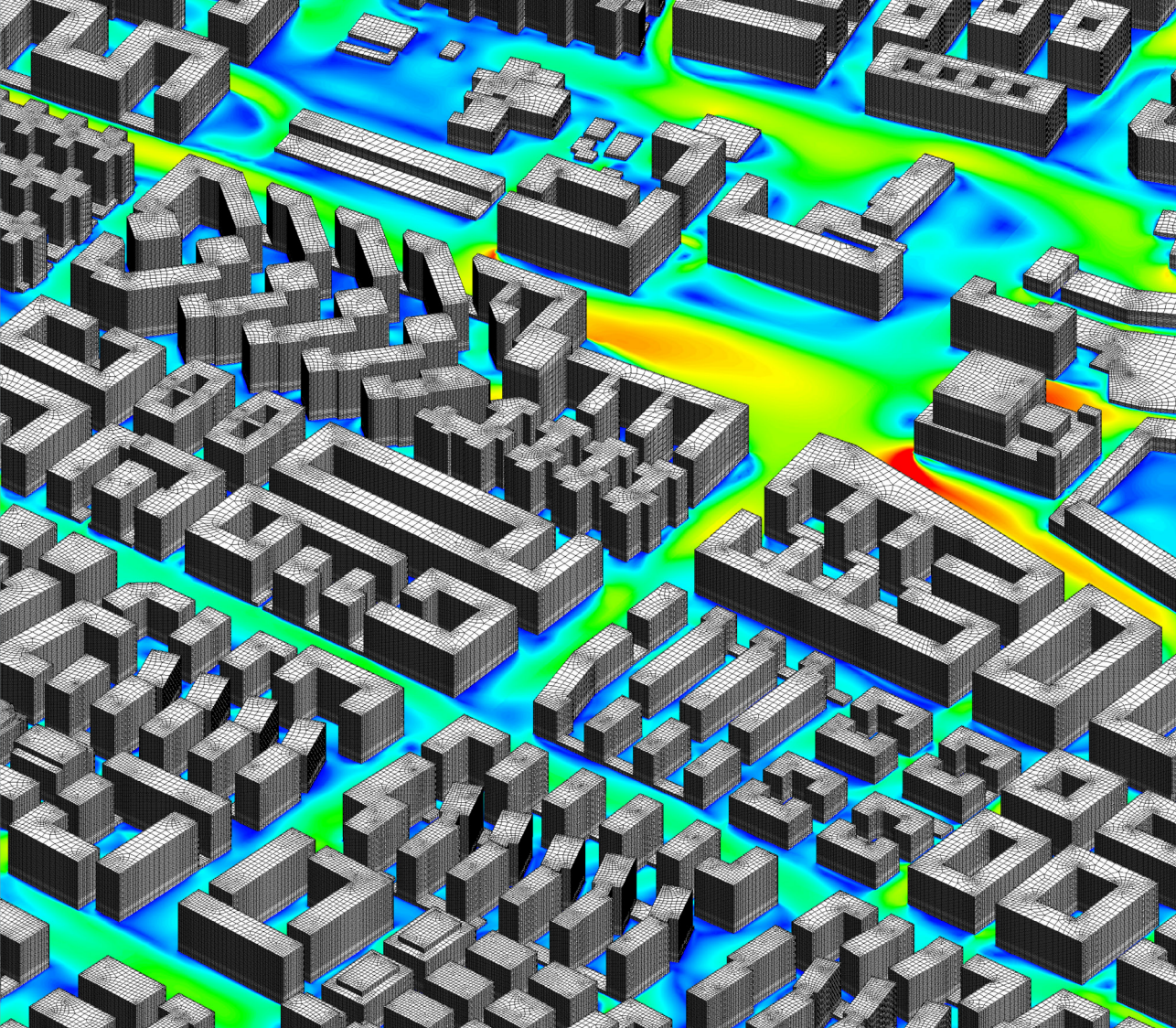




Urban Ventilation and the Compact Mediterranean City

NUMERICAL ANALYSIS OF THE DYNAMIC RELATIONSHIPS BETWEEN DENSITY,
MORPHOLOGY, AND WIND FLOW

Olga Palusci

Bouwstenen

354

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Numerical Analysis of the Dynamic Relationships between Density, Morphology, and Wind Flow

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TU/e Gedragscode Wetenschapsbeoefening.*

Urban Ventilation and the Compact Mediterranean City
Numerical Analysis of the Dynamic Relationships between
Density, Morphology, and Wind Flow

Olga Palusci

Eindhoven University of Technology
Sapienza University of Rome
May 2023



SAPIENZA
UNIVERSITÀ DI ROMA

TU/e EINDHOVEN
UNIVERSITY OF
TECHNOLOGY

The research presented in this thesis was performed within the Department of Civil, Constructional and Environmental Engineering (DICEA) of Sapienza University of Rome (Italy), and the unit of Building Physics and Services (BPS) at the Department of the Built Environment of the Eindhoven University of Technology (The Netherlands), as part of a double-degree agreement between both universities.

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“Ita scire et iudicare licet e parvo brevissimoque spectaculo de magnis et inmanibus caeli
ventorumque naturae rationibus.”

Vitruvius, De Architectura, I sec. B.C.

Thus, it is possible to discover and investigate the great and extraordinary laws of the sky,
wind, and nature from a small and brief phenomenon.

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I became an engineer because I want to make the world a better place for people. Since I was a child, I have dreamt of designing and building houses for people, homes. During my studies, I decided to contribute to improving the sustainability and livability of the urban environment. Soon, I realized that the usual way of designing, building, planning, and managing urban areas was not sufficient for making a difference. I realized that much still needed to be done in this field. Therefore, I have decided to start a Ph.D. program at Sapienza, my home university. Though, when I started my Ph.D. at the end of 2012, I could not even imagine where my Ph.D. would have brought me.

It is not the destination but the journey that matters.

Generally, I agree with this statement. However, some destinations make the journey and represent significant milestones in a person's life. I am glad about my journey, full of encounters, experiences, emotions, and trips that enriched my life, personally and professionally. I am also thrilled to have reached the expected destination: this doctoral dissertation. The journey has been long, challenging, but I met wonderful people who helped me along this path in many different ways. I am very grateful for this and thankful to every and each of those who shared even just a bit of this journey. Some of the people I met became very good friends of mine, some are still part of my life, and others are now on different paths. Nevertheless, a heartfelt "Thank you" to all of you for having accompanied me to this beautiful destination. This destination is not the end of a journey but the beginning of a new one, and I hope to share some new wonderful moments with you.

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Summary

The combination of urbanization and climate change provides new and complex challenges to our cities since they represent a vulnerable element at the center of human life. Cities have been regarded as the emblem of scientific and technological progress, health, and wealth for centuries by humankind. They have gradually attracted the majority of the world population and economic activities. In this process, cities increased in number, size, and density, leading to gradual and inexorable environmental and social degradation. Consequently, the challenge towards more sustainable and resilient built environments has become urgent, especially in existing cities. In this framework, investigations of wind flow in the urban environment are of primary importance. They involve a wide range of topics and associated processes, such as human health and comfort, energy consumption and production, durability and robustness of materials, buildings, and infrastructures. Weak wind conditions may be experienced in compact urban areas, especially at the pedestrian level. Weak wind conditions can be responsible for low air quality, hence higher potentially hazardous air pollution levels, and higher temperatures, thus increased amplification of heatwaves and human thermal stress. These phenomena cause augmented morbidity, mortality, and energy demand for air cooling and purification. The detrimental effects of air pollution and heat stress on human health and comfort may be mitigated by exploiting urban ventilation. Urban ventilation represents the capacity of a built area for introducing fresh air within its tissue and diluting pollutants and heat within its canyons. The phenomenon is closely related to the level of urbanization and the urban morphology, i.e., the form and the structure of the urban area, the physical characteristics of the buildings, and their mutual arrangement. Conversely, urban morphology can be an effective tool in renewal plans for improving urban ventilation in urban areas. For this purpose, detailed investigations of the impact of

actual urban morphologies on urban ventilation are fundamental and represent an essential step towards more sustainable and resilient cities, especially in the Mediterranean area, where a continuous increase in the mean air temperature can already be observed. Studies of the relationship between morphology and wind flows have gained popularity in the past decades in the scientific community. However, given the complexity of the phenomena in play, the majority of these studies used simplified models of actual urban areas, i.e., arrangements of generic building geometries forming idealized urban structures. Albeit useful for investigating the contribution of specific parameters, these simplified models may not reproduce the complexity of the built environment. Actual urban areas have rarely been used as case studies for investigating the impact of urban morphology on urban ventilation. Existing urban areas have mainly been used for describing phenomena in specific contexts, e.g., pedestrian wind comfort, pollutant dispersion, and microclimate. Therefore, the impact of urban density and morphology on flow patterns in actual urban areas should be further investigated.

In this regard, the main objective of the present research is to identify and validate a methodology for analyzing the effects of urban density and morphology on urban ventilation performance in actual urban areas. The research is structured in three main phases. The first phase involves describing and quantifying the physical structure of urban areas. The second phase covers the investigation of wind flows at the relevant observation scale for the selected case study. The final phase regards the correlation of the results of the analyses performed during the previous two stages.

In the first stage, through an extensive literature review, indices used by practitioners and city planners are selected to describe and quantify the densities and morphologies of different urban tissues. The district scale is used as the operational scale to perform morphological analyses because it is suitable to describe the morphological characteristics of urban areas. The Tuscolano-Don Bosco district, an area in the Southeast of Rome, is selected as the case study. The district presents morpho-typological features typical of compact cities in the

Mediterranean basin. Morphological analyses are conducted for the selected area using GIS software, and several scripts and algorithms have been used to combine the raw data to calculate the morphological parameters. In the second stage, first, appropriate tools, techniques, and indicators for investigating wind flows and assessing urban ventilation performance at the district scale in actual urban areas are selected through an extensive literature review. Then, the investigations are carried out by performing Computational Fluid Dynamics (CFD) simulations using the RANS approach. The 3D steady-state RANS simulations are performed for 12 different wind directions to investigate the impact of different urban morphologies on wind flows and urban ventilation in the selected area. The validation of the computational setting is performed using experimental data from wind-tunnel measurements found in literature and conducted for an idealized case study with physical features similar to the actual case study, applying the so-called sub-configuration approach. The results are presented in terms of non-dimensional mean wind velocity and local age of air, i.e., the time a particle of external fresh air spends replacing a particle of the pollutant in a specific location within the area of interest. The abovementioned parameters and their derivatives are employed in the research as key performance indicators for urban ventilation. In the third stage, the wind environment in the entire case study is described and analyzed. The non-dimensional mean wind velocity calculated at two different heights is correlated to the selected morphological parameters to provide linear, easy-to-use models for highlighting areas potentially vulnerable to poor air conditions without running computationally expensive simulations. Finally, the key performance indicators are used to assess the effectiveness of the different morphologies within the case study in enhancing urban ventilation.

The results show that, in a compact urban area, a drastic reduction in the mean wind velocity, up to 60%, can be experienced at the pedestrian level with a consequent worsening of thermal comfort conditions and air quality. The mean wind velocity reduction is dependent on the urban density and increases

monotonically with increases in the morphological parameters. Moreover, the linear models between urban ventilation indicators and morphological parameters show remarkable correlations, R^2 up to 89%. Furthermore, results demonstrate that specific morphologies depending on the wind direction can determine locally pronounced increases in the mean wind velocity, up to 135%, and enhance urban ventilation. The research results confirm the potential of urban morphology in enhancing urban ventilation and the need for approaching regeneration plans according to a climate-sensitive/climate-aware way since sustainability and resilience are the ultimate goals.

This research contributes to establishing a knowledge base of the wind environment in compact cities and developing guidelines for prioritizing regeneration plans in existing urban areas. This work represents a further step to integrate different disciplines, i.e., urban physics, building design, and urban planning, to ease the management of the urban environment complexity. The research outcomes are of interest to stakeholders, practitioners, policymakers, and researchers.

Introduction

I_1 Background

The world population has chosen the urban environment as its habitat. Urban areas have represented, for decades, the synonym for progress, wealth, and possibilities, driving economic development and providing services, e.g., education, transport, and healthcare [1]. Worldwide 4.2 billion people, more than 55% of the world population, live in cities as a result of a gradual and inexorable movement of the population from rural to urban areas, i.e., urbanization [2]. Urbanization is a global phenomenon that, albeit with substantial differences across continents, started during the industrial revolutions, accelerated in the 1950s, and is still ongoing [2]. In 2007, the rate of the world population living in urban areas exceeded the one living in rural areas. This rate is expected to be about 70% by 2050 (Fig. I_1).

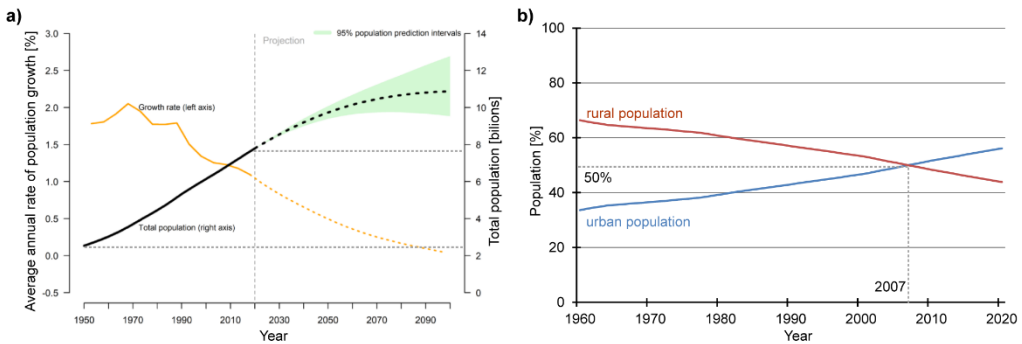


Fig. I_1 - (a) World population, modified from [3], (b) urban vs. rural population, source [4].

