novembre (aspect ratio 0,14) and Corso Enrico Tazzoli (aspect ratio 0,05), the potential air temperature at the most critical hour is mainly between 31 °C and 33 °C. In Corso Casale (aspect ratio 0,46), the third one sided canyon, the potential air temperature along the whole street is around 30 °C, while it rises at the end, at the intersection with Corso Giuseppe Gabetti, up to around 31 °C. In two streets with the highest aspect ratio, Corso Marconi (aspect ratio 0,50) and Corso Racconigi (aspect ratio 0,54) the potential air temperature at 14:00 is slightly different. In Corso Marconi, along the whole street the temperature is between 30 °C and 31 °C, except at the end, at the intersection with Corso Massimo d'Azeglio, where the temperature rises up to 33 °C, as minor shading is provided. In Corso Racconigi, the potential air temperature along

the street is almost constant, around 31 °C. It rises to 32 °C at the intersections. Corso Potenza has shallower urban canyon, with aspect ratio 0,28. The analysis shows that potential air temperature at 14:00 is different on the left and right side of the canyon, ranging from around 31 °C on the right side up to 33 °C on the left. This demonstrates that shade which the buildings provide has great impact on reduction of the potential air temperature. It also shows that deeper urban canyons, thus denser tissues, provide better potential air temperature than most of the one sided or shallow canyons. Corso Casale is an exception, highlighting the strong UHI mitigating potential of water bodies and wind.
The potential air temperature analysis for the hour 10:00 shows lower difference between the dominant temperatures of different case studies, but the same trends like in the 14:00 were demonstrated. The temperature rises at the intersections, where there are no shadows provided by buildings. Deeper canyons have lower potential air temperature than the majority of one sided and shallow ones. The analysis of potential air temperature at 18:00 h shows slightly different results. Most of the case studies have similar temperature within the canyon. An increase in temperature at the intersections is notable in Corso Potenza and Corso Racconigi only. In Corso Potenza difference in the temperature on the left and right sides of the street is much lower than at 10:00 and 14:00 h. Corso Casale has the lowest temperature of all the case studies, the same as at 10:00 and 14:00 h analysis, which indicates again that the water bodies have high microclimate mitigation potential. The main difference is Corso IV Novembre, which has lower temperature than the remaining four case studies by around 1 °C, even though it is one sided canyon. This shows that deep urban canyons have less impact on the potential air temperature in the evening hours.
Wind speed analysis at 14:00 h shows that one sided canyons,

Corso Casale, Corso IV Novembre and Corso Tazzoli have higher wind speeds than symmetric canyons. Corso Casale has the highest wind speed of around 1,47 m/s, while in Corso IV Novembre and Corso Tazzoli wind speed varies between 0,84 and 1,05 m/s. Corso Potenza, with the lowest aspect ratio of the symmetric canyon case studies, has wide range of wind speed, from 0,42 to 1,05 m/s. The strongest wind blows in the central part of the street, especially at the intersections. Wind speed in Corso Marconi is for the most part between 0,42 and 0,84 m/s, while it rises at the ends up to 1,05 m/s. Corso Racconigi has the lowest wind speed in the canyon, between 0 and 0,21 m/s, except at the intersections where it rises to 0,84 m/s, in some places even to 1,47 m/s.

The analyses in the morning and the evening, at 10:00 and 18:00 h, show similar results. The highest wind speed is in the one sided canyons, due to the lack of obstacles. The strongest wind is in Corso Casale, presumably due to the river and orientation. Corso Racconigi and Corso Marconi have lower wind speed, while Corso Potenza has a range of wind speed due to the buildings in the urban canyon which could cause turbulence, unlike in the one sided canyons, where the wind speed is rather constant. Stronger winds in Corso Potenza could be the result of the wind direction and street orientation, rather than solely urban morphology.

Wind speed analysis demonstrated that wide and one sided canyons allow for higher wind speed due to the absence of obstacles. However, street orientation and wind direction play major role in the wind speed and turbulence in the urban area.

PET analysis for the most critical hour shows that Corso IV Novembre and Corso Tazzoli have similar values, between 32 and 37 °C under the trees and 42 °C in the spaces exposed to sun. In Corso Casale, the PET values range from 28 to 32

°C in the shaded areas, to 37 °C in the non-protected areas. Corso Marconi and Corso Racconigi have similar values, between 28 and 32 °C in the shade and between 42 and 52 °C in the exposed areas. In Corso Potenza, in the shaded areas PET is between 32 and 37 °C, while in the rest it is up to 42 °C.
In the morning, PET results are quite similar to the ones at 14:00 h. Corso IV Novembre and Corso Tazzoli have similar values both in the shade and in the non-protected areas. Corso Casale has lower PET in the sun-exposed areas than the other case studies, around 32 °C. In Corso Racconigi, the shaded areas have PET less than 23 °C, while the exposed areas have higher PET than the other case studies, between 36 and 40 °C. In Corso Marconi and Corso Potenza, PET of the shaded areas varies between 27 and 32 °C. In the non-shaded areas, PET is around 36 °C.
The analysis of PET at 18:00 h shows slightly different results. Corso Casale has PET less than 24 °C in all its length. Corso IV Novembre, Corso Marconi and Corso Racconigi have similar results. They are almost entirely shaded, with PET between 24 and 28 °C, while the remaining area has PET around 36 °C. Corso Potenza and Corso Tazzoli have fairly higher PET, mainly between 28 and 32 °C, while the non-shaded areas have PET 36 °C.
The analysis demonstrated that blocking solar radiation is very important for thermal comfort, proving the stance from the literature (Battista et al., 2019; Lobaccaro et al., 2019). The most favourable conditions in the afternoon are in the streets with deep canyons, while one sided shallow canyons have less comfortable thermal conditions.

Orientation

Urban geometry cannot be examined only with urban can-

yon. Orientation has great impact on the microclimate conditions, as stated in the literature (Lobaccaro et al., 2019, Taleghani et al., 2014). In order to assess the impact of urban geometry on the climate at the micro-scale, both urban canyon and orientation must be studied.
Dominant orientations of the case studies are NE-SW and NW-SE. Preciesly, Corso IV Novembre and Corso Potenza are oriented NNE-SSW. Corso Casale, one sided canyon with buildings on SE side is oriented ENE-WSW. Corso Marconi and Corso Tazzoli have WNW-ESE orientation, while Corso Racconigi is oriented in the NNW-SSE direction.
At the most critical hour of the simulated day, 14:00 h, Corso IV Novembre has similar potential air temperature as Corso Potenza, between 31 and 33 °C. Corso Marconi and Corso Tazzoli, however, have different potential air temperature in their urban canyons. In Corso Marconi the temperature is between 30 and 31 °C along the street, while at the intersection with Corso Massimo d'Azeglio it rises up to 33 °C. In Corso Tazzoli the potential air temperature is between 31 and 33 °C along the whole street. The average potential air temperature in Corso Racconigi is around 31 °C along the whole street except for the intersections where it rises by 1 °C. Corso Casale has the lowest potential air temperature of all the case studies during the whole day. Difference between the temperature in the almost identically oriented Corso Marconi and Corso Tazzoli demonstrates that orientation as a parameter cannot be assessed separately from the urban canyon. However, the average potential air temperature in Corso Marconi, which has a deep urban canyon, is slightly lower than in Corso Racconigi, with a similar aspect ratio. This indicates that NW-SE orientation is more favourable in the afternoon than the NE-SW in the streets with deep urban canyon. On the other hand, Corso Casale shows that ENE-WSW orientation provides better conditions, as a one

sided canyon with buildings on the south-east side. In spite of that, Corso Casale is the only case study with an element of water, which is highly likely to impact the microclimatic conditions. The analysis of potential air temperature in the morning showed similar results and trends. Corso Marconi has slightly lower temperature than the rest of the case studies, with the exception of Corso Casale. This leads to the conclusion that the NW-SE orientation is more favourable than NE-SW in deep urban canyons in the morning as well. In the evening hours potential air temperature shows rather different results. The temperature is in Corso IV Novembre is lower than in the other four case studies, where the temperature is fairly similar. The two streets with the lowest temperature are both one sided canyons oriented NE-SW, indicating that it is the optimal orientation in the evening hours. However, the difference is in the buildings side, in Corso IV Novembre the buildings are on the NW side, while in Corso Casale they are on the SE. These case studies demonstrate that presence of stronger wind can have substantial impact on the potential air temperature. In the deep canyons, the temperature is almost the same regardless of the orientation. Dominant wind in Turin is blowing from NE, almost parallel to Corso Casale. The results show that during the whole day, the wind is the strongest in Corso Casale. In the afternoon hour, at 14:00, the results are similar for the rest NE-SW oriented streets, as well as for Corso Tazzoli, where the winds are stronger due to the orientation and lack of obstacles in one sided canyons. In Corso Marconi and Corso Racconigi, the wind speed is notably lower. The same trend is observed in the morning and evening hours. In Corso IV Novembre and Tazzoli wind speed is fairly similar and constant, while in Corso Potenza wind speed varies due to the turbulence in the urban canyon. Corso Marconi and Corso Racconigi have lower wind speed throughout the whole day.

The wind speed simulation results prove that the orientation is important for the urban air flow. The most favourable orientation in the case studies is NE-SW, because of the wind direction. NE-SW orientation allows for better urban ventilation, cooling and removal of pollutants.
The PET values at the most critical hour are similar in the shaded areas of Corso Casale, Corso Marconi and Corso Racconigi, between 28 and 32 °C, but they are lower in the sun-exposed areas in Corso Casale, around 37 °C, than in the rest. Corso Casale has the lowest PET index during the whole day. The non-shaded areas in Corso Racconigi and Corso Marconi have higher PET values than any other case study, rising up to around 52 °C. The remaining case studies have rather similar results, between 32 and 37 °C in the shade and around 42 °C in the sun-exposed areas.
Majority of the streets oriented NW-SE have better PET values in the shaded areas, but also higher values in the sun-exposed spaces. Corso Casale has the lowest PET values, but the remaining NE-SW streets have less favourable values.
In the morning Corso Casale and Corso Racconigi have lower PET values in the shaded areas than the rest. Corso Racconigi has higher PET in sun-exposed areas than the others. The remaining case studies have fairly similar PET, between 27 and 32 °C in the shade and 36 °C in the non-protected areas. In the evening Corso IV Novembre, Corso Marconi and Corso Racconigi have the same PET values. Corso Potenza and Corso Tazzoli have higher PET values than the remaining case studies.
This analysis demonstrates that the protection from solar radiation is very important for PET. However, the street orientation cannot be a sole determining factor of thermal comfort in the urban area, and must be considered along with the other aspects, such as urban canyon, surfaces, presence of vegetation and others.

3.5.2 Surfaces

Types of surfaces and their properties can have substantial effect on the microclimate conditions (Battista et al., 2016; Carnielo and Zinzi, 2013; Marrone and Orsini, 2018; Santamouris., 2013). The main surfaces that cover the case studies are asphalt and ground, along with pedestrian and cycling paths and sidewalks. Asphalt, which is dominant in all the case studies, contributes to the formation of UHI due to its low albedo and non-permeability.

Corso Racconigi and Corso Tazzoli are the case studies with the least percentage of asphalt surfaces, less than 60%. In Corso Casale and Corso IV Novembre over 60% of the area is covered in asphalt, while in Corso Potenza 70% of the surfaces are covered in asphalt. Corso Marconi the case study almost completely covered in asphalt, with minimum permeability.

Accordingly, Corso Potenza has the least percentage of permeable surfaces, around 13%. Corso Casale and Corso IV Novembre have between 16 and 19% of the street covered in green areas. Corso Tazzoli has the biggest percentage of permeable surfaces of all the case studies, 29,2%, while in Corso Racconigi green areas cover 25,4% of the area.

The remaining surfaces are sidewalks, walking and cycling paths, covered in concrete pavement.

In the afternoon, Corso Tazzoli, which has the lowest ratio of asphalt and green surfaces, has the highest potential air temperature, along with Corso Potenza, which has the highest ratio, and Corso IV Novembre. Corso Marconi, with minimal green surfaces has the same potential air temperature as Corso Racconigi, which has a quarter of its area covered in permeable surface. Corso Casale has the lowest potential air temperature at 14:00 h.

In the morning, the potential air temperature shows the same trends like in the afternoon.

At 18:00 h, the potential air temperature trends slightly change. Corso Casale still has the lowest potential air temperature. Corso IV Novembre in the evening hours has lower potential air temperature than the remaining four case studies. However, the remaining case studies have both higher and lower asphalt and green surfaces ratio.

The inconsistency in the ratio of permeable and asphalt surfaces and potential air temperature indicates that the surfaces do not have much impact on the potential air temperature.