In Europe, over 74% of the population lives in urban areas [5], and cities have been the hallmark of European culture for centuries. Nevertheless, two recent phenomena have changed the historical aspect of European cities, giving, first, a strong stimulus and then an acceleration toward urbanization: the economic and demographic “boom” in the aftermath of the Second World War and changes in the lifestyle connected with the improvement of economic conditions. In the past, urban expansion was often driven by speculative logic, maximization of profits, and

minimization of costs rather than performance requirements to respond quickly to the growing demand for housing and infrastructures. This poor compliance of existing urban areas with performance requirements represents an unsustainable and vulnerable element of the built environment [6]. In addition, lifestyle changes have caused a worldwide tendency toward sprawling residential areas. This phenomenon, typical of the low-density expansion of US cities in the early XX century, is driven not only by population growth but by cultural preferences and economic welfare and yields serious problems connected to resources management, transport, energy supply, land take and degradation, soil sealing, and landscape fragmentation [6].

Despite being historically more compact than most American cities, European cities also have undergone sprawl, especially in the last decades of the XX century. In 2006, the European Environmental Agency (EEA) recognized sprawl as a threat to the European culture that significantly affects the environmental, social, and economic dimensions of both cities and countryside in Europe, hindering the efforts to adapt to and mitigate climate change effects [7]. The emblem of this aspect is the role played by open spaces that, from the symbol of the European culture and society, where economic and social exchanges took place, have become places of mere traffic, parking, and pollution. In Europe, despite being sprawl recognized as a multi-facet threat and a reduction in the population growth registered, an inversion in this phenomenon has not occurred yet: the land-take trend has not stopped, and the efficiency in land use needs to improve urgently [8]. The need for renovating existing urban areas to use land and resources more efficiently and improving human health and well-being is a concept of primary importance. This concept is at the foundation of implementing sustainability and resilience in the urban environment, as attested by the 2030 Agenda for Sustainable Development [9] adopted by all United Nations Member States in 2015. In the 2030 Agenda, seventeen topics of critical importance for humanity and the planet have

been identified and transformed into achievable goals, i.e., the Sustainable Development Goals (SDGs). Among these seventeen SDGs, three recommendations advocate explicitly (Fig. I_2):

- SDG #3 - “To ensure healthy lives and promote well-being for all at all ages”;
- SDG #11 - “To make cities and human settlements inclusive, safe, resilient, and sustainable”;
- SDG #13 - “To take urgent action to combat climate change and its impacts”.

**3 GOOD HEALTH
AND WELL-BEING**



**11 SUSTAINABLE CITIES
AND COMMUNITIES**



**13 CLIMATE
ACTION**



Fig. I_2 - Icons of the three Sustainable Development Goals involved with the outcomes of the present research work. Modified from <https://www.un.org/sustainabledevelopment/>¹.

The central role played by the urban environment in the challenge towards sustainability and the urgency in taking effective actions is clear. This urgency fosters the decade-long debate about the characteristics and dimensions of the sustainable city that has been central among researchers, planners, and policymakers for the last three decades [10]. First, the *Our Common Future* report, also known as the Brundtland report [11], and then, the report of the United Nations Conference on Environment and Development, also known as the Rio Declaration or the *Earth Summit* report [12], shed light on the necessity of the sustainable development as an attainable global goal and sparked a lively debate on how to ensure sustainability

¹ The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States.

for development. Specifically, the Brundtland report, highlighting the differences between continents, identified the urban environment as one of the battlefields for the challenge to sustainability, the so-called *Urban Challenge*. As places where people, resource consumptions, and environmental problems concentrate, cities are the fundamental background for achieving sustainable development goals [13].



Fig. I_3 - Perspective views of (a) sprawl (Hong Kong), (b) compact (Rome), and (c) dense (Hong Kong). Modified from Google Earth Pro.

Nevertheless, achieving sustainability in the urban environment is a challenging task because it hinges upon many different factors, environmental, social, and economic, that often lead to conflicting solutions. Despite being based on a global framework, implementing sustainability in the built environment also means addressing site-specific issues. Consequently, a unique answer to the sustainable urban model question, valid in every climate, is impossible to achieve. Nevertheless, a broad consensus exists on assuming the compact European city as a model of a sustainable city, also in stressful climates [14]. This model involves the density of urban tissues, functional mixité, social vitality, and economic diversity [13], limiting urban sprawl and avoiding excessive densities and overcrowding (Fig. I_3). It follows that a tendency toward urban tissue densification has recently been

advocated. Densification may be achieved by building more compact built areas, preferring vertical to horizontal developments of buildings but avoiding bulky high-rise building blocks, and introducing economic and production facilities within residential areas. The aim is to reduce land take and transport and optimize the production and supply of goods, resources, and energy. Although beneficial from the point of view of the optimized use of resources, this strategy may intensify the human pressure on the environment and significantly impact the urban microclimate. If not adequately investigated from the early stages of planning, such a strategy may cause augmented heat and pollution production within urban tissues, increase trapping of long-wave radiation within urban canyons, decrease solar access, and reduce wind conditions. These features have been recognized as the causes of the increase in air temperature registered in urban areas compared to surrounding rural and sub-urban areas, i.e., the well-known Urban Heat Island (hereinafter referred to as UHI) effect.

The UHI effect is usually defined as the most evident manifestation of urbanization on climate [15,16]. It results from complex and intertwined relations between the intrinsic characteristics of urban areas and external factors [17]. The intrinsic characteristics may include city size, urban density, land-use distribution, and building materials. The external factors may be natural, e.g., location and latitude, and human-related, e.g., anthropogenic heat and pollution. Hence, urban climate does not refer only to the regional synoptic climate governed by meteorological conditions, which in reality represents its boundary conditions, but the local microclimate as modified by the presence of the urban area itself [18]. As places where people, activities, and structures concentrate, urban areas inevitably alter the radiative, thermo-hygrometric, and aerodynamic characteristics of the built environment [19]. Buildings and infrastructures absorb and release heat and pollutants, which are trapped between urban canyons; they also exert resistance to

air flows, determining an accumulation of heat and pollutants within urban canyons. The result is worsening human health and well-being (Fig. I_4).

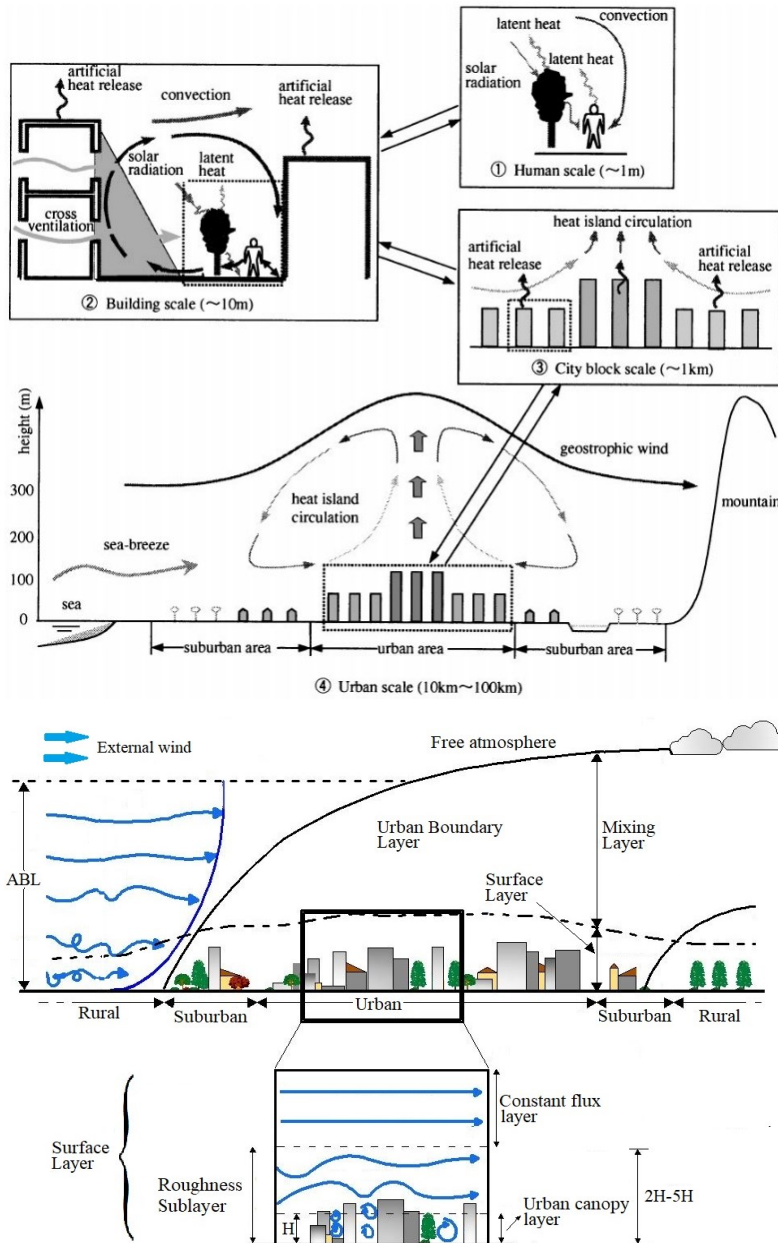


Fig. I_4 - Various scales related to wind climate [20] and a sketch of the UBL structure (modified from [21]).

The role played by the physical structure of urban areas in these processes appears fundamental. Hence, despite being essential, regenerating existing, well-structured, and stratified urban areas by densification is not an easy challenge.

I_2 Problem statement

The combination of rapid urbanization and climate change determines new threats to the health and well-being of citizens and poses new and more complex challenges to the planning and management of urban areas. Urban areas are places where people, goods, consumption, activities, and infrastructures concentrate. Over time, urban areas have increased in density, number, and extension, becoming unsustainable and vulnerable elements of human life, exposing most of the population, infrastructures, and activities to the threat of climate change. Climate change entails the extremization and increase in the frequency of extreme meteorological conditions and climate events, phenomena that are becoming increasingly frequent even in mild or temperate climates, e.g., in the Mediterranean basin and Europe [22,23] (Fig. I_5). Among these events, the increase in temperatures and the prolongation and intensification of heat waves are the phenomena that affect the most the Mediterranean area [24], finding urban areas unprepared [25] and causing augmented morbidity and mortality with different impacts on the population according to age, level of urbanization and socio-economic factors [26]. The aging of the population represents a risk factor when dealing with increased mean temperatures and prolonged heat waves; therefore, it should be considered carefully to prioritize actions [27]. By 2050, more than a third of the European population will consist of older people, one of the most vulnerable groups to the effects of climate change [27].

Rising temperatures and intensified heat waves also impact other aspects of citizens' well-being; they are responsible for economic losses, affect the use of outdoor and indoor spaces, and cause an increase in energy consumption due to air cooling

[28,29]. Cities must be prepared to face climate change challenges by implementing resilience to external stresses, promoting adaptation to changing conditions, and mitigating extreme event effects on citizens' health and well-being [30]. Within this framework, it is urgent to regenerate existing urban areas by implementing resilience and sustainability in the urban environment and promoting urban planning and management based on a holistic, multidisciplinary, and climate-sensitive/climate-aware approach. This approach should not be based on traditional planning models, criticized as inflexible and unable to adapt to environmental, social, and economic changes [31,32], but on performance evaluations.

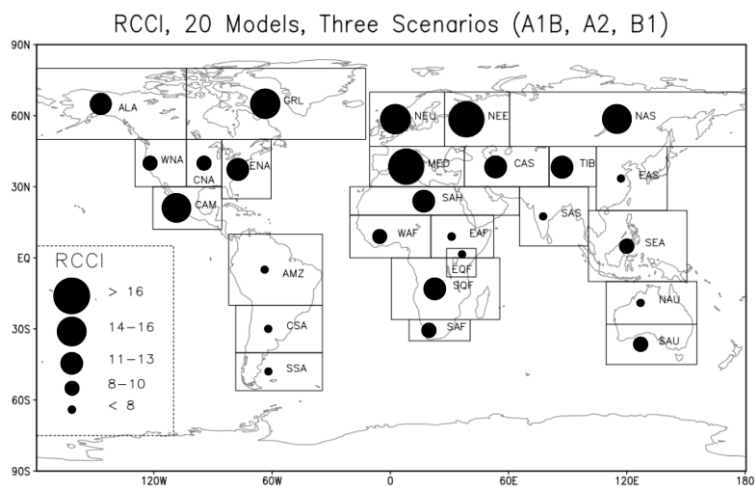


Fig. I_5 - Regional Climate Change Index (RCCI) over 26 land regions of the World (modified from[22]).

Air pollution and heat stress represent two major threats to citizens' health and well-being since they have been linked to increased morbidity, mortality, and economic loss [33–42]. They are usually associated with weak wind conditions [15,43–47] and significantly impact human life in outdoor and indoor places. Weak wind conditions may worsen citizens' health and well-being, limit the use of outdoor and indoor spaces, make ineffective passive solutions, e.g., building natural ventilation, and cause an increase in energy consumption for air cleaning and cooling [48]. Hence,

weak wind conditions directly impact cities' livability, resilience, and sustainability. Nevertheless, the detrimental effects of weak wind conditions can be partly mitigated by exploiting urban ventilation [43,49]. Urban ventilation represents the capacity of urban areas to introduce fresh air within their tissues diluting pollutants and removing heat within their canyons. This phenomenon results from the interaction between urban areas and airflows and is closely related to the level of urbanization and urban morphology, i.e., the three-dimensional structure of cities composed of buildings and the open spaces enclosed by them.

Cities are living organisms that breathe, inhaling fresh and clean air from the surroundings and exhaling polluted and warm air to the environment. Consequently, carrying on the analogy with other branches of science, e.g., anatomy and biology, this phenomenon is also described in terms of breathability, first introduced by Neophytou & Britter (2005) [47], or inhale and exhale effects, introduced by Hang et al. (2012) [44]. Nevertheless, the beneficial effects of urban ventilation may be hindered by buildings and infrastructures, which, as described above, generally cause a reduction in wind speed within and above urban canyons, reducing the removal capacity of heat and pollutants [15]. From this perspective, the morphological characteristics of urban areas can significantly affect the effectiveness of outdoor ventilation.