Surface temperature analysis shows difference in temperature among different surfaces. Corso Casale has the lowest surface temperature of asphalt throughout the whole day. At 14:00 h, in Corso Tazzoli, both the central green area with a walking path and the asphalt area close to it have lower surface temperature than the controviali. The similar results were obtained for Corso Racconigi, where the central green area with a cycling path has lower surface temperature than the asphalt surfaces of controviali. However, the controviali also have lower surface temperatures than the asphalt surfaces in the other case studies. Corso IV Novembre and Corso Potenza have similar results, higher surface temperature of all the asphalt surfaes and lower temperature of the green areas. In Corso Marconi the areas shaded by the buildings and trees have significantly lower surface temperature than the non-shaded ones. Surface temperature of the sidewalks and walking paths in all the case studies are lower than the temperature of asphalt, which proves that higher albedo surfaces do have lower surface temperature than surfaces with

low albedo.
In the morning, Corso IV Novembre has lower surface temperature of asphalt than the other case studies. In Corso Racconigi the lowest surface temperature is in the asphalt areas shaded by the buildings, followed by the surface temperature of the green areas, while the highest surface temperature is in the asphalt areas exposed to solar radiation. Surface temperature in Corso Tazzoli is similar to the one in the afternoon, the surfaces in the central area have lower temperature than in the controviali. In Corso Potenza, on the contrary, the temperature of asphalt areas in both controviali is lower than in the central area. In Corso Marconi only the areas shaded by the trees have lower surface temperature.
The analysis in the evening hour indicates that the green areas in all the case studies have lower surface temperature than the asphalt surfaces, even the shaded fragments.
Green areas have lower surface temperature than the asphalt surfaces in the morning and afternoon hours, except in the spaces shaded by the buildings and trees. In the evening, intercepting solar radiation has less effect on the surface temperature, and the temperature of the green surfaces is lower than the asphalt surface in all the cases.
The highest wind speed is in Corso Casale throughout the whole day. Corso Racconigi and Corso Tazzoli, which have similar asphalt to green surface ratio, have notably different wind speeds in the afternoon. Corso Potenza, Corso IV Novembre and Corso Tazzoli all have different ratio of surfaces, but similar wind speed. Similar results were obtained in the morning and evening hours. This indicates that the surfaces have low impact on the wind speed within urban canyon.
Similarly to the potential air temperature, Corso Casale, Corso Marconi and Corso Racconigi have lower PET values than the remaining case studies at 14:00 h. Even though Corso Marconi is almost completely covered in asphalt, the PET

values in the areas shaded by the buildings and the trees are lower than the PET values in Corso IV Novembre, Corso Potenza and Corso Tazzoli. In Corso Racconigi the PET values in the shade provided by the buildings are lower than in the central green area. In Corso Tazzoli the PET is lower in the central green area and surrounding areas than in the asphalt areas of the controviali. The results indicate that the PET values above the green areas in all the case studies are lower than the PET above the non-shaded asphalt areas.
In the morning, PET in Corso Casale is lower than in the other case studies. The values above and around green areas in all the case studies are lower than the ones above asphalt, except in the spaces shaded by buildings.
In the evening hours, all the case studies have rather similar PET despite the difference in surfaces.
The analysis proves that the surfaces do have an impact on the thermal comfort. Green areas provide more favourable effect than the asphalt surfaces. However, the shade provided by the buildings affects the microclimate conditions and lowers PET more than the sole presence of the green areas. Shaded asphalt spaces had lower PET than non-shaded permeable surfaces.

3.5.3 Vegetation

The significant impact of vegetation on the microclimate has been noted in the literature (Battista et al., 2016; Berardi et al. 2020; Lobaccaro et al., 2019; Marrone and Orsini, 2018). It has proved to lower air temperature and provide more favourable thermal comfort, along with promoting various health benefits for humans (World Bank, 2021).
Corso Casale and Corso IV Novembre are the case studies with a park on one side. The difference is in the position of the park area. In Corso Casale, the park is on the NW side of the street, while in Corso IV Novembre the park is on the SE side.
All the case studies have rows of chestnut trees of about 20 m height. In Corso Casale there is a row of trees between the controviale and the central car area. In Corso Tazzoli there are four rows of trees, two of them in the green areas between the controviali and the central car area and two rows of lower trees, of about 8 m height, in the central green area. The green areas on the NE of the street, close to the side-walk, also have a number of high trees which could possibly affect the microclimate conditions. Corso IV Novembre, has plenty of vegetation in the canyon. In addition to the park area, within the canyon there are three rows of high chestnut trees in the areas between controviali and the central car area, one on the west and two on the east side of the street. Corso Potenza has two rows of chestnut trees, one in each green area between the controviali and the central car area. Despite being covered almost entirely in concrete, Corso Marconi has

different kinds of trees in the urban canyon. The area NW of via Madama Cristina is characterized with high chestnut trees, while the other side has lower trees of around 15 m height. In Corso Racconigi the vegetation is placed only in the central green areas, in two rows of trees approximately 8 m high.

Corso Casale and Corso IV Novembre, which have the most vegetation within and surrounding them have different potential air temperature in the morning and afternoon hours. Corso Marconi and Corso Racconigi have similar potential air temperature, but different vegetation in their urban canyons. Similarly, Corso Tazzoli and Corso Potenza have close potential air temperature, yet the vegetation in Corso Potenza is denser than in Corso Tazzoli, where it is more sparsely arranged.

In the evening hours, the more vegetated areas, Corso Casale and Corso IV Novembre, have lower potential air temperature than the rest of the case studies. However, the vegetated areas in the other case studies do not appear to have a significant impact on the potential air temperature.

Big area of vegetation, such as a park, could have impact on the potential air temperature in combination with another element, like orientation or presence of water, as demonstrated in the case of Corso Casale. Even though Corso Casale has the lowest potential air temperature during the whole day, the analysis in Corso IV Novembre indicates that sole presence of vegetation is not enough to improve potential air temperature.

The analysis of surface temperature in the afternoon indicates that the vegetation has impact on the surface temperature. In all the case studies, the surfaces under the trees are cooler than the surrounding surfaces.

In the morning hours, surface temperatures in Corso Casale and Corso IV Novembre are notably lower than in the remaining case studies, which suggests that the presence of parks or big vegetated areas contributes to the reduction of surface temperature. The same as in the afternoon, the areas under the trees have lower surface temperature than the surrounding areas.

Surface temperature in the evening hours is the lowest in Corso Casale and Corso IV Novembre, the same as in the morning. The temperature in the surfaces under the trees is lower than in the surrounding areas, with the exception of the surfaces shaded by the surrounding buildings.

Vegetation has significant impact on reduction of the surface temperature. However, the shade provided by the surrounding buildings proves to be more effective.

The case studies with more vegetation within or surrounding them, Corso Casale, Corso IV Novembre and Corso Tazzoli, have higher wind speed than the remaining case studies during the whole day. The analysis in Corso Casale demonstrates that trees help reduce the wind speed, but do not block it entirely. All of the above mentioned case studies also have one sided canyon and two of them are oriented in the direction of the wind. However, due to their porosity, trees allow the air flow through the street, resulting in the decrease in wind speed and its continuity. Even though the other elements, such as orientation and aspect ratio, have primary impact on the wind speed, the vegetation is important factor in the urban air flow.

The PET analysis in the afternoon shows that in all the case studies the PET values are lower in the areas close to the trees. However, in Corso Marconi and Corso Racconigi, the PET values in the shade provided by the buildings are lower than in the shade under the trees.

In the morning, PET in Corso IV Novembre is lower in more places due to abundance of trees. In all the case studies, the PET values are the lowest under the trees, except for

the areas shaded by the buildings.
The PET values in the evening are fairly similar for all the case studies regardless of the difference in the amount of vegetation.
The PET analysis suggests that the presence of vegetation is important for the thermal comfort of the pedestrians. The element which appears to provide better thermal comfort is the shade cast by the buildings.
Another element, which appears only in one case study, close to Corso Casale, and has potentially the biggest impact on the microclimate is water. Corso Casale has the best thermal comfort values, the lowest potential air temperature and surface temperature, and the highest wind speed. This is highly likely to be connected to the presence of river Po, because the other examined elements are all similar to the rest of the case studies. However, since it is the only case study that includes water, its effect cannot be compared or verified, but only suspected.

3.5.4 Strategies

The results discussed in this chapter helped recognize which elements have the most impact and should be applied through mitigation strategies to improve thermal conditions on the streets of Turin.

Due to urban density, the scope of mobility and features of the street, there cannot be only one definite strategy proposed. In the urban area, the space for intervention is the main problem. Therefore, the first condition for microclimate improvement and implementation of strategies is creating space for them. In the avenues with controviali, where hard mobility is dominant in the whole street, the reduction of the space designated for the cars and hard mobility could provide more area for mitigation and adaptation strategies. Dedicating either the central part of the street or the controviali to soft mobility would open up possibilities to implement UHI mitigation strategies, promote sustainable mobility, reduce air and noise pollution and stimulate the quality of urban spaces in general. However, it is not possible in all the streets or at the same extent, so different strategies could be applied depending on the possibilities. The strategies proposed are ranked according to their effectiveness inspected in the research.

The element that has the most impact on thermal conditions of the streets in Turin is presence of significant amounts of water. Therefore, the most effective strategy to implement would be addition of floodable space or a rain garden, or even water bodies along the street (fig. 144, fig. 146, fig. 148).

The essential feature of the climate conditions is the solar radiation. Interception of the solar rays is proved to be highly effective in improving thermal comfort and potential air temperature, especially with solid barriers. Vegetation helps improve the microclimate, both by shading and evapotranspiration, but due to its porosity, it is slightly less effective than the solid barriers. However, it was demonstrated to have a major impact in the outdoor thermal comfort, especially in the shallow or one sided canyons. Therefore, increasing vegetation density and introduction of solar barriers are the strategies that would have a great impact and are relatively easy to implement (fig. 143, fig. 145, fig. 146, fig. 148).
Elimination of hard mobility from one part of the street allows for the replacement of the low albedo asphalt surfaces with low albedo materials, permeable pavement or green areas (fig. 144, fig. 147, fig. 148). All of these would result in lower surface temperature and thermal comfort.
If due to the scope of mobility or urban features there is no space for the strategies, urban vegetation could be applied vertically, on the facades and some asphalt surfaces used for parking could be replaced with permeable pavements (fig. 145).
Even though the strategies were prioritized, their combination would have a greater effect. The strategies proposed are general recommendations based on the research and simulations, but for each case in the urban area, an individual analysis of the climate conditions and urban features must be performed in order to propose an optimal strategy for each space.

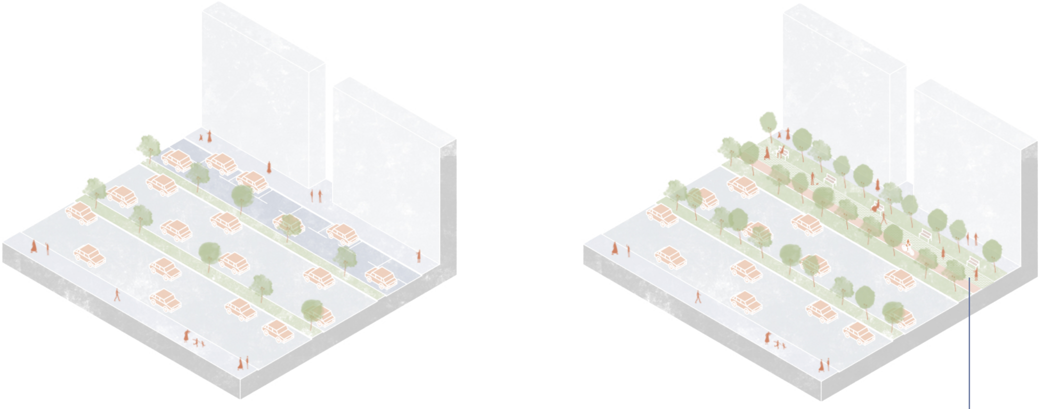
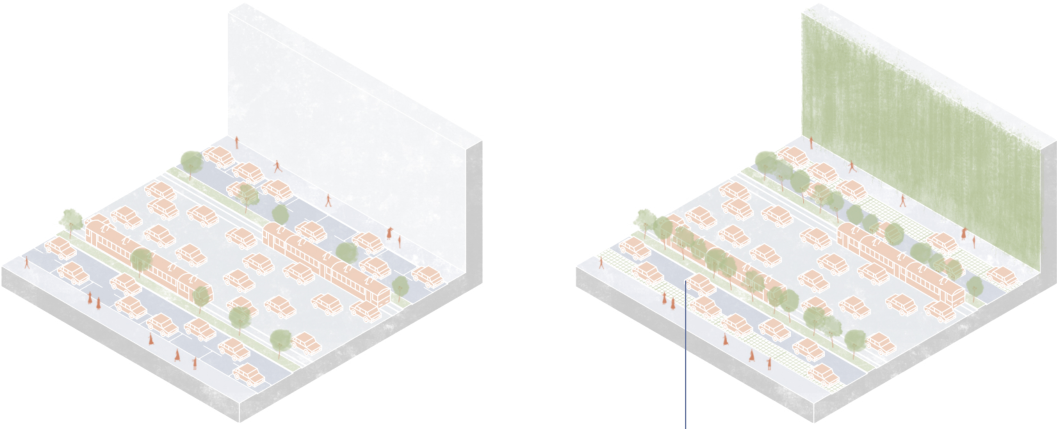


fig. 143 Examples of existing condition (left) and applied strategies (right)

Closing controviale for hard mobility, introducing soft mobility, increasing vegetation, green areas and permeable pavement