Therefore, the interactions between urban morphology and urban wind flow need to be investigated in detail to exploit their effects favorably for improving urban ventilation and curbing air pollution and heat stress in urban areas. In fact, the nature of these effects on human life may be beneficial or detrimental, depending not only on the characteristics of the synoptic wind, i.e., gust, speed, and direction, but also on the features of the obstacles and environments that wind encounters along its path. Hereunto, Baruch Givoni states, "Of all the climatic elements, the wind conditions are modified to the greatest extent by urbanization" [18]. As reported above, adequate wind conditions within urban areas may represent an

environmental and economic resource to be exploited by contributing to the fulfillment of requirements for indoor and outdoor thermal comfort and air quality, promoting the integration of passive strategies for building ventilation, but also facilitating the incorporation of micro-wind turbines in the urban landscape for electricity production. Nevertheless, inadequate wind conditions may be responsible for the exacerbation of thermal discomfort and the worsening of air quality. In addition, high wind speed, vortices, and turbulence may cause wind discomfort and nuisance for pedestrians and damage buildings, infrastructures, and vegetation. These detrimental effects are enhanced by specific characteristics of urban areas, e.g., the presence of tall buildings facing open spaces introduces high wind speed from high altitudes and vortices at the pedestrian level [52–55], and alignments of particular morphological configurations with prevailing wind directions are responsible for local increases in the wind speed caused by pressure short-circuiting [56] (Fig. I_6).

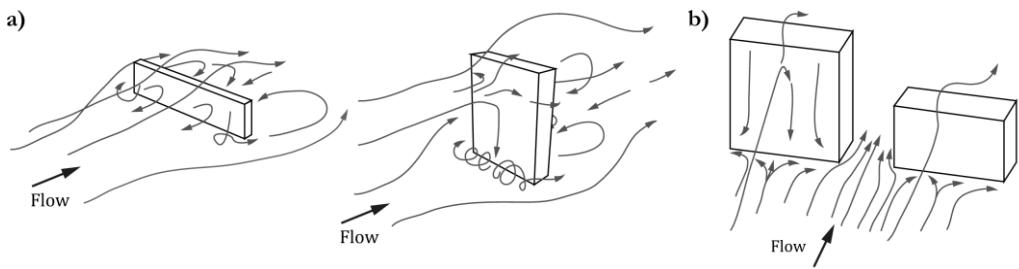


Fig. I_6 - Sketches of the flow pattern around **(a)** two isolated buildings (modified from [57]); and **(b)** and two aligned buildings highlighting the modifications due to the passage and the differences between the buildings (modified from [58]);

It appears evident that these effects significantly affect human life and activities in urban areas; however, they may be exploited to enhance wind conditions locally. Hence, specific morphologies may be used to improve urban ventilation performance and human well-being if adequately investigated during the renovation planning phase by adopting a climate-aware approach. This strategy is not a new

attainment of human knowledge. However, different tools are available nowadays, which may ease the adoption of a performance-based approach to urban planning and building design.

The beneficial or detrimental effects of airflows in urban areas have been known since ancient times. In the I century B.C., Marcus Vitruvius Pollio pointed out in *De Architectura* the necessity to consider wind direction and characteristics when a new city is founded [59]. The author gives instructions on how to direct streets and distribute activities within the city wall based on prevailing winds, highlighting the effects on citizens' health and reporting the city of Mitilene as an example to avoid.

“Moenibus circumdatis secuntur intra murum arearum divisiones platearumque et angiportuum ad caeli regionem directiones. Diriguntur haec autem recte, si exclusi erunt ex angiportis venti prudenter. Qui si frigidi sunt, laedunt; si calidi, vitiant; si umidi, nocent. Quare vitandum videtur hoc vitium et avertendum, ne fiat quod in multis civitatibus usu solet venire. Quemadmodum in insula Lesbo oppidum Mytilenae magnificenter est aedificatum et eleganter, sed positum non prudenter. In qua civitate auster cum flat, homines aegrotant; cum corus, tussiunt; cum septentrio, restituuntur in salubritatem, sed in angiportis et plateis non possunt consistere propter vehementiam frigoris. Ventus autem est aeris fluens unda cum incerta motus redundantia. Nascitur cum fervor offendit umorem et impetus factionis exprimit vim spiritus flatus. Id autem verum esse ex aeolis aereis licet aspicere et de latentibus caeli rationibus artificiosis rerum inventionibus divinitatis exprimere veritatem. Fiunt enim aeoli pilae aereae cavae, hae habent punctum angustissimum, quae aqua infunduntur conlocanturque ad ignem; et antequam calescant, non habent ullum spiritum, simul autem ut fervere coeperint, efficiunt ad ignem vehementem flatum. Ita scire et iudicare

licet, e parvo brevissimoque spectaculo, de magnis et inmanibus caeli ventorumque naturae rationibus. Exclusi fuerint; non solum efficient corporibus valentibus locum salubrem, sed etiam si qui morbi ex aliis vitiis forte nascentur, qui in ceteris salubribus locis habent curationes medicinae contrariae, in his propter exclusiones ventorum temperatura expeditius curabuntur.”

When the walls are set around the city, there follow the division of the site and the arrangement of squares, streets, and alleys within the walls according to the direction of the sky. These elements will be rightly laid out if the winds are carefully shut out from the alleys. If the winds are cold, they damage; if they are hot, they infect; if they are humid, they hurt. Therefore, it seems that this fault must be avoided and averted to prevent what is not infrequent in many cities. For example, the town of Mytilene on the island of Lesbos is magnificently and elegantly built but not placed wisely. In this city, when the South wind blows, people fall ill; when the North-west wind blows, people cough; when the North wind blows, people are restored to health; but they cannot stand in the squares, streets, and alleys because of the vehemence of the cold. The wind is a wave of air flowing with uncertain intensity and direction. It rises when heat strikes moisture, and the intensity of the wind derives from the collision. It is possible to see that this is true from the aeolipiles and express the truth of the divinity about the hidden systems of heaven from the inventions. The aeolipiles are hollow bronze spheres with very narrow holes, and they are filled with water and placed on the fire. Before the aeolipiles are heated, there is no steam; however, as soon as they become hot enough, a violent flow blows on the fire. Thus, it is possible to discover and investigate the great and

extraordinary laws of the sky, wind, and nature from a small and brief phenomenon. Hence, suppose the winds are excluded from the buildings. Not only will this make a place healthy for sound people, but if any diseases arise due to other reasons, those who will not find a cure from medicine in other healthy places will be cured more quickly here by the warmth since winds are excluded.



Fig. I_7 - Aerial maps of different cities in the Mediterranean area, modified from Google Map: **(a)** Brindisi, **(b)** Orvieto, **(c)** Lecce, and **(d)** Ostuni; **(e)** image of Zisa² in Palermo, Italy and **(f)** image of Pavilion in Dolat Abad Garden³, in Yazd, Iran.

Within this framework, the investigation of the wind environment in urban areas emerges as a primary topic that needs to be considered in urban renewal plans since it involves many different phenomena whose effects on human life may be

² <https://it.wikipedia.org/wiki/File:Palermo-Zisa-bjs2007-01.jpg>

³ https://commons.wikimedia.org/wiki/File:Dolat_Abad_Garden_-_Pavilion_01.jpg

beneficial or detrimental. Investigation of the urban wind environment was established as an issue in the scientific literature in the late 1950s due to the rise of a new branch of civil engineering, i.e., wind engineering. Bluff-body aerodynamics, wind loads on structures, natural ventilation, pedestrian wind comfort, pollutants concentration, and dispersion are examples of the main topics of this field. In the last two decades, the investigation of wind flows in urban areas has gained popularity in the literature as a result of increasing concerns about the effects on human health of high pollutants concentration [60,61] and poor wind conditions [43] in cities. Figure I_8 reports the yearly distribution of research papers, review papers, books, and book chapters in English available in the Scopus database and published between 1960 and 2021. The rise of the investigation of urban ventilation and wind flow in urban areas is evident.

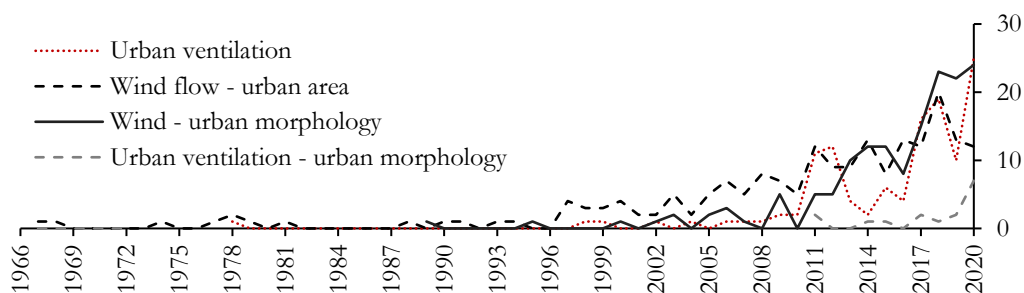


Fig. I_8 - The yearly distribution of documents in the Scopus database published between 1960 and 2021. Legends report the search queries.

Albeit the investigation of the wind environment in urban areas emerges as a primary topic to address sustainability and resilience, actual urban areas have rarely been used as case studies for investigating the impact of urban morphology on urban ventilation performances and evaluating its effectiveness. Given the complexity of the phenomena in play, most previous studies used simplified models of actual urban areas, i.e., arrangements of generic building geometries forming idealized urban structures. Despite helping conduct parametric studies, these

simplified models may not reproduce the built environment's complexity. Therefore, the impact of urban density and morphology on the wind environments in actual urban areas needs further investigation.

Within the framework established in the first two sections, the present thesis hinges upon the following research questions:

- Bearing in mind the necessity of reducing land take and soil degradation and promoting efficient management of resources, how can we advocate densification and enhance urban ventilation without hindering the efforts to adapt to and mitigate climate change effects?
- What are the impacts of compact urban tissues on the ventilation performance of an actual urban area?
- How can we adequately integrate the urban ventilation assessment into the renovation planning phase by adopting a climate-aware/climate-sensitive approach?

I_3 Research objectives and methodology

This research aims to investigate the complex interactions between density, morphology, and wind flow in an actual compact urban area by evaluating their impact on urban ventilation performance. The purpose is to identify and validate a methodology that can be integrated into building design and urban planning processes.

In this regard, the specific objectives of this research can be presented as follows:

- To examine prior research on the wind environment in urban areas identifying the features of interest and the available investigation methods.
- To develop a methodology for assessing urban ventilation performance, highlighting indices suitable to describe and quantify the three-dimensional

structure of urban areas and key performance indicators able to assess the urban ventilation performance of actual urban areas.

- To test and validate the developed methodology for investigating urban ventilation in an actual compact urban area.
- To provide simple models to relate urban morphology to urban ventilation at the early stages of urban planning and building design.
- To assess the effectiveness of different urban morphologies in enhancing urban ventilation.

An actual urban area of Rome, Italy, i.e., the Tuscolano-Don Bosco district, is chosen as a case study for its morphological characteristics, which make it an example of a compact city in the Mediterranean climate. Morphological analyses are conducted to describe and quantify the three-dimensional structure of the case study. Computational Fluid Dynamics (CFD) simulations are performed to simulate the wind environment in the case study. Finally, statistical analyses have been conducted to provide simple models and assess the effectiveness of different urban morphologies in enhancing urban ventilation.

I_4 Thesis outline

The thesis is composed of seven chapters, including the Introduction. The main chapters are four, followed by Discussion and Conclusions, and are structured as follows.

Chapter II is entitled “Air circulation in urban areas” and is an extended version of a published peer-reviewed book chapter:

Air Circulation in Urban Areas, 2021 in: *Urban Microclimate Modelling for Comfort and Energy Studies*. Springer, Cham, 195–221.

This chapter presents a critical review of the literature on air circulation in urban areas, also providing an overview of the numerical and experimental techniques used to investigate wind flow in generic and real urban areas at different scales. Detailed information about the governing equations, including the most commonly used RANS turbulence models, is given in this chapter. Finally, airflow above and within the urban canopy was addressed by reporting common flow topologies investigated in previous studies using archetypal simplified geometrical configurations, such as isolated buildings, street canyons, groups of buildings, and street intersections.

Chapter III is entitled “Urban ventilation in compact cities: a review and a multidisciplinary methodology” and is published as a peer-reviewed journal paper:

Urban Ventilation in the Compact City: A Critical Review and a Multidisciplinary Methodology for Improving Sustainability and Resilience in Urban Areas, 2022. *Sustainability* 12, 44.

This chapter presents a conceptual framework and a multidisciplinary methodology to integrate the urban ventilation performance assessment into renovation plans of existing urban areas. The conceptual framework focuses on four main themes, i.e., urban morphology, urban density, sustainable urban form, and performance-based approach to urban planning and building design. A comprehensive review of the evaluation of the performance of urban tissues is provided by examining 144 published documents. The multidisciplinary methodology is developed based on a critical review of the literature on the urban ventilation concept focusing on morphological parameters, investigation methods, and performance indicators used. The workflow embedded into the developed methodology consists of three main phases: urban morphology quantification, wind environment simulation, and performance evaluation.

Chapter IV is entitled “Urban ventilation in compact cities: impact of morphological parameters” and is published as a peer-reviewed journal paper:

Impact of morphological parameters on urban ventilation in compact cities: The case of the Tuscolano-Don Bosco district in Rome, 2022 *Science of the Total Environment* 807, 150490.

In this chapter, high-resolution CFD simulations, validated with experimental data, are performed to assess the impact of morphological parameters on the effectiveness of urban ventilation in a real compact urban area in Rome, Italy. Thirty-one areas of interest have been identified within the case study, and eight morphological parameters are employed to describe and quantify their characteristics. The non-dimensional mean wind velocity at two different heights, i.e., pedestrian level and half of the average urban canyon height, are employed as performance indicators to evaluate urban ventilation. Finally, linear correlations between morphological parameters and performance indicators are obtained using linear regression analysis.