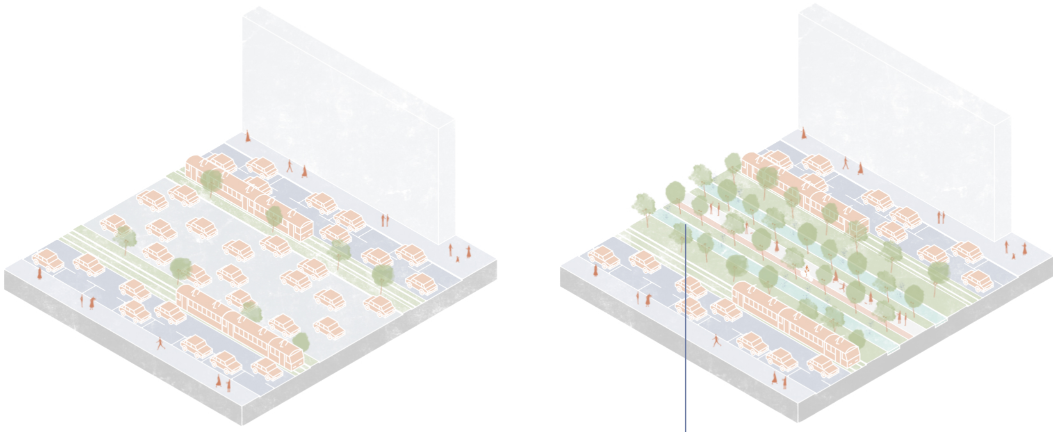
fig. 144 Examples of existing condition (left) and applied strategies (right)

Closing controviali for hard mobility, promoting soft mobility, increasing vegetation, adding green areas and water body



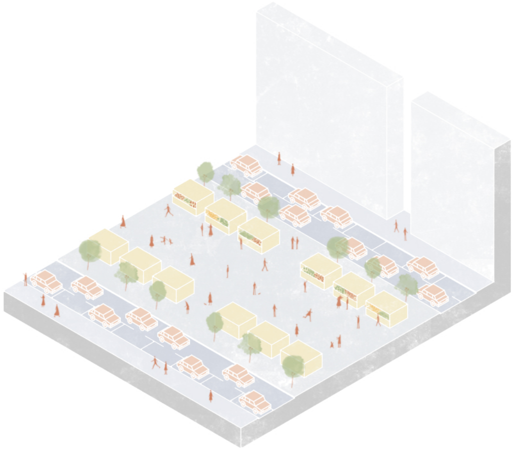
Increasing vegetation density, adding vertical greenery, replacing asphalt parking with permeable pavement

fig. 145 Example of existing condition (left) and applied strategies (right)



Closing central area for hard mobility, increasing vegetation and green areas, promoting soft mobility, adding water stripes

fig. 146 Example of existing condition (left) and applied strategies (right)



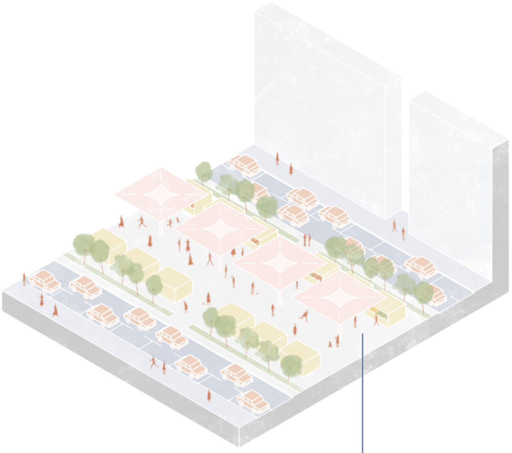


fig. 147 Example of existing condition (left) and applied strategies (right)

Replacing asphalt with high albedo pavement, adding solar shading system, increasing vegetation and green areas

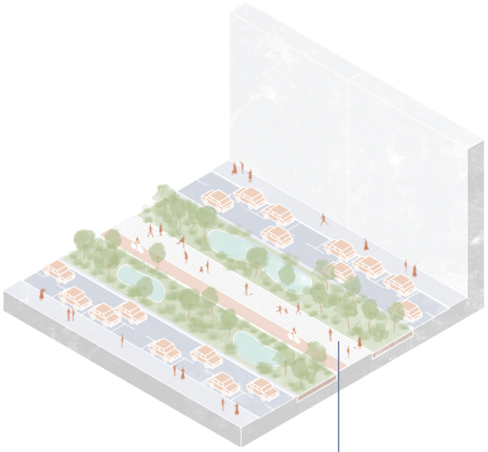
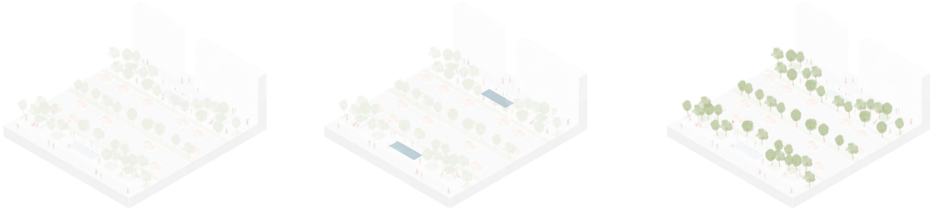


fig. 148 Example of existing condition (left) and applied strategies (right)

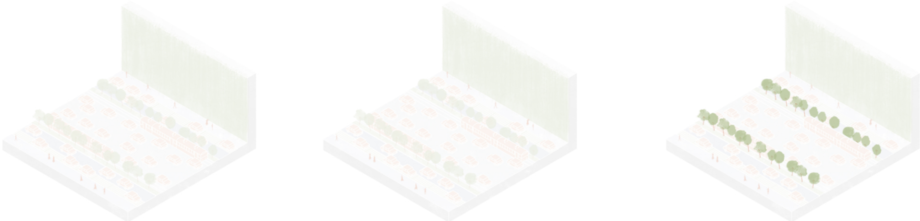
Implementing floodable spaces and rain gardens, increasing vegetation, applying high albedo pavements

Cluster 1

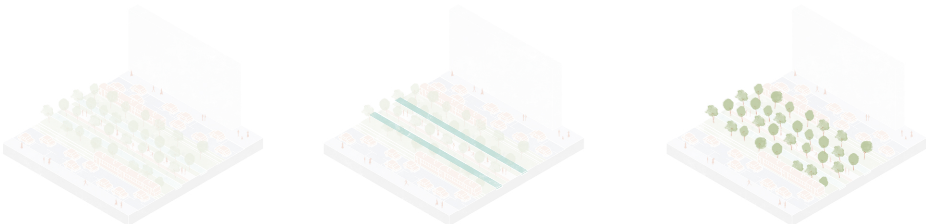
Cluster 2



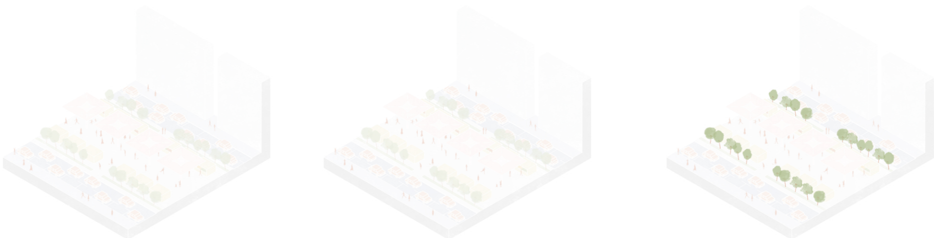
Cluster 3



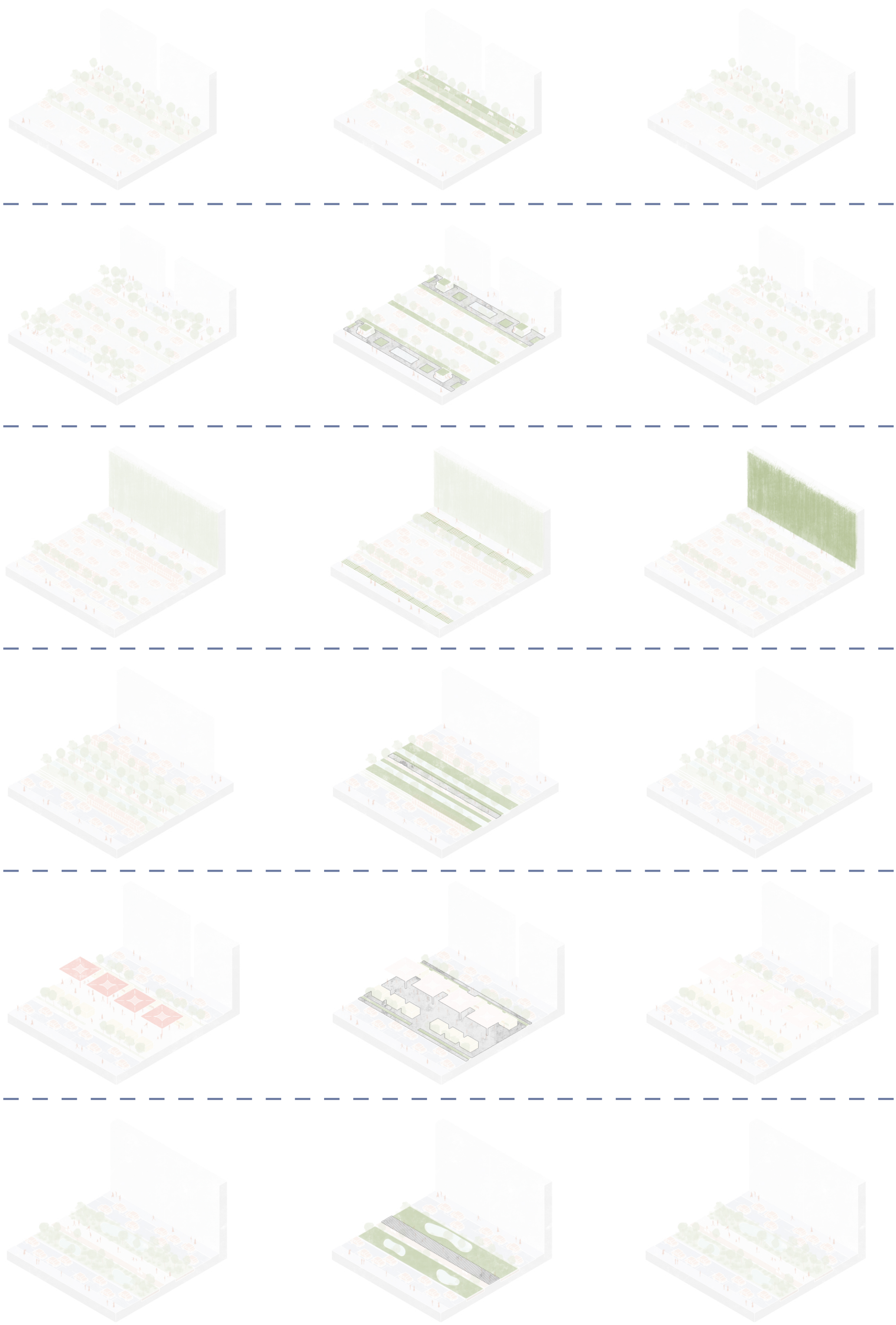
Cluster 4



Cluster 5



Cluster 6



Conclusion

The objective of this thesis is to determine the principal urban elements which shape the microclimate of the streets of Turin and to propose strategies for its mitigation, in relation to mobility, climate and Sustainable Development Agenda.
The research indicates that the presence of considerable amount of water, in this research a river, has the greatest impact on the microclimate conditions of the adjacent area. It confirms the stances from multiple researches where this element was proved to be the most effective in the UHI mitigation (Taleghani et al., 2014). However, since water element is present in only one case study, this factor cannot be fully examined and compared.
Interception of the solar radiation is a crucial factor in mitigating the effects of urban heat island, as proved in the research, and it should be achieved wherever possible in order to provide better thermal comfort. Shade cast by solid elements, like buildings, was confirmed to have a better effect than the porous one, cast by vegetation. This leads to a conclusion that urban canyon and orientation together have major roles in the microclimate conditions. Deep canyons, especially the ones oriented NW-SE, have better thermal comfort indexes and potential air temperature than the shallow ones. The case studies oriented NNE-SSW have less favourable thermal conditions.
Examination of the vegetation impact indicates that trees do improve thermal comfort, due to the shading and evapotranspiration, but not to the same extent as the solid elements. In spite of that, they have more impact than the sole presence of permeable green surfaces.
Green areas have lower surface temperature than the areas covered in non-permeable surfaces. Temperature analysis also confirmed that higher albedo pavement surfaces have lower surface temperature than low albedo asphalt surfaces. Therefore, increasing the amount of green areas and replac-

ing asphalt surface with some high albedo materials would improve thermal conditions. However, PET analysis demonstrates that shaded areas covered in low albedo surfaces have more favourable thermal comfort than the non-shaded green areas, which confirms that the interception of solar radiation is substantial in the microclimate mitigation.
In relation to the aspect of mobility, the two case studies with soft mobility in the centre have better thermal comfort results than the majority of the hard mobility centred ones.
Based on the results of the research, optimal microclimate mitigation strategies can be proposed. In the urban area with already formed morphology, it is nearly impossible to modify the aspect ratio or orientation of the streets. This can only be done in the planning of new urban areas or sometimes in the restoration of the old ones. Due to the inability to implement the same strategies in each space, the prioritization of the strategies was done.
The main issue is the urban area is the space for intervention. In the streets where the mobility requirements allow it, hard mobility should be limited to either the central area or the controviali. This would provide space for implementation of strategies, promote soft mobility and decrease pollution.
Implementation of blue infrastructure, such as rain gardens, floodable spaces or water bodies in large amount along the streets is proved to be the most effective in microclimate mitigation and should be applied if the space and urban characteristics allow it.
Application of green infrastructure, like increasing vegetation density and providing solar barriers is highly important for outdoor thermal comfort, since the interception of solar radiation is the major determinant in the thermal conditions of a place.
The third strategy is to replace low albedo surfaces with permeable pavement, green areas or surfaces with higher albedo,

which have lower surface temperature when exposed to solar radiation, resulting better thermal comfort for the pedestrians.
In the streets where urban density or scope of mobility leave no space for adaptation, vertical greenery could be introduced to improve thermal conditions.
Depending on the street features and mobility, in some cases the combination of the aforementioned strategies could be implemented, which would result in better thermal comfort and quality of space.

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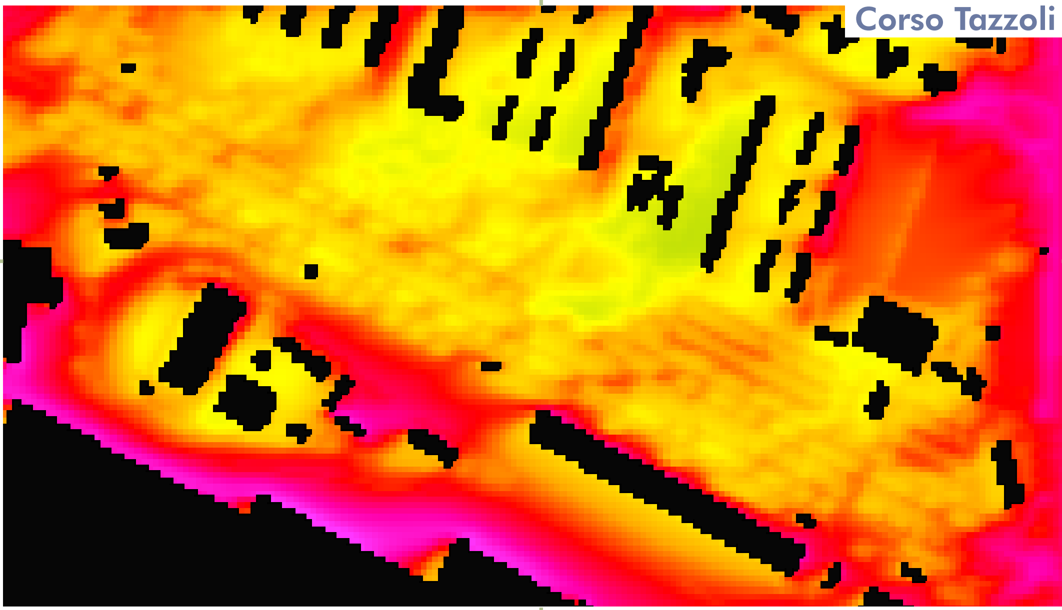
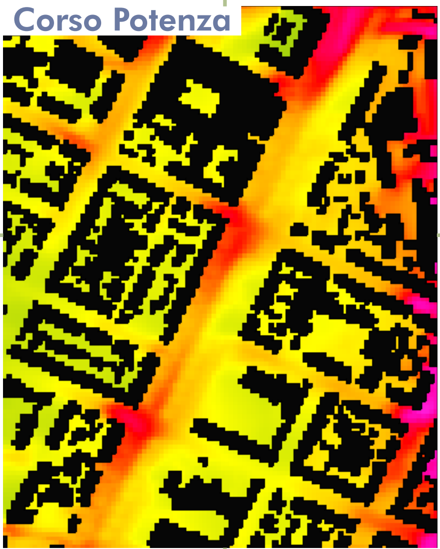
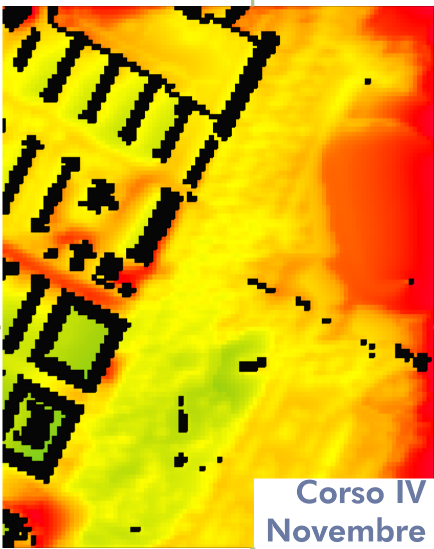
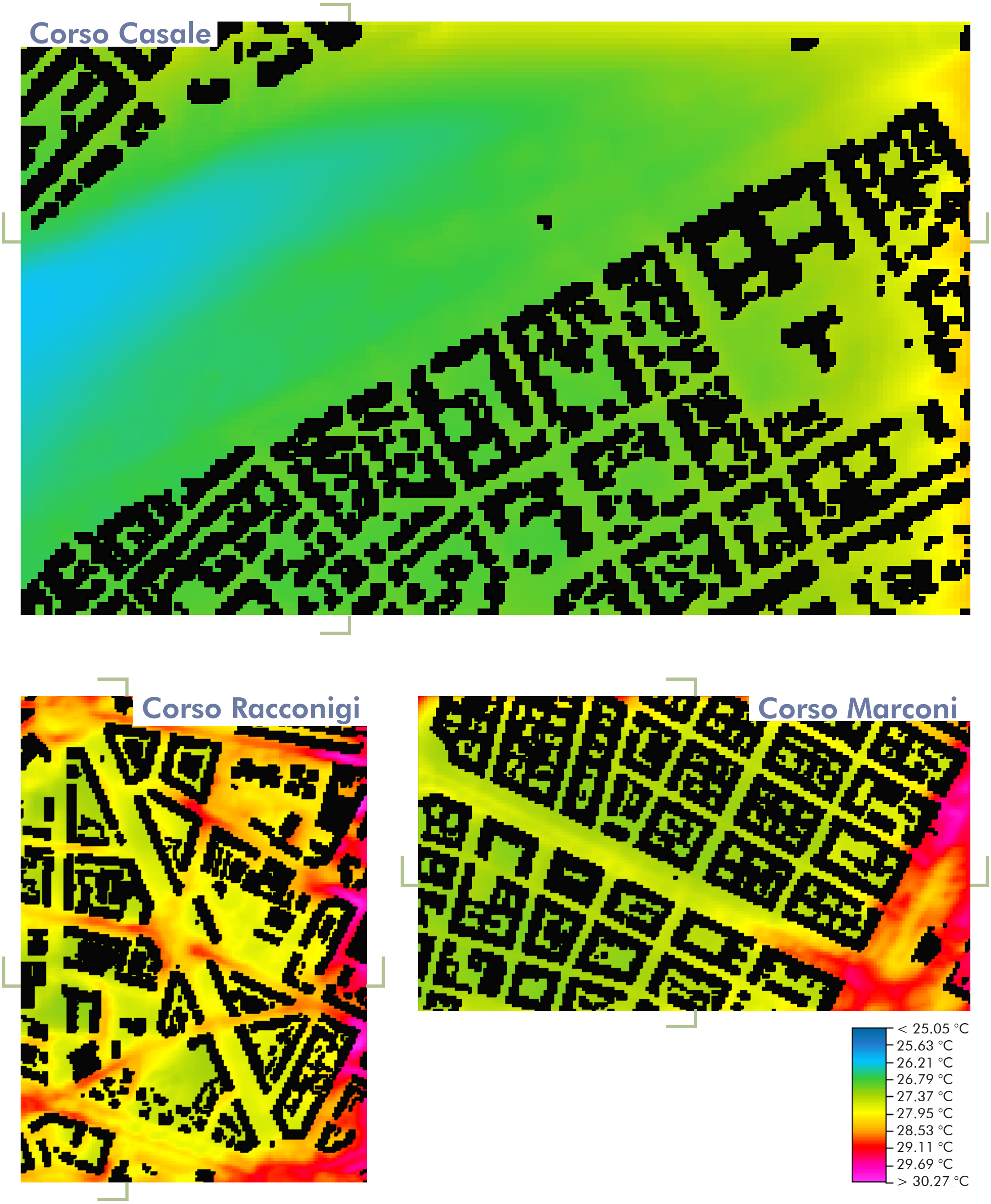
Appendix