Chapter V is entitled “Urban ventilation in compact cities: wind-sensitive urban morphologies” and is prepared for submission to an ISI journal:

The effectiveness of urban morphology in enhancing urban ventilation: a numerical study for a real compact area in Rome (in preparation)

This chapter investigates in detail urban ventilation and the effectiveness of urban morphology in enhancing urban ventilation in the selected compact area of Rome. The evaluation is based on a set of performance indicators assessed at the pedestrian level, including non-dimensional mean wind velocity and local age of air. The evaluation is conducted by comparing the performance of selected urban morphologies to the entire area of interest, considering the results of both specific wind directions and the average over the twelve wind directions.

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Air Circulation in Urban Areas

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One of the consequences of the dramatic increase in urbanization that has taken place in recent years is the replacement of rural and green areas with roads, vast extents of concrete, and large vertical surfaces. The air circulation in urban areas is different from that in the surrounding rural environment, and it is difficult to predict because it largely depends on the arrangement of buildings and streets, the presence of vegetation, and other topographic features. In order to improve our understanding of the wind field in cities, field measurements, laboratory-scale physical modeling, and numerical simulations have been widely used during the last decades. This chapter provides a summary of the present knowledge of air circulation in urban areas, focusing on the case of a neutral atmosphere. The most common flow topologies encountered in urban canopies are described, which include archetypal simplified geometrical configurations such as isolated buildings, street canyons, groups of buildings, and street intersections.

II_1 Introduction

From a fluid-dynamic point of view, the airflow above the Earth's surface is comparable to that developing above an unevenly warm, rough surface. On a large scale and away from the Earth's surface, winds are mainly governed by Coriolis and pressure forces. These forces affect the intensity and direction of the synoptic (or geostrophic) wind, which defines the boundary condition for the underlying boundary layer.

The wind speed at the surface must necessarily be zero due to the viscosity of the air. Exhaustive studies, observations, and theories concerning atmospheric flows can be found in several textbooks, including Stull (1988) [1], Garrat (1992) [2], Holton (1992) [3], and Jacobson (2005) [4]. Atmospheric flows can be classified according to the spatial scales of the phenomena involved and range from the planetary scale ($>10,000$ Km) to the microscale (1 mm–1 Km). These include the synoptic scale (500–10,000 km), the mesoscale (2–2,000 km), and subsequent subdivisions such as the urban scale (1 m–100 km), encompassing towns and neighboring areas, the district scale (10 m–1 km), the urban canyon scale (~ 10 m) and the human scale (1 cm–1 m). The physical processes associated with these scales are complex, especially in the presence of reservoirs and mountain ranges and when chemical, biological, geological, and physical transformations are considerable [5].

The Atmospheric Boundary Layer (ABL) structure is influenced by soil properties, e.g., aerodynamic roughness, emissivity, albedo, heat capacity, thermal conductivity, and water availability. The set of these parameters determines the surface temperature, which, in turn, regulates long-wave radiation towards space, molecular heat flux into the ground, and the turbulent exchanges of heat and water vapor with the overlying air. The ABL depth varies considerably over time and space (usually from 100 m to 2,000 m) and evolves with the diurnal cycle of solar radiation (Fig. II_1a). Over land surfaces in high-pressure regions, the ABL is generally subdivided

into several layers. At the bottom, there is the surface layer (10–100 m deep), where the turbulent fluxes are approximately constant. Above, the convective (or well-mixed) boundary layer and the stable (or nocturnal) boundary layer characterize daytime and nighttime hours, respectively (Fig. II_1b).

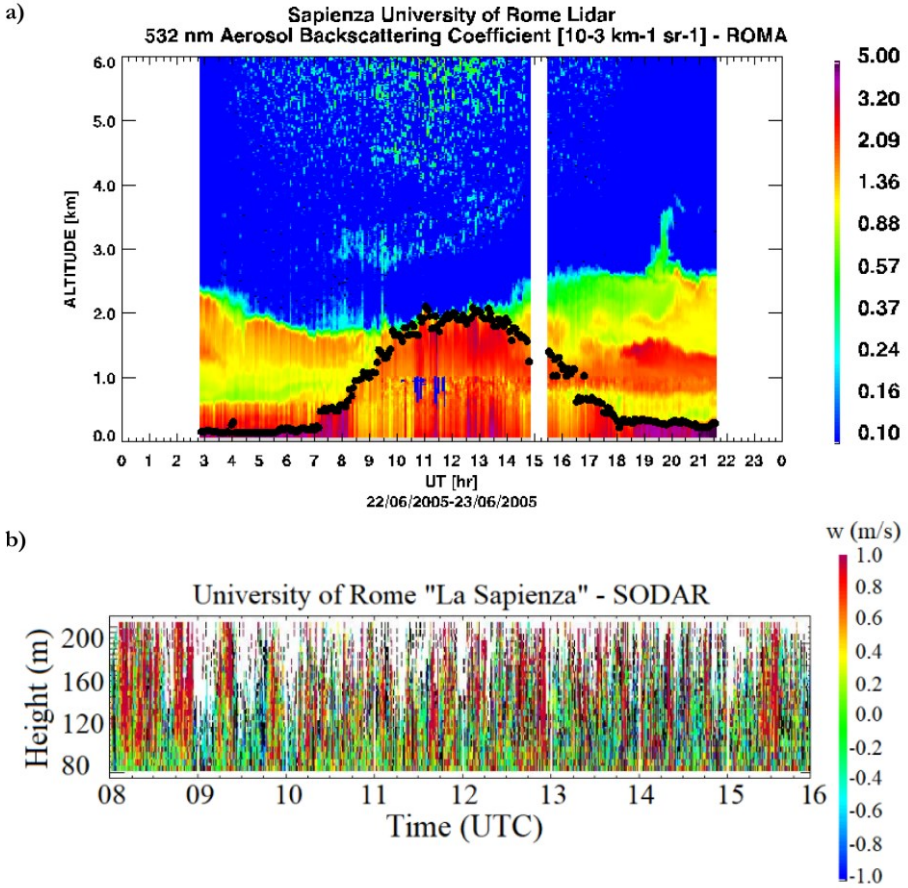


Fig. II_1 - (a) Example of LIDAR (Light Detection And Ranging) scans of the backscattered light from the atmosphere on the 22nd of June 2005. The LIDAR is installed on the rooftop of the Department of Physics of the University of Rome “La Sapienza”, Italy [6]. The intensity of the backscatter (color) is proportional to the aerosol concentration. The black dots denote the ABL height inferred from the vertical backscatter gradient. **(b)** Example of the time history of the vertical velocity (w) profile measured by a SODAR (SONic Detection And Ranging) apparatus placed next to the LIDAR. The features in red are signatures of thermals of warmer air rising from the ground during periods of strong convection, i.e., coherent vortical structures having diameters and depths of the order of the ABL depth [7].

Although terrain effects are present even in nominally flat areas, the ABL is broadly classified in literature into that existing over flat terrain and that existing over complex terrain. When the ground is neither flat nor uniform, the ABL can be modified in terms of heating, moisture, and momentum. Typical examples are geographically generated local winds, e.g., slope flows and sea breezes [8], as well as Urban Heat Island (UHI) circulations (e.g., [9]).

UHIs are defined as the warmth produced by cities [10]. They may form above an urban area during both daytime and nighttime, showing peculiar characteristics with respect to the ABL generally existing in rural areas. The difference in terrain coverage between urban and rural areas is mainly responsible for nighttime and daytime urban-rural temperature anomalies that can even exceed 10°C in the case of large cities (e.g., [11–13]). Possible causes for UHI formation are (i) reduced vegetation and increased paved terrain that lower the potential for evapotranspiration, which, in turn, implies that energy is converted into sensible rather than latent heat, (ii) properties of urban materials, such as albedo, thermal emissivity, thermal conductivity, and heat capacity, (iii) urban geometry, which enhances the trapping of short and long-wave radiations and interacts with air flows determining a reduction in wind speed, and (iv) anthropogenic heat [10].

Knowledge of the wind-flow structure within and above an urban area is of considerable interest in many respects, e.g., urban energy conservation [14], air pollution [15], indoor air quality [16], and human comfort [17]. Unfortunately, owing to the complexity of the geometric configurations involved, the wind flow is largely site-dependent, thus limiting the application of simple models and formulations to predict wind flow in cities [18]. This chapter illustrates the influence of urban morphology on the flow field within urban areas. After a brief description of the gross features of ABLs above cities, the main characteristics of the wind flow around an isolated building and in correspondence with street canyons and groups of buildings are described and discussed.

II_2 Wind Flows Above Urban Canopies

Buildings and other urban infrastructures substantially change the dynamic and thermodynamic fields. Figure II_2 shows a schematic of an urban environment and the modifications induced by buildings on the undisturbed wind.

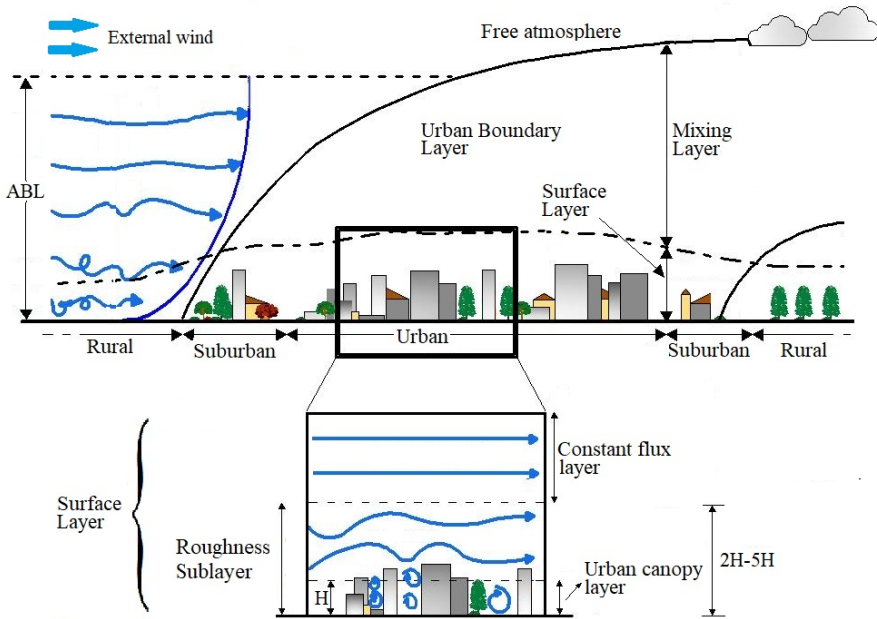


Fig. II_2 - Sketch of the UBL structure (modified from [19]).

Wind flow over an urban canopy, defined as the layer that extends from the ground up to the mean building height, is governed by the geometrical, thermal, and radiative characteristics of the site. The Urban Boundary Layer (UBL) is defined as the portion of the ABL between the surface and the height at which the underlying city no longer affects the airflow.

The similarity theory by Monin-Obukhov [20] has stimulated the profusion of considerable efforts in the search for general laws for average wind and air temperature profiles suitable for ABL analysis in various stability conditions in the

past. Most studies reported in the literature show the considerable progress made hitherto but also highlight the absolute shortage of laws valid in general for the urban environment.

The particular nature of city centers does not allow the development of robust parameterizations and theories for the velocity and temperature, as is the case of flat terrain, where the vertical profile of the average wind speed U reads:

$$U = \frac{u_*}{k} \left[\ln \left(\frac{z}{z_0} \right) + \Psi \left(\frac{z}{L} \right) \right] \quad \text{II_1}$$

where z is the height, u_* the friction velocity (i.e., the scaling velocity, which is related to the drag force at the surface), and $k = 0.41$ the von Karman constant. L and z_0 are the Obukhov length and the aerodynamic roughness length, respectively, and assume the role of scaling lengths. The latter is usually parameterized by means of descriptive land-use types (e.g., [21]), while L is proportional to the height above the surface at which buoyant factors first dominate over mechanical (shear) production of turbulence (e.g., [7]). $\Psi(z/L)$ is a universal dimensionless function that equals zero in neutral conditions [22].

Conversely, an open question is the determination of the wind-speed profile above cities. For example, within the roughness sublayer, i.e., the portion of the UBL immediately above the urban canopy (Fig. II_3), Eq. II_1 is not applicable. In such a sublayer, the flow is three-dimensional, non-homogenous, and strongly influenced by vegetation, buildings, and other roughness elements that constitute the urban canopy [23]. Above urban or vegetation canopies, a region of constant flux generally exists (the constant flux layer), and Eq. II.1 now assumes the form:

$$U = \frac{u_*}{k} \left[\ln \left(\frac{z-d_0}{z_0} \right) + \Psi \left(\frac{z}{L} \right) \right] \quad \text{II_2}$$

where d_0 is the displacement height, i.e., the effective height of the ground due to the vertical flow displacement through the canopy. Both z_0 and d_0 are linked to

the surface roughness elements. While u_* to be used in Eq. II_2 is commonly measured within the constant flux layer, z_0 and d_0 are generally estimated by using the morphometric or anemometric methods [24]. In UBL studies, Eq. II.2 is generally applied also within the roughness sub-layer, where the condition of momentum flux constancy is never satisfied [25]. An alternative formulation of Eq. II_2 has been proposed recently by Pelliccioni et al., (2015) [26], in which z_0 varies with height.

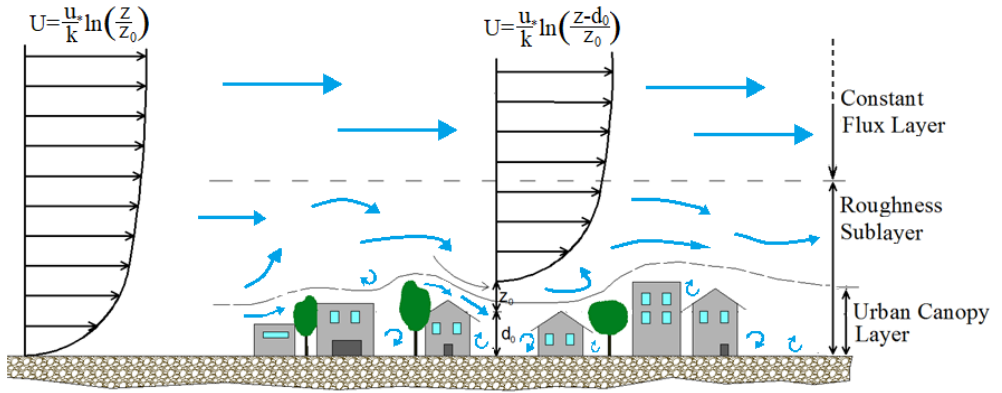


Fig. II_3 - Sketch of the wind profile above an urban area in neutral conditions (modified from [21]).

The picture described above is made even more complicated by the presence of complex terrain, in which airflows are mainly driven by local pressure gradients and thermal forcing [19,27]. This is the case of cities located, for example, in valleys surrounded by mountains (e.g., [28,29]), in which the airflow is determined mainly by terrain-induced perturbations to geostrophic flow (e.g., [30]) or in coastal areas (e.g., [31]).

II_3 Field measurements, laboratory experiments, and numerical simulations

In order to solve practical problems in the urban fluid mechanics area, the turbulent nature of wind flows must be considered. Randomness and nonlinearity are two of the intrinsic characteristics of turbulence that make it impossible to solve the governing equations of fluid flows analytically. Nevertheless, three methods have been developed to solve urban fluid mechanics problems: field measurements, laboratory experiments, and numerical simulations.

II_3.1 Field measurements

In principle, field measurements could be considered the ideal method since they provide values of the meteorological variable collected in the site of interest. Moreover, data coming from measurement campaigns may also be used to validate numerical simulations and laboratory experiments. Measurement instruments can be classified as either direct sensors or remote sensors. Direct sensors are placed on instrument platforms (e.g., masts and towers) and measure the parameters of interest at the sensor locations. Remote sensors measure waves (electromagnetic or sound) and provide information about points and surfaces far away from the instrument locations. Examples of classical direct instruments are anemometers (wind velocity), thermometers (air temperature), hygrometers (humidity), barometers (air pressure), and radiometers (solar, air, and Earth radiations). Meanwhile, SODAR and LIDAR (see Fig. II_1) belong to the class of remote sensors.

It is worth noting that sensor siting (in addition to their cost and management problems) represents one of the critical factors of field experiments, especially in an urban environment where air circulates with small spatial scales. Another critical aspect of the field measurements concerns the uncontrollability of boundary conditions and, therefore, the significance of the data. In fact, there is the

superposition of many simultaneous effects and processes. Nevertheless, it is possible to focus on specific processes by carefully selecting weather patterns (e.g., fair weather). In this regard, it is necessary to consider that micro-scale processes dominate a measurement station within the urban canopy layer. It would be advisable to avoid siting in parks if the aim is to collect data representative of the urban area. Choosing a location that is not affected by site-specific microclimatic effects is essential.

Another important problem is repeatability, which strictly does not occur in reality. In this respect, field measurements are fundamentally different from laboratory experiments and numerical simulations, in which the boundary conditions can be easily controlled, and repeatability should be straightforward. The variability and uncontrollability of field measurement conditions imply that validation of laboratory results and CFD simulations with field measurements only makes sense when these have been obtained based on quasi-steady boundary conditions (e.g., in the presence of persistent winds).

II_3.2 Laboratory experiments

Laboratory experiments have been the only alternative to direct field measurements for years. They create an artificial turbulent domain in the laboratory (wind tunnel or water channel, see, e.g., Fig. II_4), where only a limited number of processes or boundary conditions act on the flow. One of the advantages of using laboratory models lies in the fact that it is generally easy to control the boundary conditions as well as to investigate the role played by the non-dimensional variables governing the flow field. Laboratory experiments require similarity between modeled and real-world processes. To fulfill the similarity requirements, a consistent match between critical ratios of physical and atmospheric properties in both modeled and real-world systems should be ensured [32]. Generally, this is not feasible since some aspects of the real world cannot be scaled. Hence, the attention is on a few

fundamental aspects, i.e., geometric, dynamic, and thermal similarities. However, it should be noted that sometimes it is complicated (or even impossible) to match the non-dimensional parameters of models with their full-scale flow counterparts. For example, the major restriction in laboratory simulations of the whole UHI is caused by the difficulty in reproducing the small UBL height–UHI diameter ratio observed in real UHIs ([33,34]). Further problems and limitations are due to the low Reynolds number (the ratio between inertial and viscous forces) attainable in the laboratory compared with that of real UHIs.

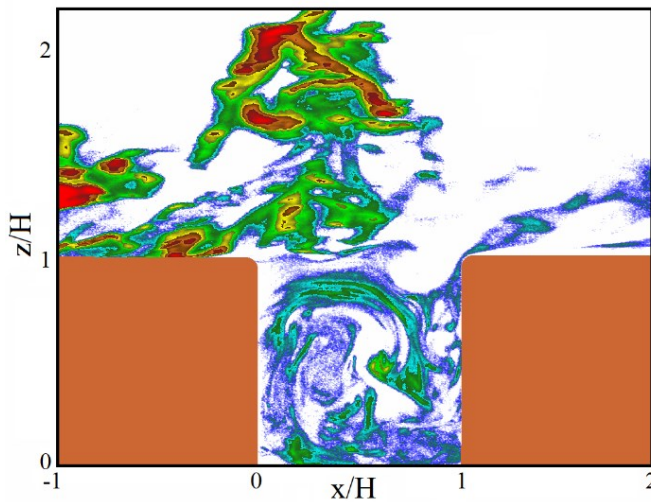


Fig. II_4 - Sketch of the instantaneous pollutant concentration field simulated in a water-channel experiment simulating flow and dispersion in a street-canyon. The flume is directed to the right. Each feature in brown represents a building $H=2$ cm tall. The pollutant is emitted from a point source mimicking a chimneystack placed on the rooftop of one of the buildings located upwind of the building on the left (not included in the picture). The concentration is in arbitrary units (red refers to the maximum value, while white denotes zero). The pollutant enters the cavity mostly due to flow instability occurring at the interface between the cavity and the outer region (see Sect. II.4.2). (The dataset used refers to the experiment described in [35]).

II_3.3 Numerical simulations

Numerical simulations prove to be a powerful investigation method able to overcome the main disadvantages of the previous methods as they provide detailed information about all simulated variables, allow full control over the boundary

conditions, and can be integrated into the design process. Nevertheless, this method suffers from inherent issues, e.g., great attention should be paid while setting the boundary conditions that need to be realistic to obtain meaningful results. Computational Fluid Dynamics (CFD) is a well-established tool for solving urban fluid mechanics problems using numerical simulations. Initially, CFD was integrated with the design process of aircraft and jet engines during the '60s [36]. Over time, CFD has also been employed in other scientific fields, e.g., civil and wind engineering, that has led to the establishment of a well-defined branch, i.e., Computational Wind Engineering [37]. Since the early '90s, an increasing interest in CFD has been recorded in a wide range of research activities and industrial applications thanks to the availability of user-friendly commercial CFD software and affordable high-performance computational resources. Nowadays, despite some drawbacks still present in its fundamental formulation (e.g., [38]), CFD is routinely employed to study wind flow and pollutant dispersion in urban areas [37,39–41].

CFD is based on the numerical solution of fluid mechanics equations that describe the dynamics and thermodynamics of the gases in the atmosphere. Unlike analytical models, which provide a solution at each point of the domain, numerical models discretize the flow field to determine a solution only in discrete points of a numerical grid. The continuous differential equations that govern the flow field are approximated by a large number of algebraic equations describing local processes around the discrete points.

II_3.2.1 Governing equations

In urban fluid mechanics environmental studies, the fluid is considered a continuum. Its molecular structure is ignored as it is not significant compared to the length scales of interest. Hence, its behavior during the flow is described using macroscopic properties, such as velocity, u [m/s], pressure, p [Pa], density, ρ

[kg/m³], temperature, T [K], and their space and time derivatives [36]. The governing equations of fluid flow are based on the conservation laws for mass, momentum, and energy [42]. In other words, the mass of a fluid is conserved, the rate of change of its momentum equals the sum of the forces on a fluid particle (Newton's second law), and the rate of change of energy is equal to the sum of the rate of heat added to and the rate of work done on a fluid particle (first law of thermodynamics) [36]. The governing equations of fluid mechanics for a Newtonian fluid are (for not rotating frame):

- Continuity equation (Conservation of mass):

$$\frac{D\rho}{Dt} + \rho \underline{\nabla} \cdot \underline{u} = 0 \quad \text{II_3}$$

- Newton's second law (Momentum balance):

$$\rho \frac{D\underline{u}}{Dt} = \rho \frac{\partial \underline{u}}{\partial t} + \rho \underline{u} \cdot \underline{\nabla} \underline{u} = \rho \underline{g} - \underline{\nabla} p + \mu \nabla^2 \underline{u} \quad \text{II_4}$$

- Energy equation:

$$\rho c_p \frac{DT}{Dt} = \underline{\nabla} \cdot (K_T \underline{\nabla} T) \quad \text{II_5}$$

- Equation of state:

$$\rho = \rho_0 [1 - \alpha_0 (T - T_0) + \beta_0 (p - p_0)] \quad \text{II_6}$$

where g is the gravity force, μ viscosity [Pa s], K_T is the thermal conductivity [W/mK], α_0 is the thermal expansion coefficient at constant pressure [K⁻¹], and β_0 is the compressibility coefficient at constant temperature [Pa⁻¹]. The variables ρ_0 , T_0 , and p_0 refer to the reference state, e.g., the hydrostatic case. Note that the underscore is used to identify vectors.

The governing equations of fluid flow form a set of six scalar differential equations with six unknowns, two independent variables, and five parameters. In most cases of interest, entailing air circulation in urban areas, this set of equations is not solvable analytically because of the highly turbulent nature of the processes involved and the complexity of the case study. Therefore, simplifications are necessary for closing the set. These simplifications depend on many factors, e.g., the properties of the fluid, the initial or boundary conditions, the phenomenon under investigation, its state, i.e., transient or steady, and the approaches used for the numerical solution.

II_3.2.2 The RANS approach

There are three main approaches for conducting CFD simulations, i.e., direct numerical simulation, large-eddy simulations, and Reynolds-averaged Navier-Stokes simulation. Direct numerical simulation (DNS) solves all the scales of the turbulent fluctuating motions, and the flow can be obtained in every detail of its very complex behavior. Since only motions of scales larger than the mesh size can be resolved, the number of grid points required for solving the turbulent flow in the whole domain is too large, and DNS cannot be used for practical applications in urban climate processes. Large-eddy simulations (LES) and Reynolds-averaged Navier-Stokes (RANS) are the most common alternatives to DNS.

LES solves the large energy-containing eddies in the flow field, which are usually anisotropic and contain most of the turbulence kinetic energy. Conversely, the small-scale eddies are modeled with a sub-grid-scale model. LES intrinsically performs better than RANS but requires finer grids than RANS, and the computational cost is, therefore, considerably higher. With RANS, all stochastic turbulent fluctuations are filtered out, and only averaged equations are solved. In essence, only the mean flow field is explicitly solved, and all scales of turbulence are

modeled by solving additional balance equations for the closure (e.g., for the turbulence kinetic energy and its dissipation rate).

The basis of the RANS approach is the application of the Reynolds decomposition, which consists of expressing the solution variables as the sum of a mean (ensemble-averaged or time-averaged) and a fluctuating component around the mean. Hence, applying the Reynolds decomposition on the variable, ψ , it follows that:

$$\psi = \Psi + \Psi' \quad \text{II_7}$$

where Ψ is the ensemble-averaged value of the variable, ψ , and Ψ' is the fluctuating component of the same variable.

Applying the Reynolds decomposition, the governing equations for an incompressible, viscous, isothermal Newtonian fluid in a three-dimensional domain in Cartesian coordinates x_i can be written using the suffix notation by a set of partial differential equations as follows:

- Continuity equation:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad \text{II_8}$$

- Reynolds-averaged Navier–Stokes equations:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = g_i - \frac{1}{\rho} \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} (2 \nu S_{ij} - \overline{u_j' u_i'}) \quad \text{II_9}$$

$$\text{where } \nu = \frac{\mu}{\rho} \text{ and } S_{ij} = \frac{1}{2} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)$$

where U_i is the mean velocity component, ν is the kinematic viscosity, S_{ij} is the mean strain-rate tensor, $\overline{u_j' u_i'}$ represents the Reynold stresses, μ is the dynamic viscosity. An additional equation may be added to the previous set to model

transport and diffusion of scalars, e.g., pollutant. This equation can be expressed as follows:

$$\frac{\partial \Phi}{\partial t} + U_j \frac{\partial \Phi}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_j} - \overline{u_j' \Phi'} \right) + S_\Phi \quad \text{II}_{10}$$

where Φ is an arbitrary scalar quantity, Γ_Φ is its diffusion coefficient, $\overline{u_j' \Phi'}$ represents its turbulent flux, and S_Φ is the source term of Φ .

The averaging process has generated additional independent unknowns, i.e., the Reynolds stresses for the momentum equations and turbulent scalar fluxes for the arbitrary scalar quantities that maybe be involved in the process, e.g., species. Consequently, the RANS equations do not form a closed set. In problems related to air circulation in urban areas, these stresses and fluxes represent the influence of turbulence on the mean flow, mean concentration field, and mean temperature distribution if considered in the simulations. Therefore, additional information is required, and approximations must be made to achieve closure. The closure of the equations set is obtained by employing turbulence models that predict the Reynolds stresses and the scalar transport terms approximating all scales of the turbulence.

II_3.2.3 Turbulence models

Four main categories of turbulence models have been developed over the years [43]:

- algebraic (zero-equation) models;
- one-equation models;
- two-equation models;
- second-order closure models.