Potential Air Temperature at 10:00 h

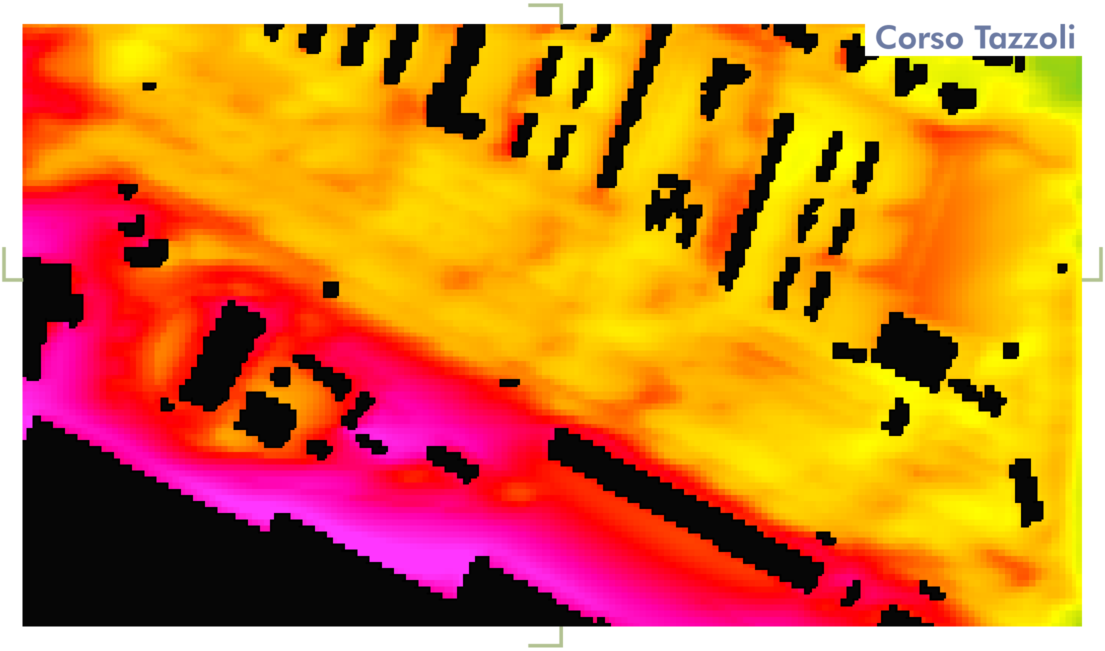


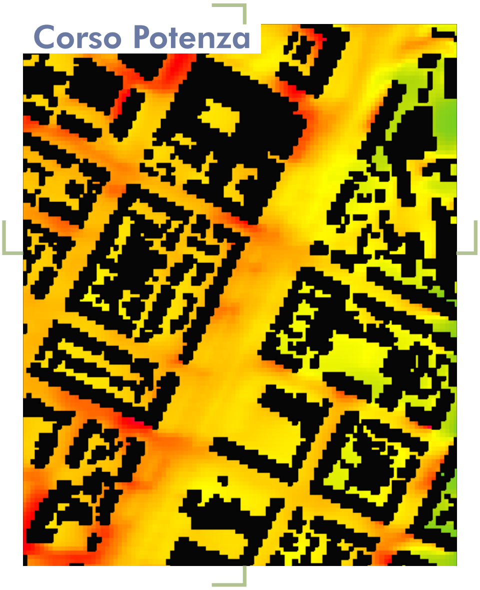


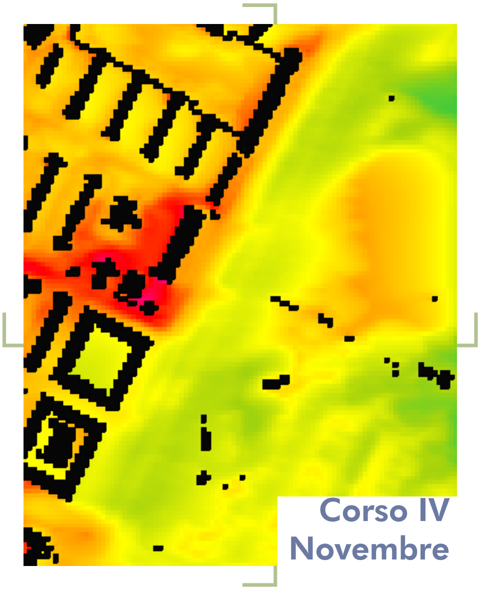


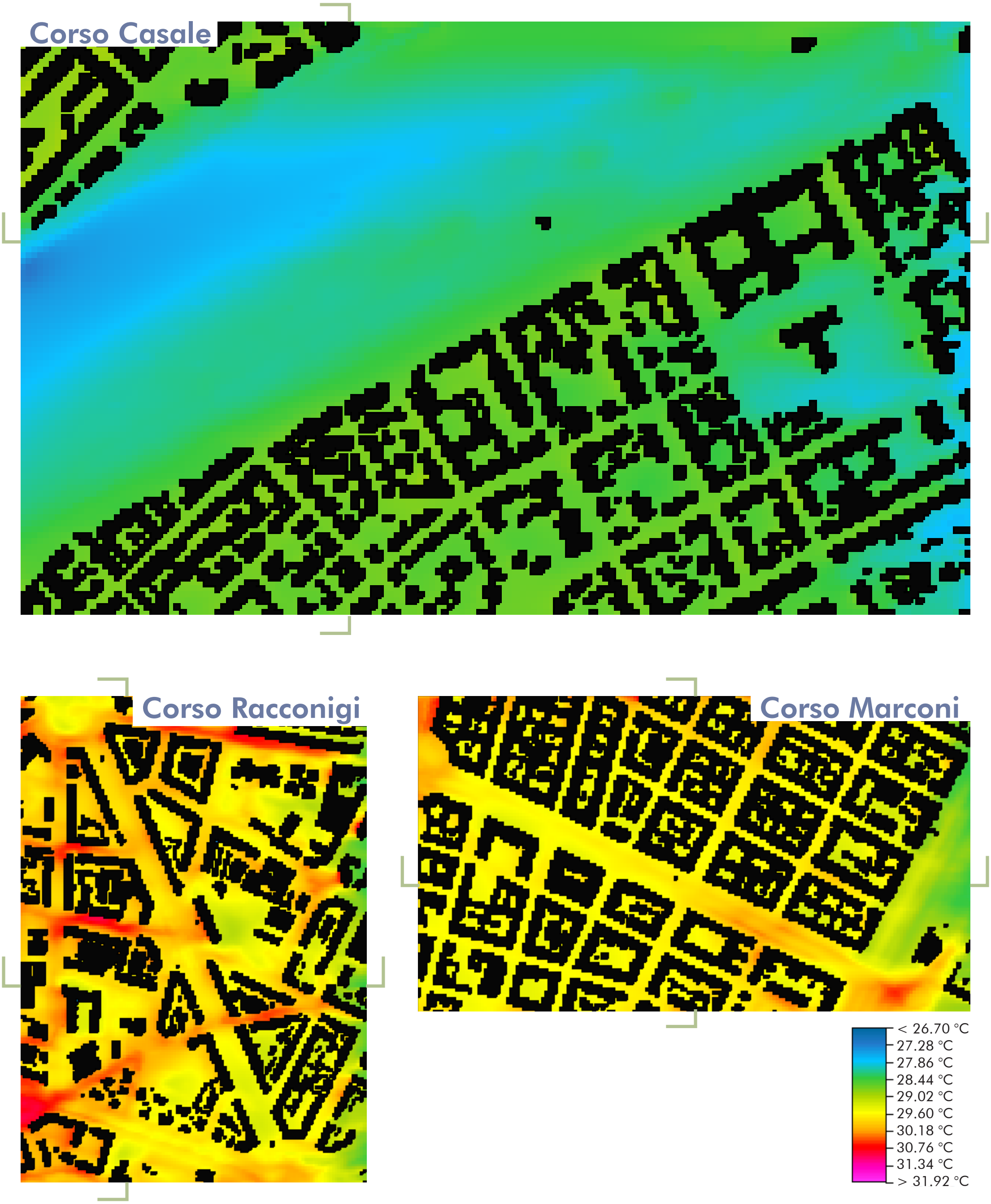

Corso Casale
Corso Racconigi
Corso Marconi
< 25.05 °C
25.63 °C
26.21 °C
26.79 °C
27.37 °C
27.95 °C
28.53 °C
29.11 °C
29.69 °C
> 30.27 °C

Potential Air Temperature at 18:00 h







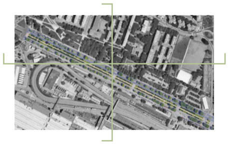

Corso Casale
Corso Racconigi
Corso Marconi
< 26.70 °C
27.28 °C
27.86 °C
28.44 °C
29.02 °C
29.60 °C
30.18 °C
30.76 °C
31.34 °C
> 31.92 °C

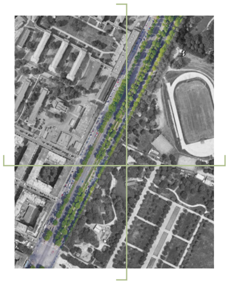
Potential Air Temperature urban sections at 10:00 h

Corso Tazzoli

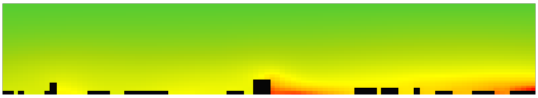
section x/z, y=230 m

section y/z, x=358 m



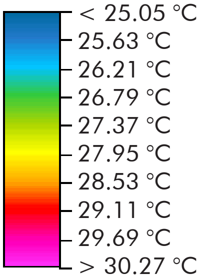


Corso Potenza



section x/z, y=290 m

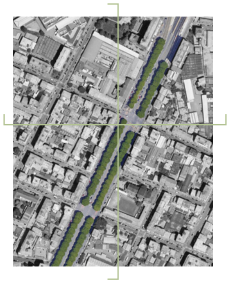
section y/z, x=198 m



Corso IV Novembre

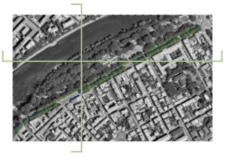
section x/z, y=210 m

section y/z, x=230 m



Corso Casale

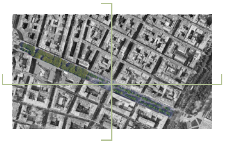
section x/z, y=302,5 m



section y/z, x=302,5 m

Corso Marconi

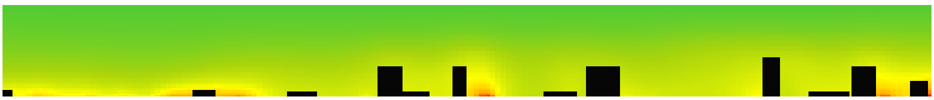
section x/z, y=162 m



section y/z, x=354 m

Corso Racconigi

section x/z, y=274 m

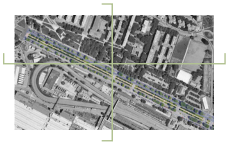


section y/z, x=158 m

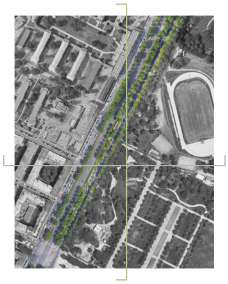
Potential Air Temperature urban sections at 18:00 h