The most common RANS turbulence models are classified based on the number of additional transport equations that need to be solved along with the RANS flow equations [36]:

- Mixing length model: zero additional transport equations;
- Spalart–Allmaras model: one additional transport equation;
- k - ε model: two additional transport equations;
- k - ω model: two additional transport equations;
- Algebraic stress model: two additional transport equations;
- Reynolds stress model (RSM): seven additional transport equations.

The most common turbulence models used to simulate urban fluid mechanics are the k - ε and k - ω models, where k is the turbulence kinetic energy [m^2/s^2], ε is the dissipation rate of k [m^2/s^3], and $\omega = \varepsilon/k$ [s^{-1}] is the specific dissipation (also known as turbulence frequency). They are based on the presumption that an analogy exists between the action of viscous stresses and Reynolds stresses on the mean flow, known as the eddy viscosity hypothesis. This hypothesis, proposed by Boussinesq in 1877, suggests that Reynolds stresses are proportional to mean deformation rates and implies an isotropic assumption.

The standard k - ε model is the most widely used and validated turbulence model [36]. The model was proposed by Jones and Launder in 1972 [44]. It is robust and performs particularly well in confined flows, where the Reynolds shear stresses are important [36]. Conversely, it shows only moderate agreement in unconfined flows. Furthermore, it does not perform well in weak shear layers, in flows with large additional strains (e.g., swirling flows), rotating flows, and flows driven by anisotropy of normal Reynolds stresses [36]. Hence, modifications have been applied to the standard k - ε model over time to overcome these issues. Yakhot and Orszag proposed the Renormalization Group (RNG) k - ε model representing the effects of the small-scale turbulence using a random forcing function in the Navier–Stokes equation [45]. A more recent modification is the realizable k - ε model, which consists of a new model dissipation rate equation and a new realizable eddy viscosity formulation [46]. The former is based on the dynamic equation of the mean-square vorticity fluctuation at large turbulent Reynolds numbers. The latter is based on the

realizability constraints, i.e., the positivity of normal Reynolds stresses and the Schwarz inequality for turbulent shear stresses. This model was developed to overcome the deficiencies of the traditional k - ε model in modeling the dissipation rate, i.e., the well-known round-jet anomaly. Incidentally, this anomaly entails that the spreading rate in planar jets is predicted reasonably well, but the prediction of the spreading rate for axisymmetric jets is unexpectedly poor.

The most prominent alternative to the k - ε model is represented by the k - ω model proposed by Wilcox in 1988, which uses the turbulence frequency ω as the second variable [36]. The model proves to be quite accurate for attached boundary layers in adverse pressure gradients, compressible boundary layers, and free shear flows [47]. Nevertheless, this turbulence model is extremely sensitive to inlet boundary conditions set to ω in a free stream. Contrary to the k - ε model, the results tend to depend on the assumed free stream value of ω [36]. Starting from this notation and bearing in mind that k - ε models do not perform satisfactorily near walls for boundary layers with adverse pressure gradients, Menter introduced the shear stress transport (SST) k - ω model in 1992 [48]. The SST k - ω model is a hybrid model that uses a transformation of the k - ε model into a k - ω model in the near-wall region and the standard k - ε model in the fully turbulent region far from the wall [36]. The main advantage of this turbulence model is that it can be applied to the viscous sublayer without further modification; nevertheless, it can be inadequate at predicting the wake region in the boundary layer [36].

It is evident that none of the available turbulence models presented above provide an accurate description of turbulence flows in the entire domain. In addition, some experts believe that the choice of the turbulence model is problem-specific [49]. Consequently, it is necessary to conduct validation studies of turbulence models and computational settings prior to the actual investigation to verify the reliability of the results.

In the following subsection, the Boussinesq hypothesis adopted in the k - ε turbulence models is reported since they have been used to validate the computational setting employed in the present research work for investigating urban ventilation in a compact urban area numerically.

II_3.2.4 The k - ε model

The Boussinesq hypothesis adopted in the k - ε turbulence models is expressed as follows:

$$-\rho \overline{u_j' u_i'} = 2\mu_t S_{ij} - \frac{2}{3}\rho k \delta_{ij} \quad \text{II_11}$$

where

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad \text{II_12}$$

$$k = \frac{1}{2} \overline{u_i' u_i'} \quad \text{II_13}$$

$$\delta_{ij} = \begin{cases} 1 & \text{for } i = j \\ 0 & \text{for } i \neq j \end{cases} \quad \text{II_14}$$

$$\varepsilon = \nu \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \quad \text{II_15}$$

$$\nu_t = \frac{\mu_t}{\rho} = Sc_t D_t \quad \text{II_16}$$

μ_t is the turbulent dynamic viscosity, δ_{ij} is the Kronecker delta, C_μ is an empirical constant and its value depends on the turbulence model employed, ν_t is the turbulent kinematic viscosity, Sc_t is the turbulent Schmidt number, and D_t is the turbulent diffusion coefficient for a generic scalar.

Readers may refer to Versteeg and W.Malalasekera (2007) [36] for detailed information about the equations and the values of the constants for the different k - ε turbulence models.

II_4 Wind Flow Inside Building Canopies

As mentioned above, airflow through real urban canopies is extremely complex. It depends on several geometrical parameters, e.g., the arrangement and shape of the buildings and the thermal and radiative properties of the materials. Furthermore, it is also strongly affected by the direction and turbulence characteristics of the approaching flow [50,51].

Knowledge of how an isolated building or a group of buildings affect the local wind is important for several reasons, e.g., it allows us (i) to estimate how the wind could buffet people at ground level or on aerial walkways; (ii) to model concentration of pollutants emitted by urban sources (e.g., vehicles and chimneys) and (iii) to analyze the influence of wind on heating and ventilating systems and thus to estimate their performance correctly.

Although a few pioneering efforts to model the spatially-averaged wind-speed profile within the canopy have been proposed in the past (e.g., [52–55]), the complexity of the problem usually requires site-specific measurements performed by means of expensive field campaigns (e.g., [56]), numerical simulations (e.g., [40]) or scaled physical models (e.g., [57]). Alternatively, investigating simple, basic configurations may help to interpret and physically comprehend the basic mechanisms involved. It can also give useful guidance for interpreting and sometimes estimating flows through real building canopies [18].

II_4.1 Wind Past an Isolated Cubic Obstacle

The cube is the simplest idealization of a real building and has been extensively investigated in the past both numerically and experimentally (e.g., [58–64]).

Despite the simple geometry, the flow pattern past a cube is very complex, even when the approaching wind is perpendicular to one of the façades. The shear in the approaching wind causes a downward flow over the lower portion of the upwind façade of the building and a “horseshoe vortex” at the upwind base, which wraps around the building near the ground, extending further downstream (Fig. II_5). At the upwind edges, the flow separates, producing separation zones on the rooftop and the lateral sides of the building. At the downwind edges, the flow separates again, producing a cavity region and the associated bow vortex. The flow there interacts with the current merging from the roof and the sidewalls as well as with the horseshoe vortex. These vortex structures play a significant role in the physical processes governing pedestrian comfort and pollutant dispersion (e.g., [65,66]). Their complex shape and structure should be considered in designing field campaigns in urban areas, where the siting and exposure of meteorological sensors are often, or to put it better, always, incredibly complicated problems.

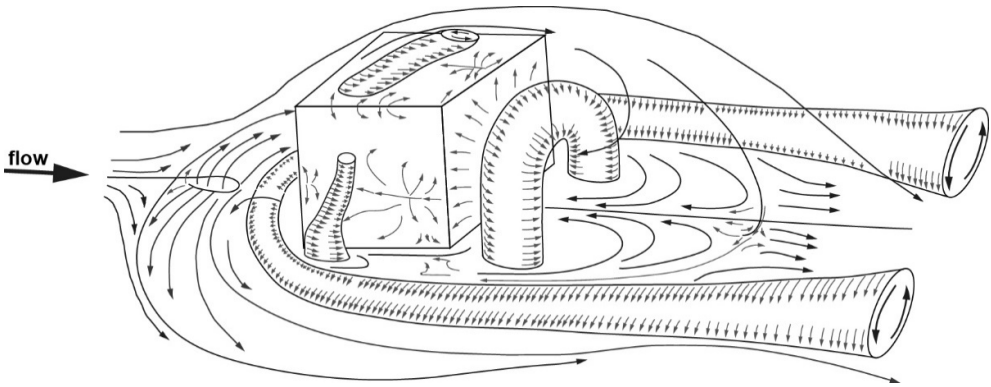


Fig. II_5 - Sketch of the flow pattern around an isolated building (modified from [67]).

Figure II_6 shows an example of the vector field of the mean velocity along a vertical plane passing through the centerline of a cubic obstacle. The eddy structure *A* refers to the bow vortex, while *B* is the signature of the horseshoe vortex located upstream of the cube. The recirculation region is about $1.3 H$ long, where H is the

building height, and R is the re-attachment point. A third vortical structure, C , can also be seen and is located on the first half of the rooftop, while S is the stagnation point forming on the upwind façade.

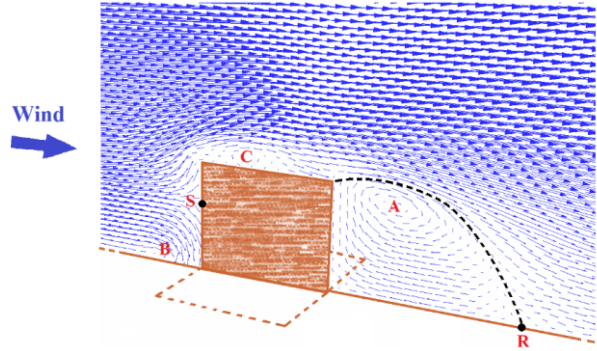


Fig. II_6 - Flow field around an isolated cubic obstacle. The approaching flow is directed rightward. Vectors indicate the velocity magnitude (in arbitrary units) along the vertical section parallel to the streamwise velocity passing through the obstacle centerline. The black dashed line refers to the upper limit of the recirculating region (the dataset used refers to the water-channel experiment described in [68]).

The three panels in Fig. II_7 show the mean concentration fields of a passive tracer emitted from a point source located upwind and downwind of the building and on the rooftop. Passive tracers have been extensively used in the past to identify coherent structures in turbulent flows. They can help analyze flow in both field campaigns (e.g., [69]) and laboratory experiments (e.g., [70]). When the source is upwind of the building (Fig. II_7a), the pollutant is partially advected upstream and remains mainly trapped within the horseshoe vortex. Then, the tracer moves laterally and is carried downwind. Only a small part of the tracer penetrates the cavity region in the lee of the building. Similarly, when the tracer is emitted from the rooftop source (Fig. II_7c), it remains, on average, confined in the vortex located in the upwind half of the cube top. For the case of the source located downwind of the building (Fig. II_7b), the concentration field is quite different: the mean concentration shows much lower values because of the higher pollutant

dilution caused by the bow vortex. Furthermore, the polluted plume moves upwind, rising towards the upper levels of the building.

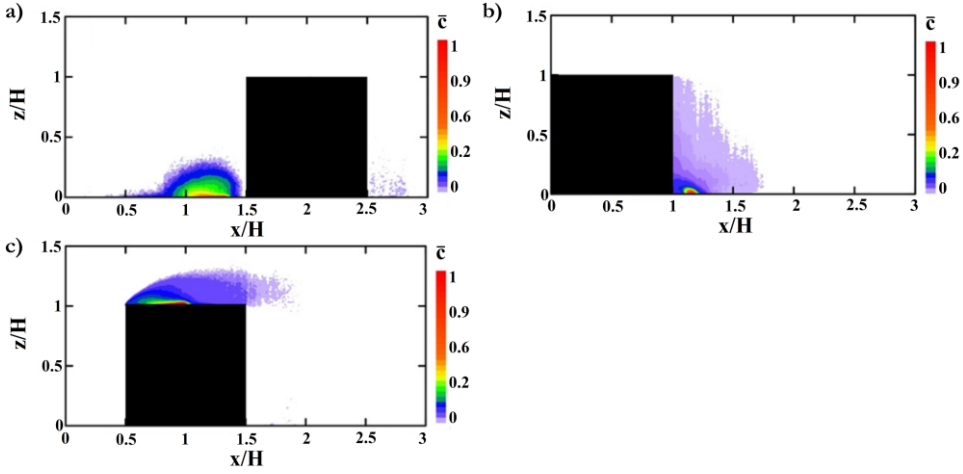


Fig. II_7 - Map of the mean concentration field $\bar{C}$ (in arbitrary units) of a passive tracer emitted from a point source located **(a)** upwind of the building; **(b)** in the lee of the building; and **(c)** at the rooftop. The three panels refer to the same vertical section and dataset of Fig. II_6 (modified from [68]).

It is worthwhile bearing in mind that the sketches depicted above can be considered representative only of cases of wind perpendicular to one of the façades. For all other wind directions, the airflow pattern changes dramatically and depends on the angle between the approaching flow and the façade (Fig. II_8).

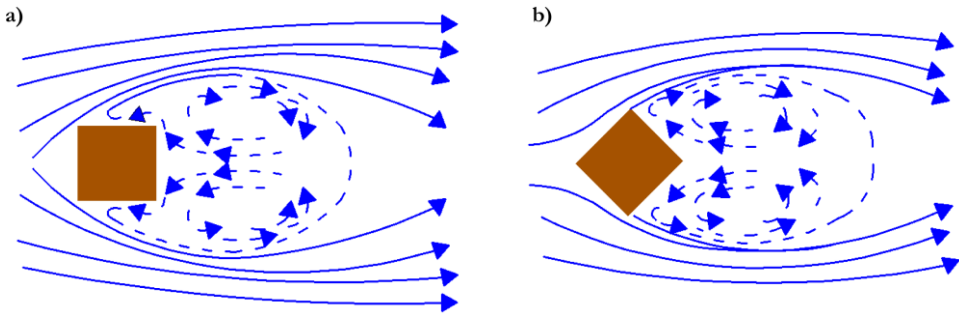


Fig. II_8 - Sketch of the flow patterns around an isolated cubic building along a horizontal plane in the case of approaching wind **(a)** perpendicular to a façade; and **(b)** forming an angle of 45° with the façade (modified from [71]).