Corso Tazzoli

section x/z, y=230 m



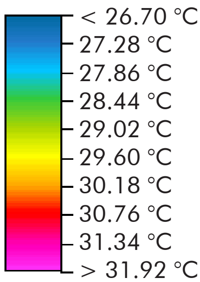
section y/z, x=358 m



Corso Potenza

section x/z, y=290 m

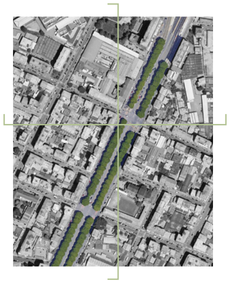
section y/z, x=198 m



Corso IV Novembre

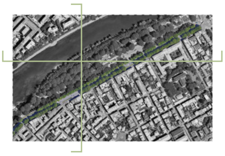
section x/z, y=210 m

section y/z, x=230 m



Corso Casale

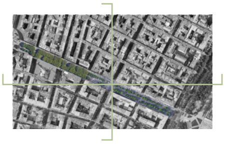
section x/z, y=302,5 m



section y/z, x=302,5 m

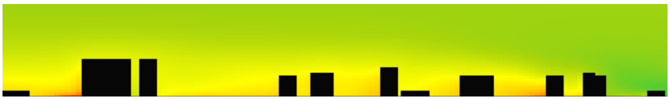
Corso Marconi

section x/z, y=162 m



section y/z, x=354 m

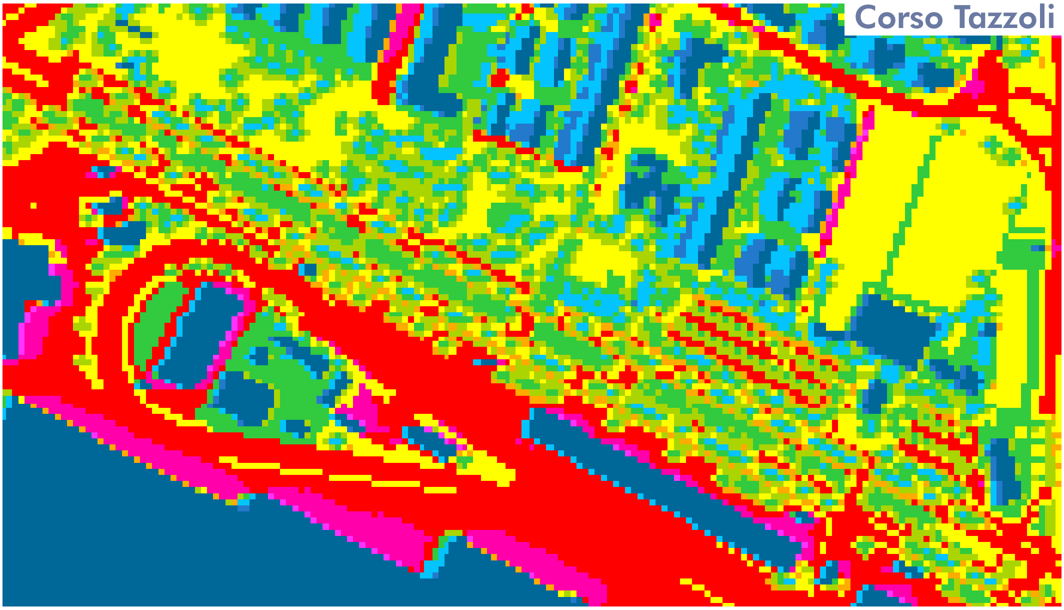
Corso Racconigi

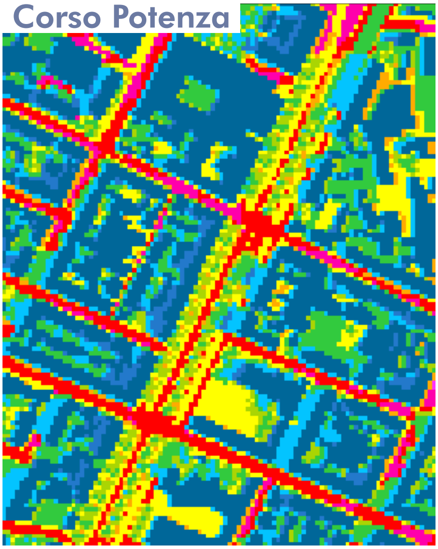


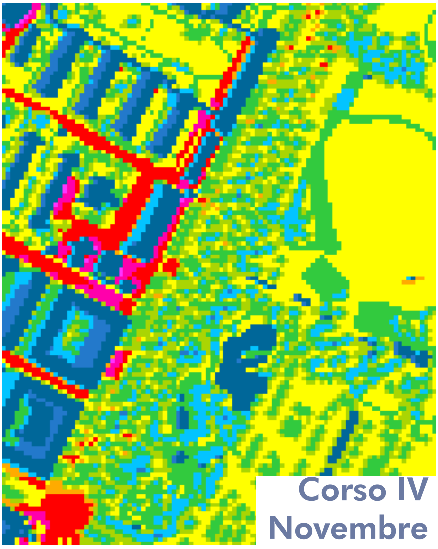
section x/z, y=274 m

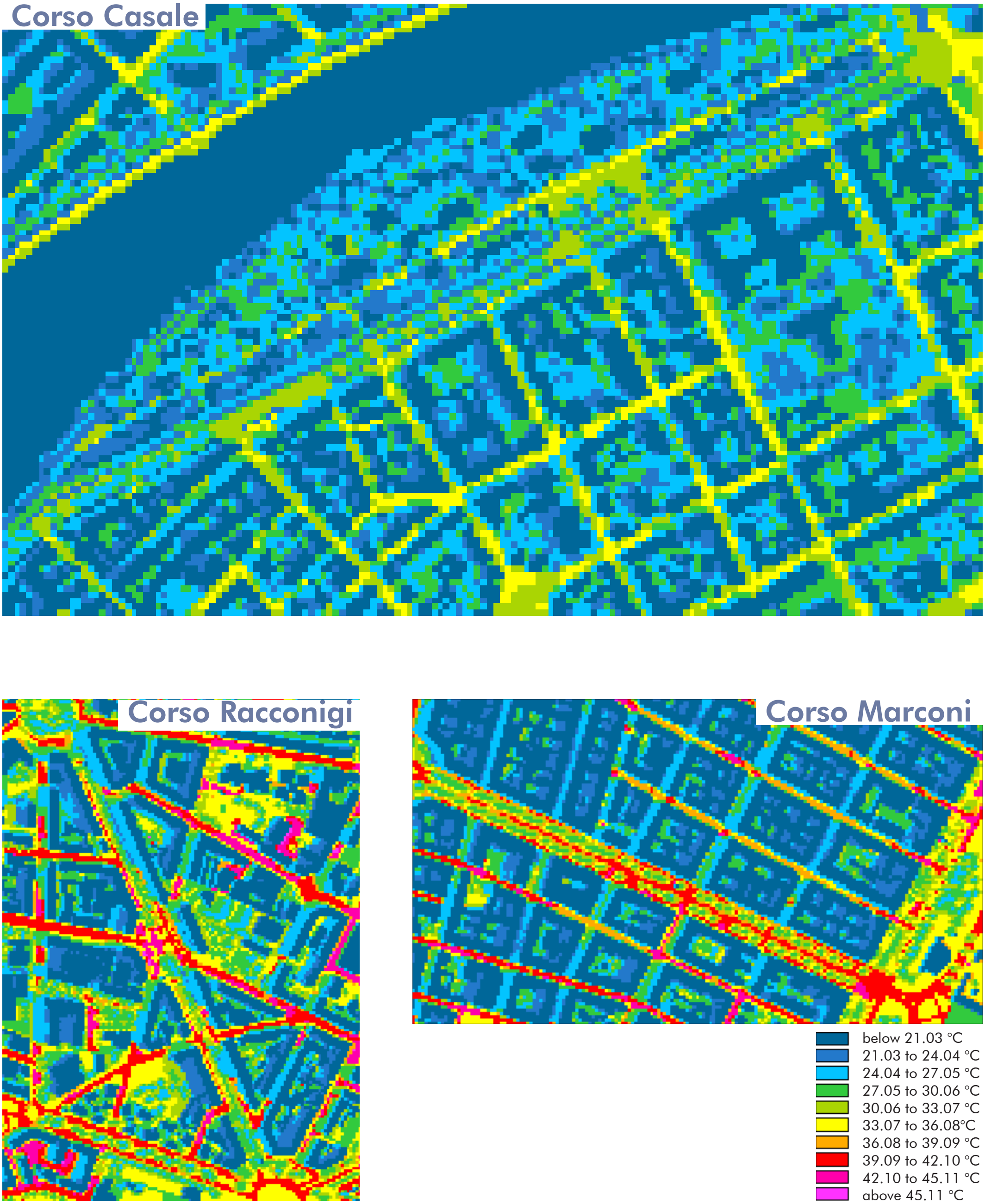
section y/z, x=158 m

Surface Temperature at 10:00 h

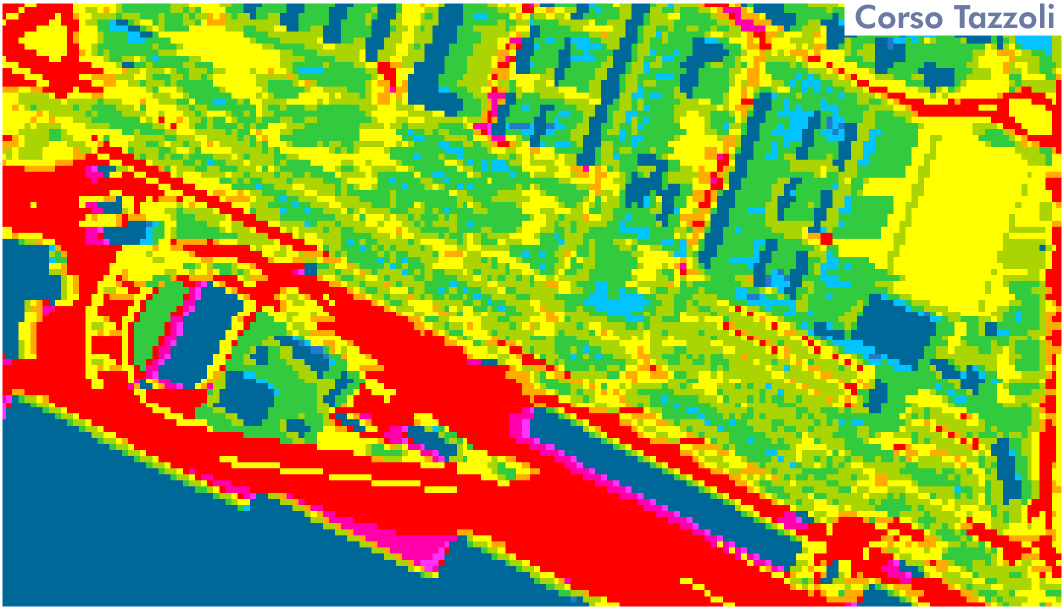


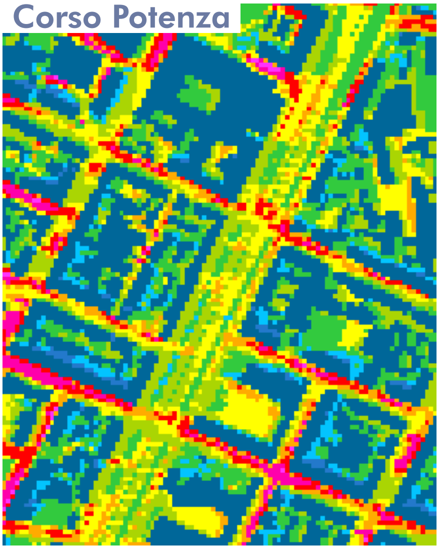


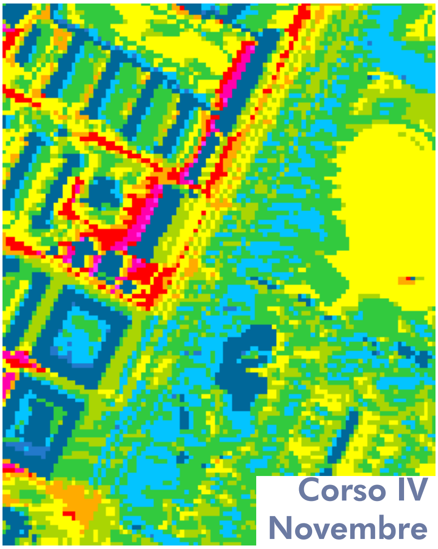


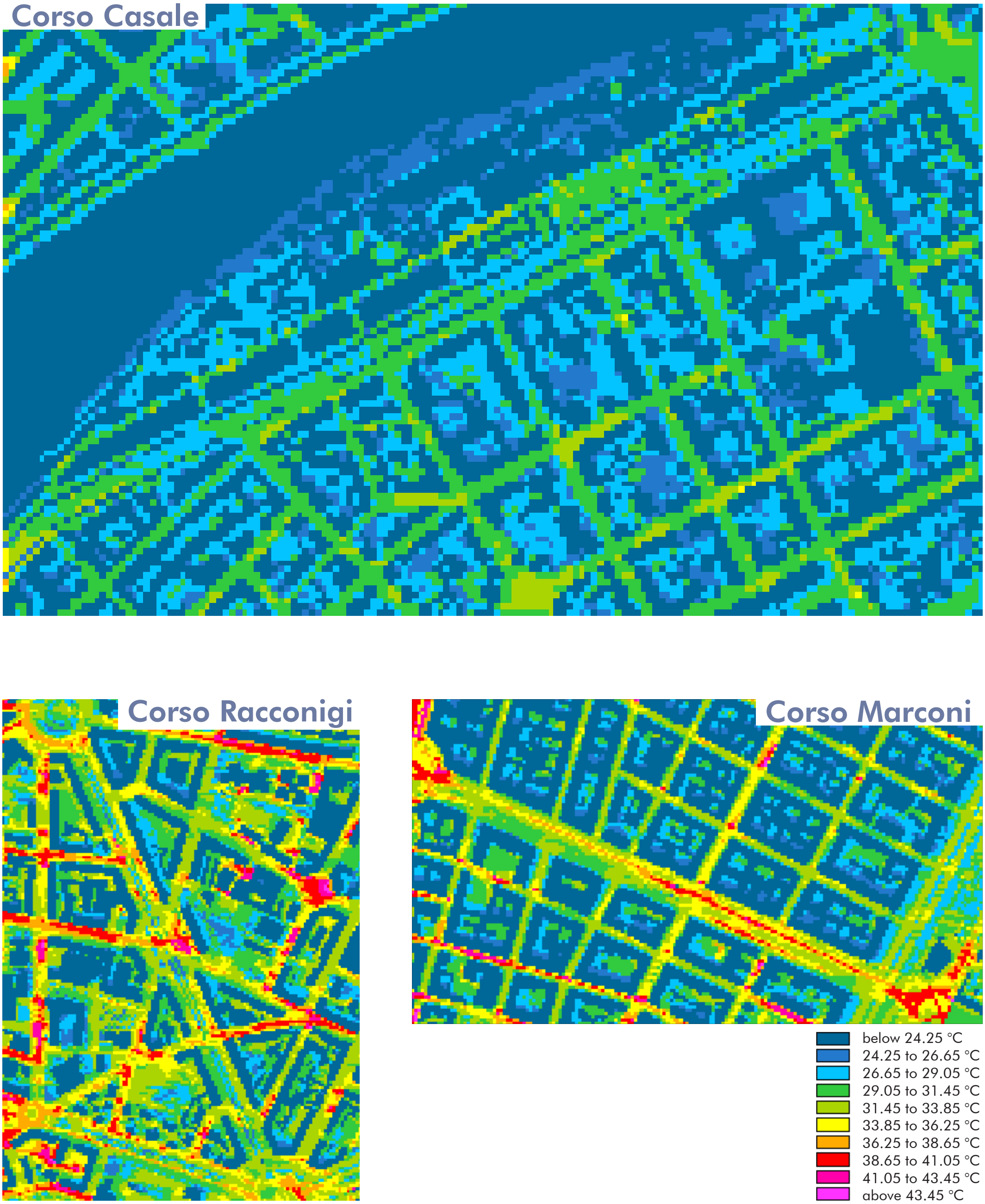

Corso Casale
Corso Racconigi
Corso Marconi
below 21.03 °C
21.03 to 24.04 °C
24.04 to 27.05 °C
27.05 to 30.06 °C
30.06 to 33.07 °C
33.07 to 36.08°C
36.08 to 39.09 °C
39.09 to 42.10 °C
42.10 to 45.11 °C
above 45.11 °C