II_4.2 Wind in Street Canyons

The street canyon is defined as a geometric entity developed mainly along the street axis (in theory, of infinite length) and having the characteristic U-shape along the cross-section. The street canyon is an archetype for more complex and realistic urban geometries. One of the geometrical parameters to be considered is the aspect ratio $AR = H/W$, i.e., the ratio of the mean height of the buildings, H , to the spacing between them, W . Based on past studies conducted in wind tunnels and water channels, Oke (1987) [71] summarized the nature of the flow in urban canopies in terms of AR (Fig. II_9), viz.: the skimming flow ($AR > 0.7$), in which a single vortex develops within the street canyon; the wake-interference flow $0.3 < AR < 0.7$, which allows the development of two counter-rotating vortices; and the isolated obstacle regime ($AR < 0.3$), where the flow strictly resembles that observed for the isolated building case. It is worth mentioning that the three flow conditions hold strictly in a neutrally stable atmosphere and wind blowing perpendicularly to the street axis. In all other cases, the flow pattern may change substantially due to wind canalization (e.g., [72,73]) and buoyancy effects. The latter can come into play when the wind speed is low [19,74,75]. Both these factors play an essential role in UHI dynamics [76] and cannot be neglected in UBL modeling (e.g., [77,78]).

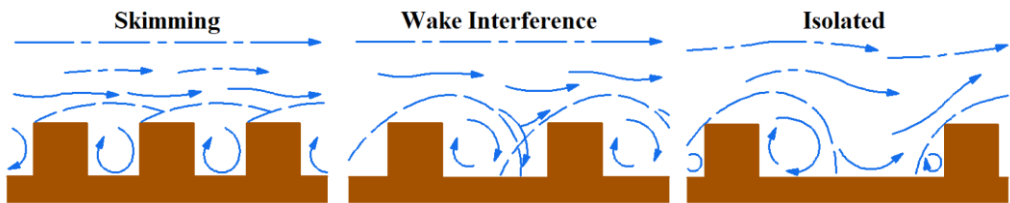


Fig. II_9 - Schematic of flow regimes for two-dimensional street canyons in the case of approaching wind perpendicular to the street axis (modified from [79]).

A sketch of the wind circulation for the skimming flow with $AR = 1$ in the case of uniform building height is depicted in Fig. II_10. The former is one of the

archetypal flow configurations adopted in street flow studies (e.g., [80,81]) and represents the basic flow field for any further analysis concerning more realistic canyon geometry. The external wind (from left to right) flows almost parallel to the building rooftop above the canopy and separates from the flow inside the cavity, where a main vortex forms. A counter-rotating recirculating region, located in the upper part of the façade of the leeward building, and two other smaller vortices, located at the bottom corners of the canyon, complete the flow picture (see also Fig. II_11 for a sketch of the average velocity streamlines). The instantaneous concentration field depicted in Fig. II_10a highlights the Kelvin–Helmholtz billowing at the cavity top, triggered by dynamic instability that, in turn, is generated by the high shear levels at the top of the canyon. These billows govern mass and momentum transfer between the cavity and external flow (e.g., [82] and references cited therein).

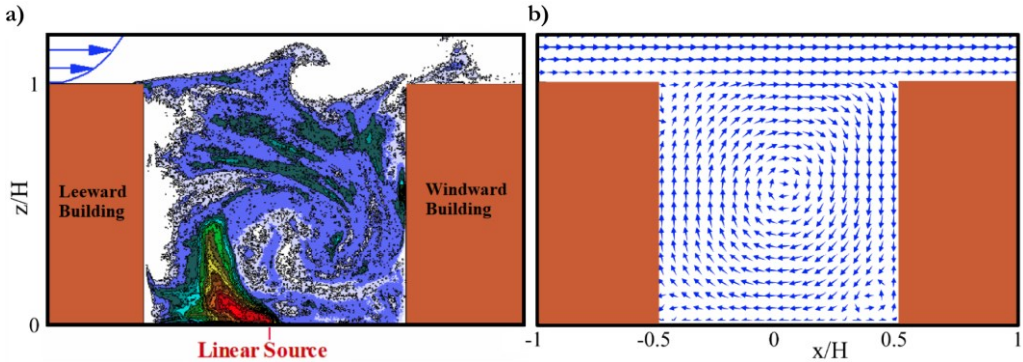


Fig. II_10 - (a) Color map of the instantaneous concentration field (in arbitrary units; red is the maximum concentration value, white indicates zero) of a pollutant emitted from a linear source at ground level within an $AR = 1$ street canyon. **(b)** As in **(a)**, but for the mean velocity vectors (in arbitrary unit). The external flow is rightward (the dataset used refers to the water-channel experiments described in [83]).

The interaction between the canyon and outer flow is greater for the wake-interference regime, where the size of the secondary vortex at the bottom of the leeward building grows with AR (e.g., [85]). Flow separation at the cavity top is,

however, still present. Case $AR = 0.5$ shows two well-defined adjacent vortices: the downstream one is by far the larger and rotates clockwise, while the upstream one is smaller, occupying nearly one-fourth of the canyon, and rotates counter-clockwise (Fig. II_11). For this geometry, the outer flow has difficulty penetrating the canyon. As a result, it skims and remains nearly parallel to the roofs, thus preventing the formation of the recirculating region at the building top seen previously for the isolated cubic building (Figs. II_5 and II_6). This feature causes poor canyon ventilation, even for strong external winds, and it is one of the main causes of air quality deterioration and air stagnation in cities. Canyon ventilation is essentially governed by the dynamics of the shear layer at the canyon top, which forms because of the large velocity gradients occurring in this area (see also Fig. II_4). The shear layer plays a key role in the exchange of air and scalars between the canopy and the overlying region ([83,86,87]).

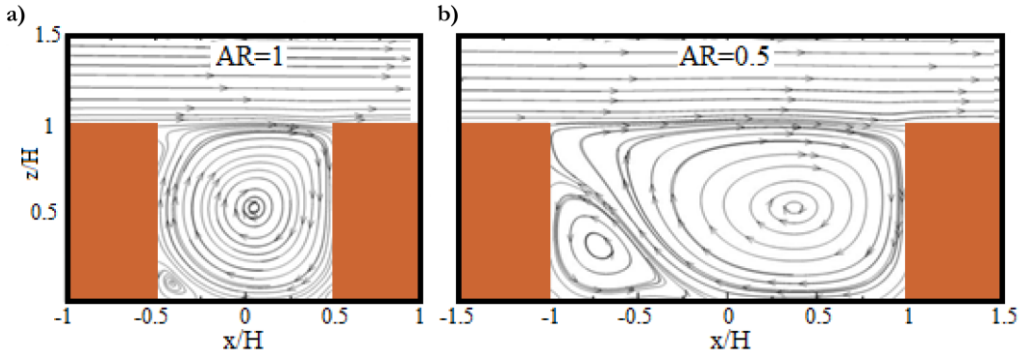


Fig. II_11 - Examples of streamlines of the mean velocity. The external flow comes from the left (modified from [84]).

Similarly to what happens in the case of isolated building flows, wind direction plays a significant role in the flow field inside the cavity. In principle, the flow topology changes dramatically within the canyon if the external wind has a component along the street axis. It is no longer two-dimensional and is characterized by an irregular helix (Fig. II_12).

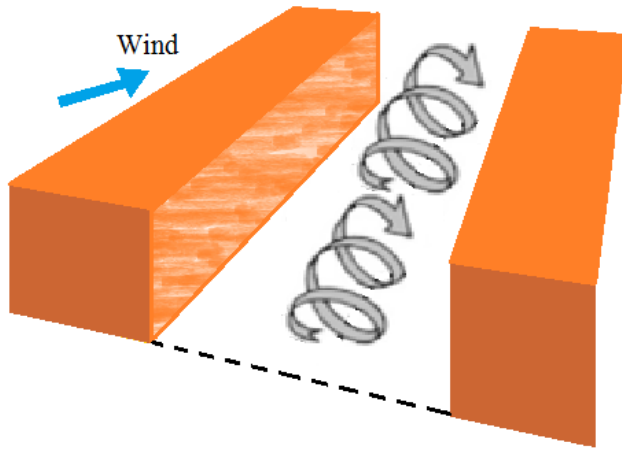


Fig. II_12 - Sketch of flow topology inside a street canyon in the case of external wind not perpendicular to the street axis.

The main difference with the case of the approaching wind perpendicular to the street axis is the presence of a wind component parallel to the street axis itself. This channeling effect increases close to the ground and causes the progressive reduction of the angle between the wind direction and the street axis (e.g., [72,73]). Another parameter to be considered is the canyon asymmetry, i.e., the ratio between the heights of the buildings facing the streets. The asymmetry of the canyon has different effects on airflow, pollutant dispersion, and thermal comfort ([80]).

To conclude this section, it should be observed that aspect ratios $AR = 1$ and 0.5 do not cover all possible situations found in real urban areas, not even with regard to archetypal street canyon shapes ([17,88,89]). Hence, it is necessary to analyze other street canyon geometries and describe their characteristics separately.

II_4.2.1 Effects of Aspect Ratio and Building Rooftop Shape

In principle, a decrease in AR is accompanied by an increase in canyon ventilation and vice versa. Figure II_13 illustrates the streamlines of the average velocity for three skimming flow configurations. While for $AR = 1.33$, no substantial differences with $AR = 1$ appear, further increases in AR give rise to multi-vortex

configurations (e.g., [18] and references cited therein). For $AR = 2$, the two vortices at the bottom seen for $AR = 1.33$ merge to form a larger counterclockwise structure. Hence, two large, separated regions appear inside the canyon. Further increases in AR lead to the formation of additional vortices. For example, for $AR = 4$, three vortices form, with the lowest of them of a smaller size. The configuration of narrow canyons is particularly interesting for investigating dispersion phenomena and air ventilation (e.g., [90]) in that the bottom region is practically disconnected from the outer flow. In essence, the narrower the street canyon, the lower is canyon ventilation. For this reason, it is fundamental to consider correct urban planning to minimize the unwanted effects of pollutant accumulation or air stagnation.

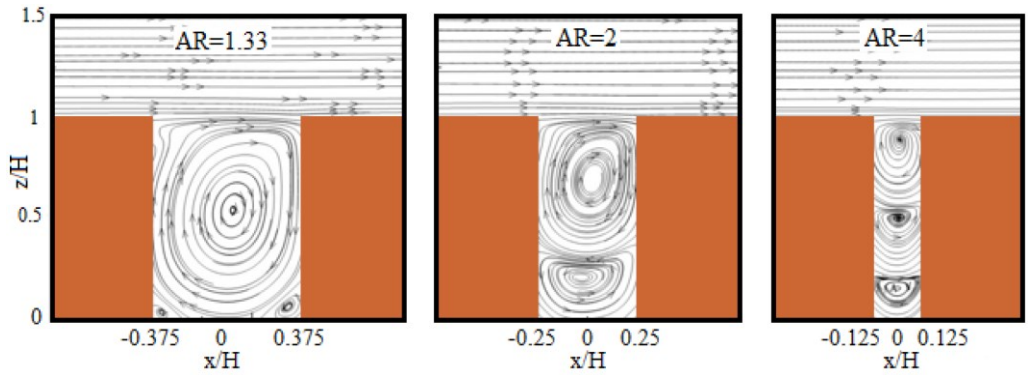


Fig. II_13 - Streamlines of the mean velocity magnitude for the skimming flow regime. The external flow comes from the left (modified from [84]).

In contrast, reductions in the value of AR are accompanied by a progressive increase in canyon ventilation. Figure II_14 shows velocity maps obtained numerically by Badas et al., (2017) [91] for $AR = 0.25$ and 0.17 (colors represent mean velocity magnitude made non-dimensional by the free stream velocity). Although both are considered as belonging to the isolated flow regime ($AR < 0.3$), the two maps show that the two vortical structures within the canyon are still interconnected to each other in the first case, as expected for the wake-interference

regime ($0.3 < AR < 0.7$). However, the vortex in the lee of the upwind building is considerably longer in both geometries.

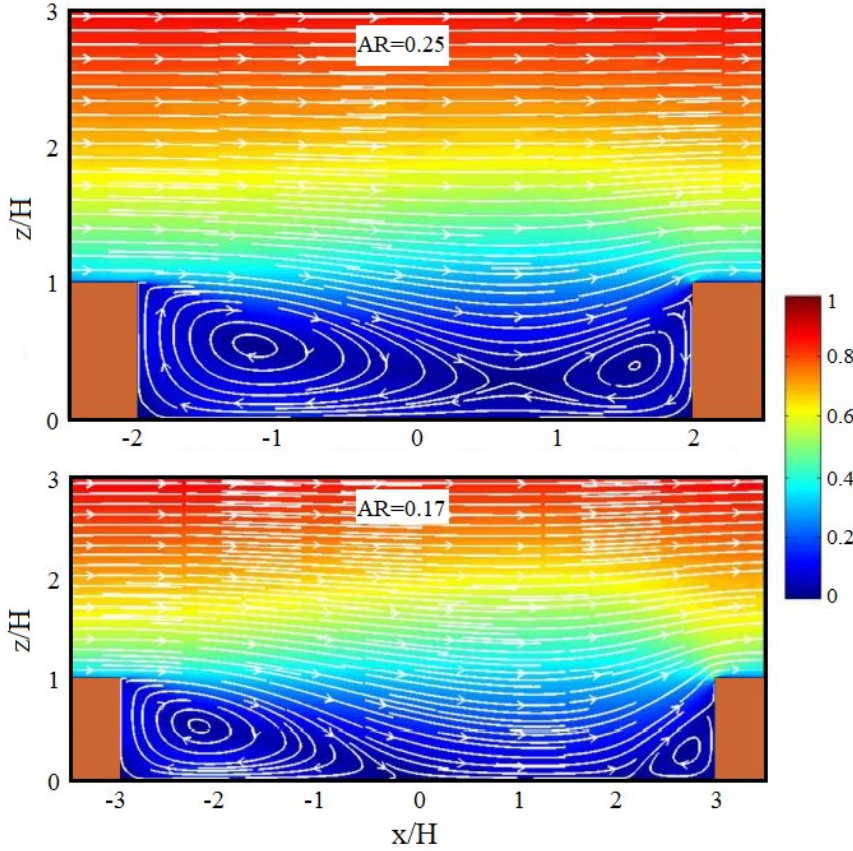


Fig. II_14 - Examples of the mean velocity magnitude normalized with the free stream velocity for the isolated flow regime (colors). The lines denote streamlines (modified from [91]).