Surface Temperature at 18:00 h

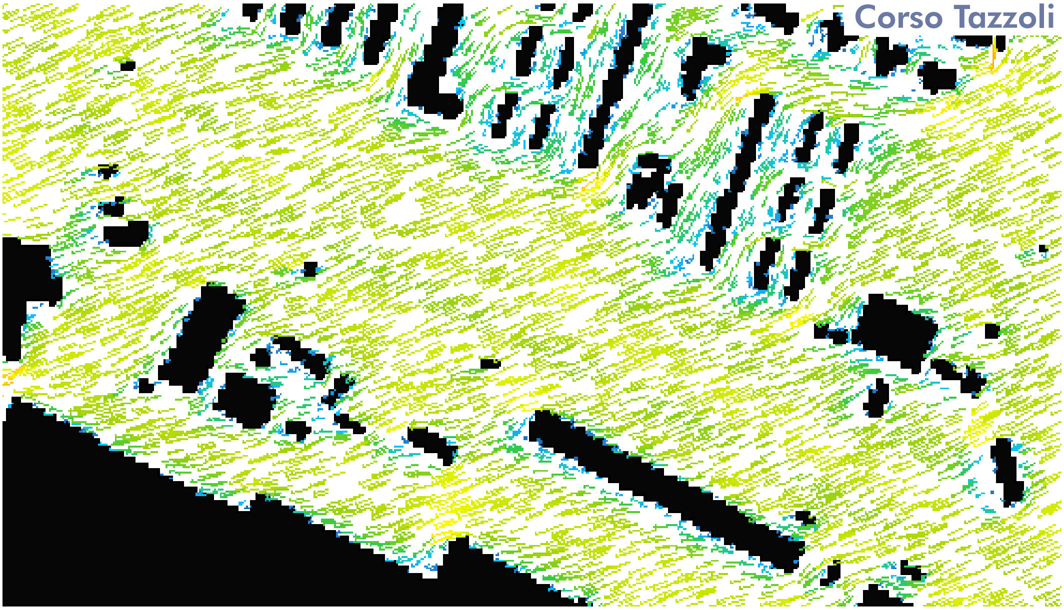


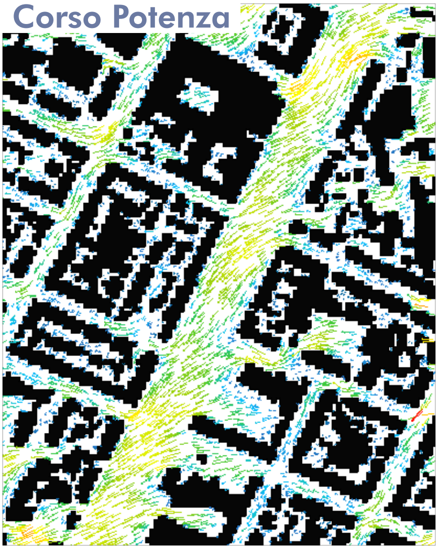


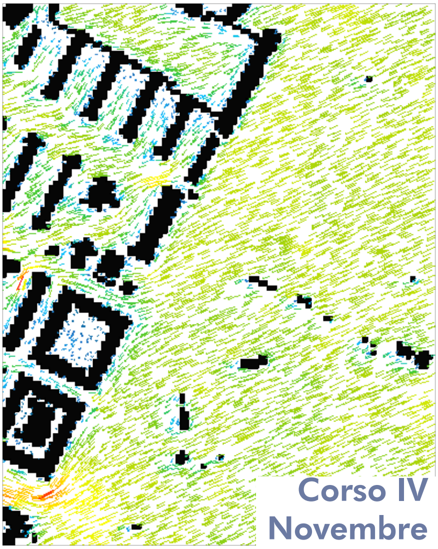


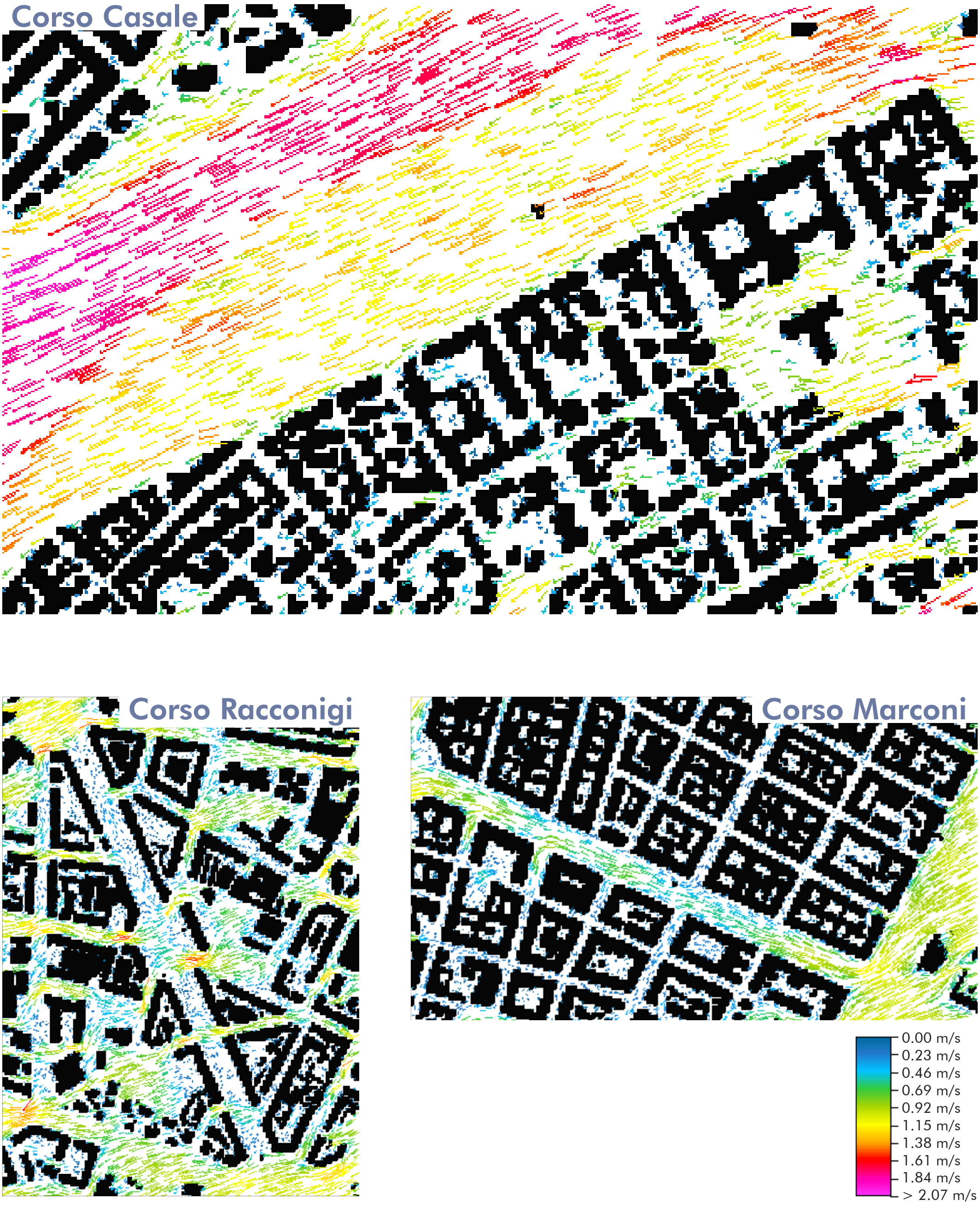

Corso Casale
Corso Racconigi
Corso Marconi
below 24.25 °C
24.25 to 26.65 °C
26.65 to 29.05 °C
29.05 to 31.45 °C
31.45 to 33.85 °C
33.85 to 36.25 °C
36.25 to 38.65 °C
38.65 to 41.05 °C
41.05 to 43.45 °C
above 43.45 °C

Wind Speed at 10:00 h

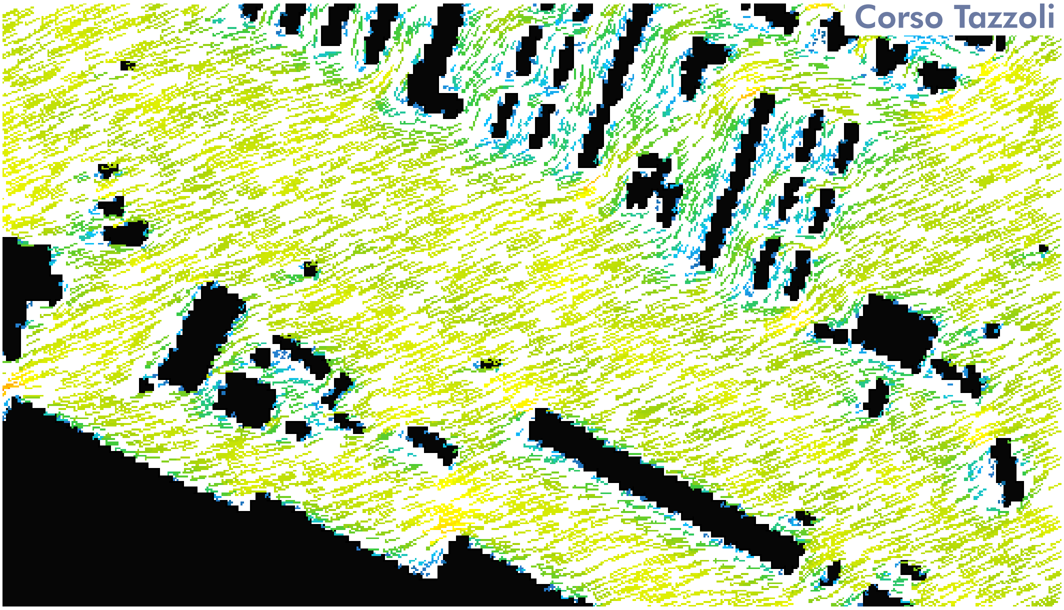


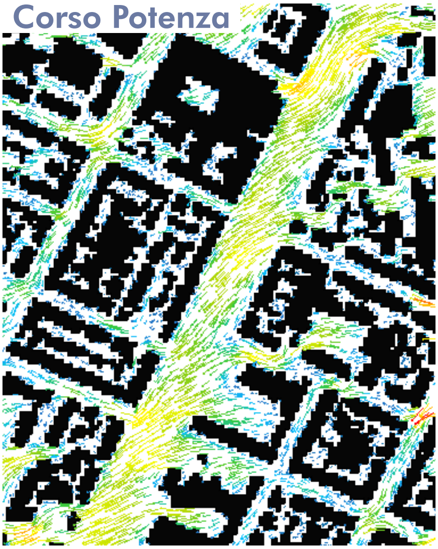


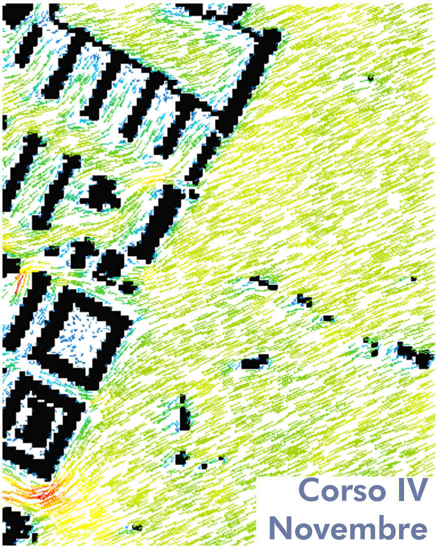


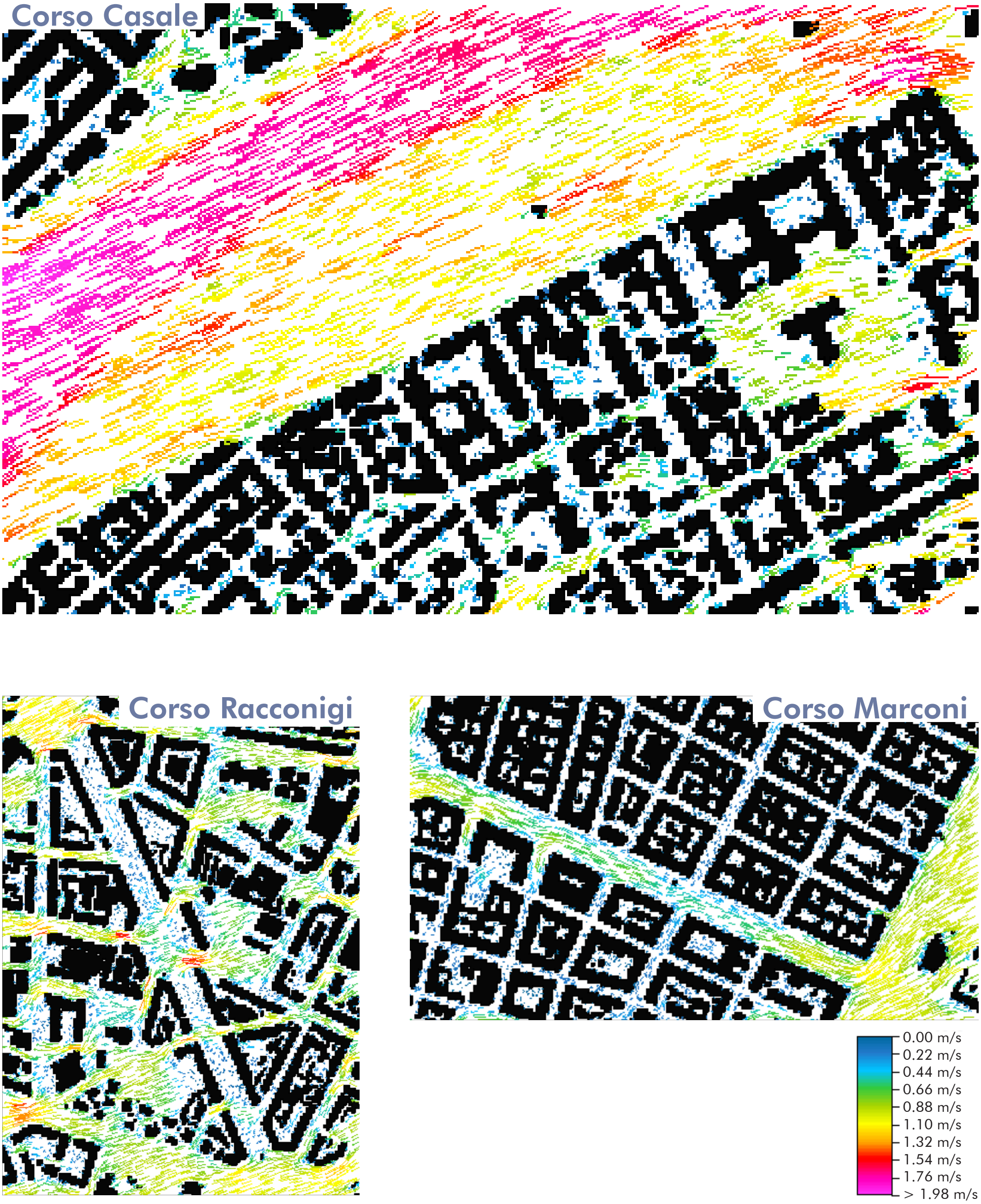

Corso Casale
Corso Racconigi
Corso Marconi
0.00 m/s
0.23 m/s
0.46 m/s
0.69 m/s
0.92 m/s
1.15 m/s
1.38 m/s
1.61 m/s
1.84 m/s
> 2.07 m/s

Wind Speed at 18:00 h

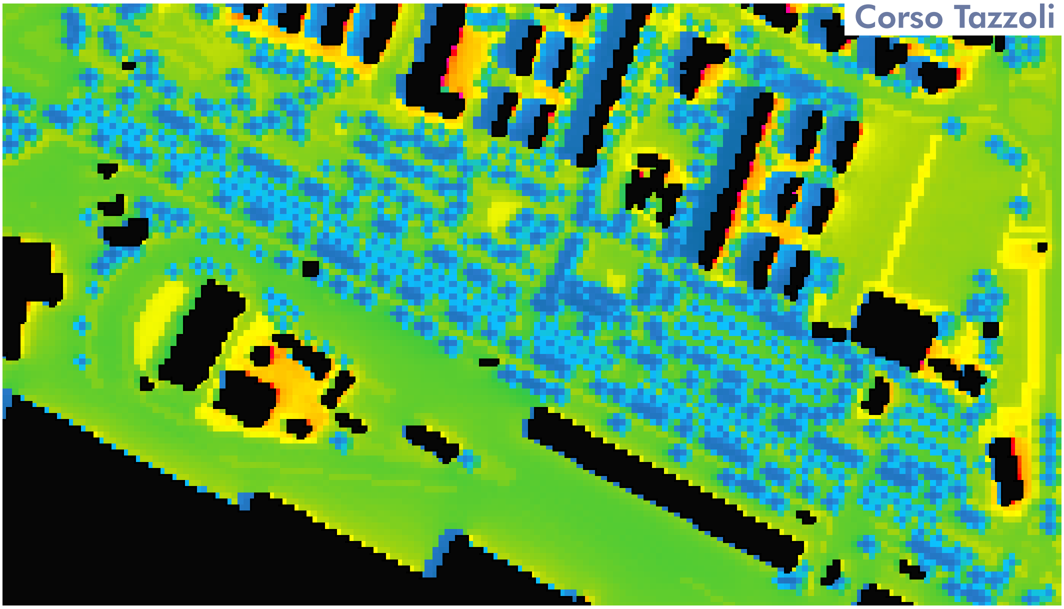


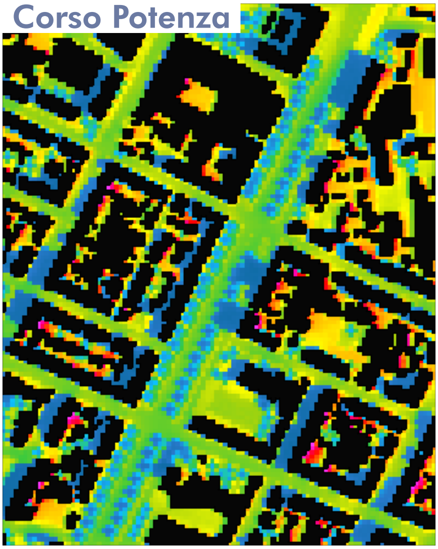


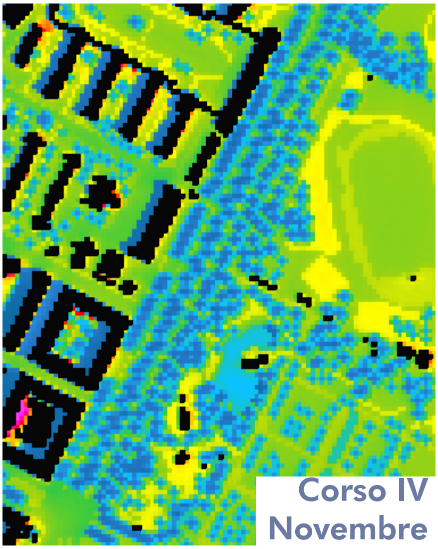


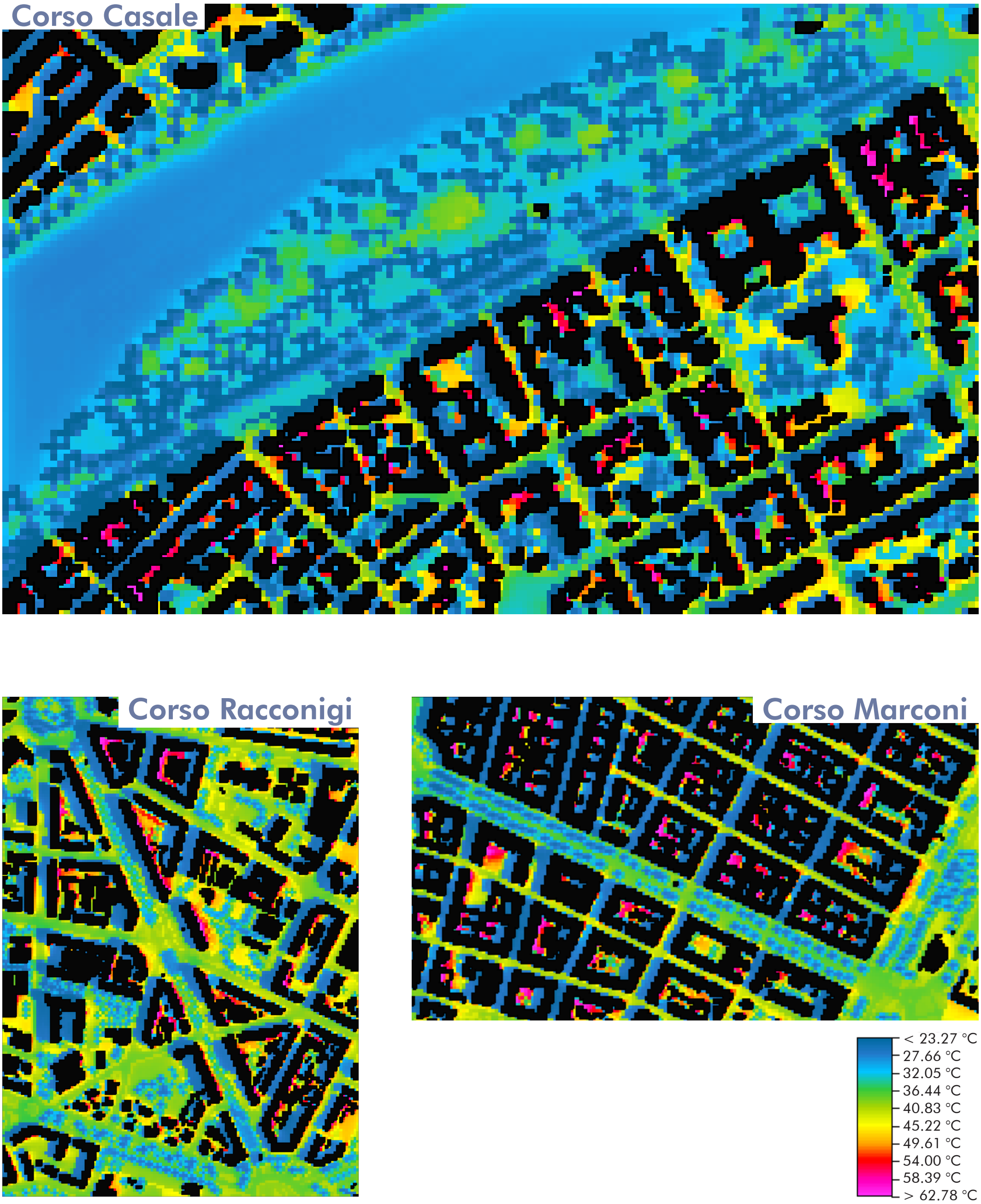

Corso Casale
Corso Racconigi
Corso Marconi
0.00 m/s
0.22 m/s
0.44 m/s
0.66 m/s
0.88 m/s
1.10 m/s
1.32 m/s
1.54 m/s
1.76 m/s
> 1.98 m/s

PET at 10:00 h

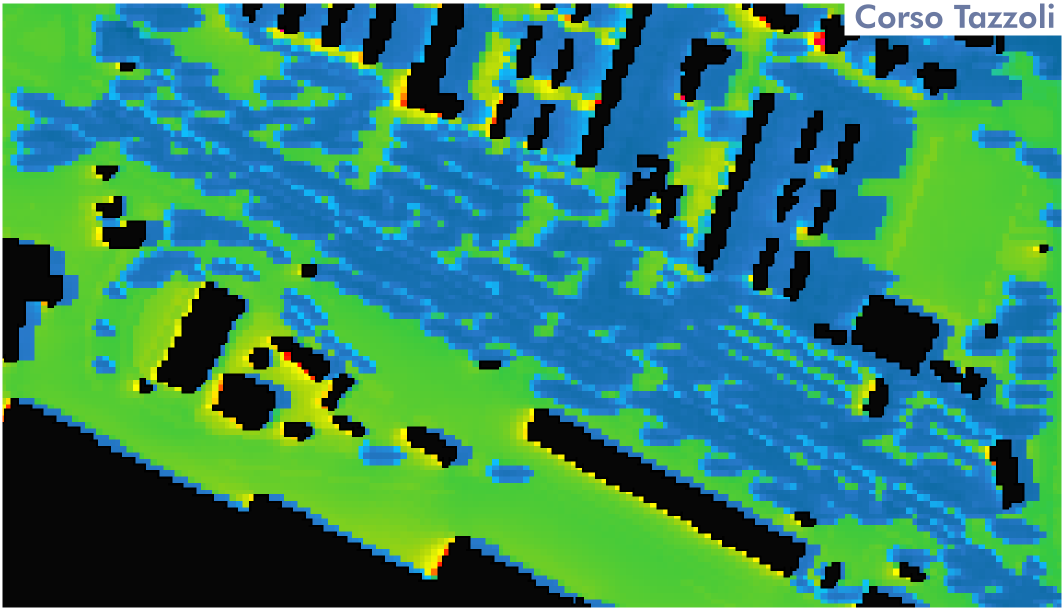


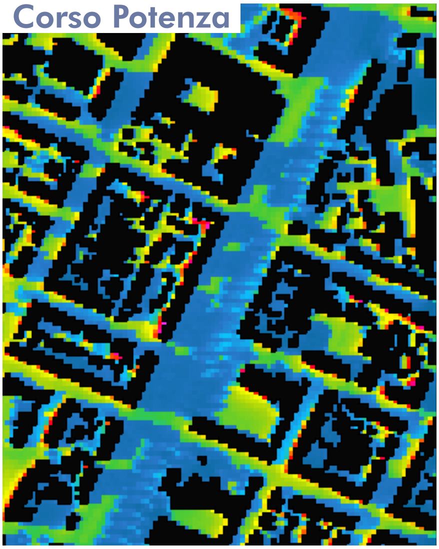


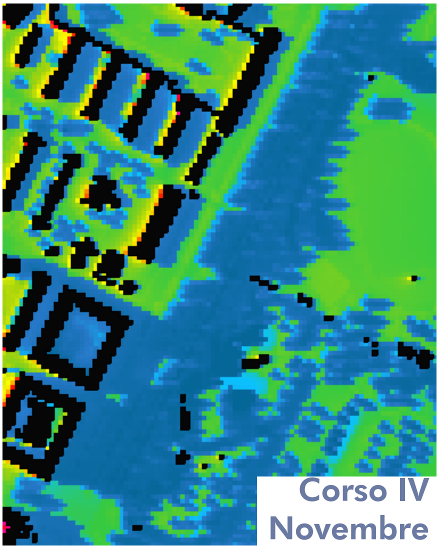


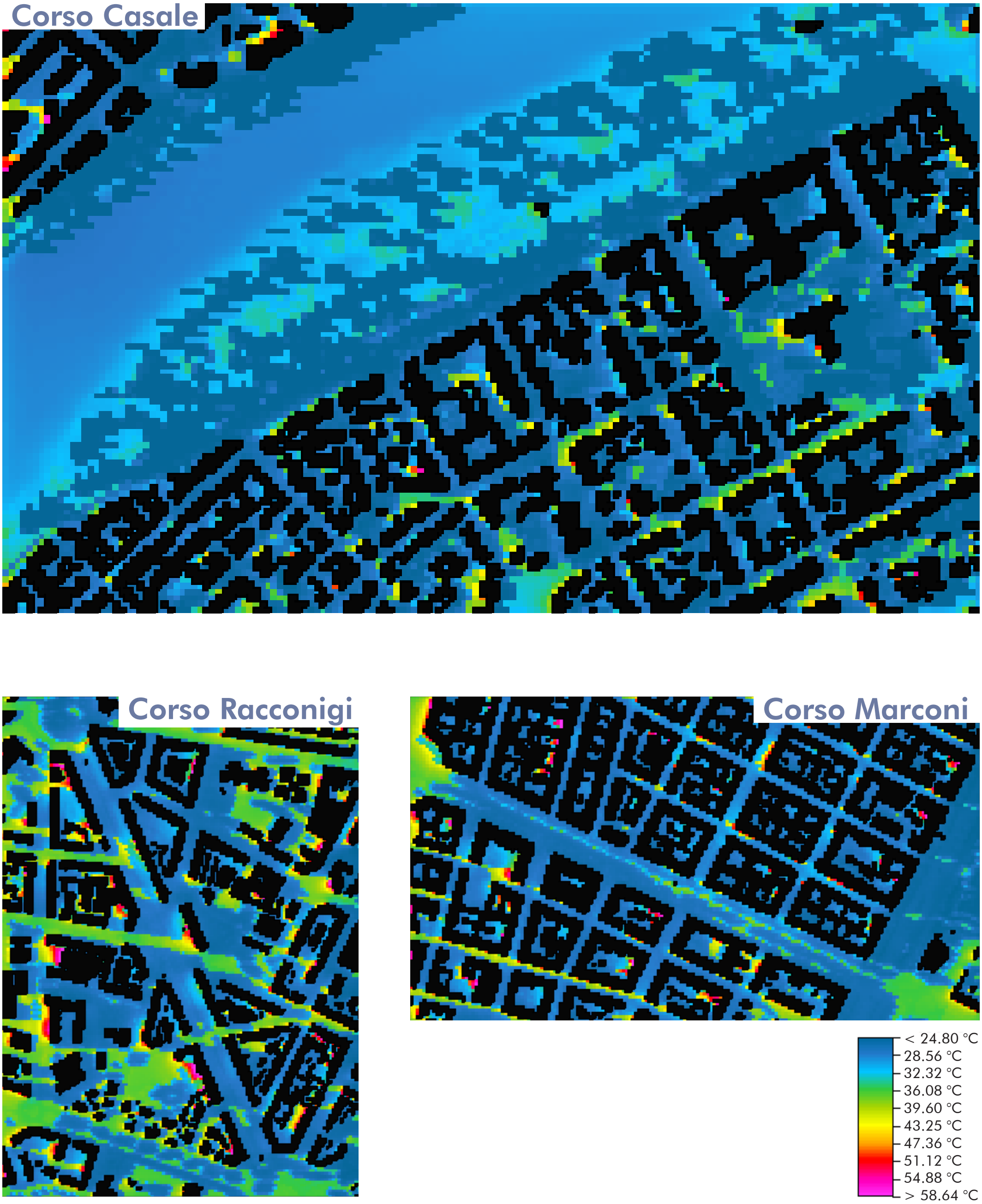

Corso Casale
Corso Racconigi
Corso Marconi
< 23.27 °C
27.66 °C
32.05 °C
36.44 °C
40.83 °C
45.22 °C
49.61 °C
54.00 °C
58.39 °C
> 62.78 °C

PET at 18:00 h








Corso Casale
Corso Racconigi
Corso Marconi
< 24.80 °C
28.56 °C
32.32 °C
36.08 °C
39.60 °C
43.25 °C
47.36 °C
51.12 °C
54.88 °C
> 58.64 °C