One of the parameters mainly used in evaluating air quality and human comfort at street level is the air-exchange rate, ACH , i.e., the rate of air removal from a street canyon. Due to the flow two-dimensionality, ACH equals the mean upward velocity at the canyon top [92]. By definition, the larger ACH , the better the canyon ventilation. Badas et al., (2017) [91] calculated the ACH for the arrangements shown in Fig. II_14 plus other 21 geometries for 23 cases, which include AR values ranging between 0.07 (isolated flow regime) to 3 (multi-vortex skimming flow

regime). The ACH shows relatively large values for low aspect ratios, a region of low values for large AR , where it is about 0.25 compared to the maxima, and an intermediate trend in between (Fig. II_15).

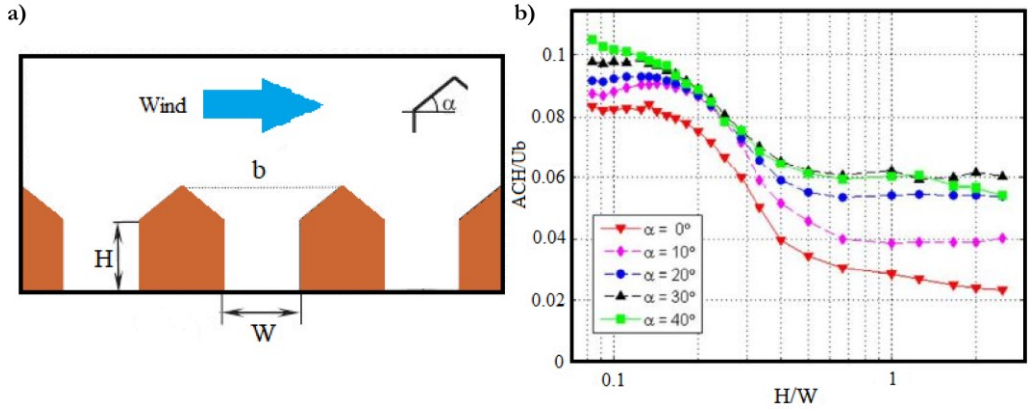


Fig. II_15 - (a) Sketch of the computational domain (adapted from [91]). **(b)** Non-dimensional ACH versus H / W for two-dimensional street canyons with planar rooftop (the red line indicates roof slope $\alpha = 0^\circ$). The other curves refer to ACH calculated for different α . U indicates the free stream velocity.

Badas et al., (2017) [91] also focused on assessing the effect of gable roofs on the flow regimes and their implications in terms of ACH . Their results corroborated the idea that a pitched roof strongly modifies the low-level flow and increases the turbulence and the air exchange between the canyon and the external flow (see [93] for a discussion on the effect of the shape of buildings and chimney stacks on ventilation and pollutant dispersion). In particular, they found that the pitch has a positive effect on ACH both in the high and low AR ranges. Such an increase is particularly significant in the range of the narrow canyons (up to a factor of three), mainly because of the larger contribution of the mean flow compared to that present in the case of a flat roof (Fig. II_16). Note that the curves of ACH collapse onto a single curve in the intermediate, descending range of aspect ratios.

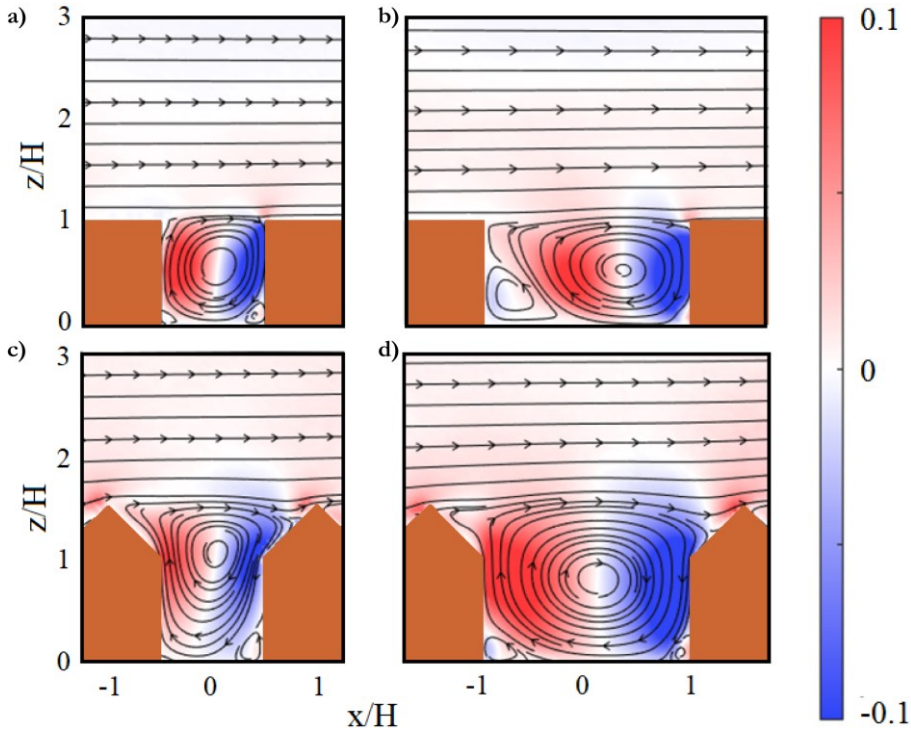


Fig. II_16 - Streamlines of the mean velocity field for different aspect ratios and roof shapes. Colors indicate the vertical wind velocity component made non-dimensional by the freestream velocity for **(a)** $AR = 1$ and $\alpha = 0$, **(b)** $AR = 0.5$ and $\alpha = 0$, **(c)** $AR = 1$ and $\alpha = 45^\circ$ and **(d)** $AR = 0.5$ and $\alpha = 45^\circ$ (modified from [94]).

II_4.2.2 Effect of Building Height Variation

The role played on the flow topology by the ratio between the height of the windward and the leeward buildings, $R = H_w / H_L$, has been extensively investigated in the past (e.g., [18] and references cited therein). Regarding the case of flat rooftops, Nardecchia et al., (2018) [84] focused on the combined effect of the variability of both R and AR by considering six values of R and five AR s. In particular, they analyzed the step-up configurations ($H_L < H_w$), where the leeward building is shorter than the windward building, and the step-down configurations ($H_L > H_w$). Figure II_17 shows examples of streamlines for step-up ($R = 1.5, 2$, and 2.5) and step-down ($R = 0.67, 0.5$, and 0.4) geometries and $AR = 0.5, 1.5$, and 4 .

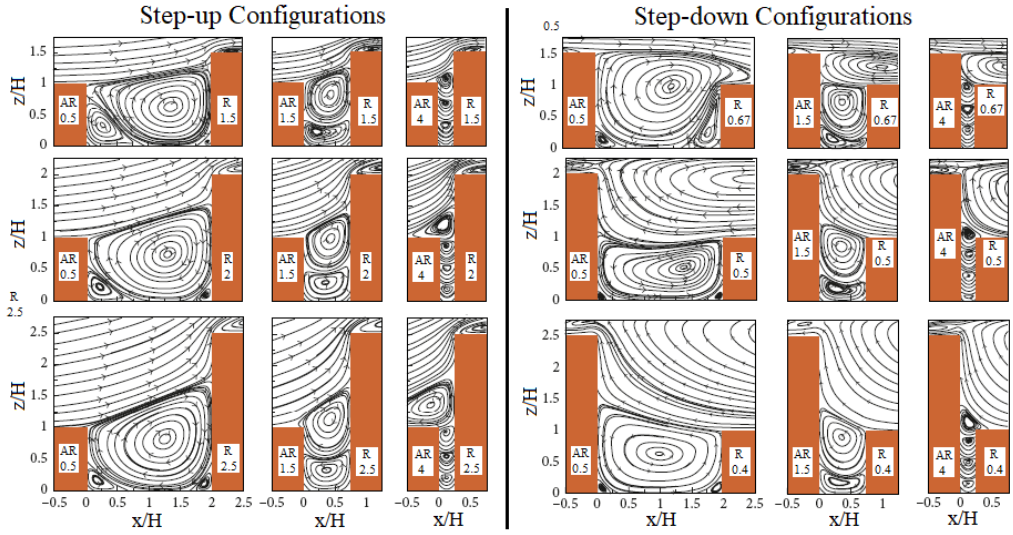


Fig. II_17 - Streamlines of the mean velocity for different aspect ratios (AR) and relative height (R) of the buildings (modified from [84]).

For the step-up configurations ($R > 1$), the flow fields for $AR = 0.5$ and 1.5 do not change much from that seen for $R = 1$ (Fig. II_10). The main vortex increases in size and moves upward as R grows. Regarding the skimming flow cases, their dependence on R is greater for $AR=1.5$. A progressive ejection of the upper vortex from the canyon into the overlying layer appears from $R = 1.5$ to 2.5 . Regarding ventilation, this is reflected in the fact that ACH does not depend significantly on R when $AR = 0.5$ and 1 (Fig. II_18). In contrast, a clear decrease in ACH for increasing R occurs for the other aspect ratios. Taller windward buildings allow lower vertical mass transfer between the canyon and the overlying region. On the other hand, the step-down configurations ($R < 1$) show a wide clockwise vortex placed over the canyon and the top of the windward building. Overall, the lower the R , the smaller the ACH , except for the case $AR = 0.5 - R = 0.67$, where there is only a large vortical structure, and it occupies both the canyon and the overlying region up to $z = H_L$. This configuration corresponds with the largest ACH calculated for all the cases analyzed. In contrast, the main vortex (or the two or

more vortices) remains confined within the canyon for all the other step-down configurations. This characteristic represents the main difference between step-up and step-down configurations, and it greatly influences pollutant concentration and dispersion, particularly at the street level. From the point of view of air quality analysis, the development of secondary vortices in the lower corners of the canyon for $AR = 0.5$ and 1 should determine an accumulation of pollutants near the sidewalk, regardless of R . For $AR = 1.5$ and 2, the presence of the two counter-rotating vortices further limits the canyon ventilation, especially at ground level. For $AR = 4$, the vertically aligned multiple vortices configuration strongly inhibits the air exchange with the higher layers and paves the way to the stagnation of pollutants at the pedestrian level.

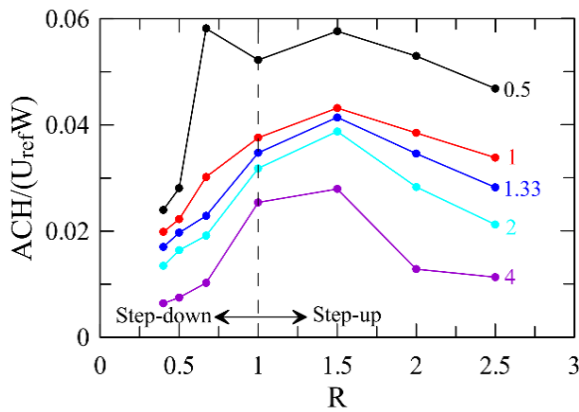


Fig. II_18 - Non-dimensional ACH versus R . Numbers near the curves denote AR (modified from [84]).

To conclude this subsection, the effects on the flow pattern of street canyons having a flat roof on one street side and a gable roof on the opposite side are presented. The results found numerically for several rooftop geometries by Xie et al., (2005) [95] show a substantial resemblance of A and B cases to the step-up and step-down configurations seen above for $AR = 1$ and $R = 1.5$ and 0.67 , respectively (Fig. II_19). On the other hand, cases C and D clearly show the role played by the

approaching wind direction, even for winds perpendicular to the street axis. This fact further proves that the knowledge of prevailing winds can be beneficial during the earlier design stage.

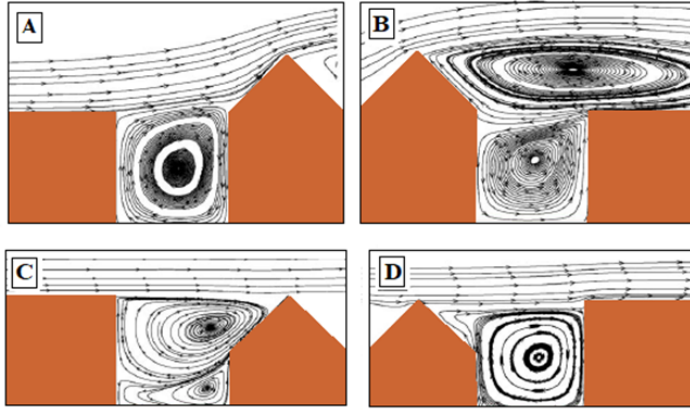


Fig. II_19 - Influence of roof shape on streamlines in street canyon (modified from [95]).

II_4.3 Groups of Buildings

As mentioned above, the turbulent nature of the urban flow makes it impossible to solve the wind field in urban environments analytically. Similar to the street canyon case, most CFD and laboratory studies on groups of buildings consider idealized situations like the regular arrangement of obstacles depicted in Fig. II_20a, i.e., an approaching wind perpendicular to the façades of a group of regular cubes mimicking a real urban complex. Generally, the geometrical parameters used to classify urban canopies are the plan area density, λ_p , and the frontal area density, λ_f , defined respectively as the plan area and frontal area occupied by buildings divided by the total area of the land on which they are located. It should be noted that λ_p and λ_f are just two of the several parameters involved in urban canopy classification. For additional information about the parameters, the readers may refer to [88,96,97]. Nevertheless, the description of urban morphology employing

parameters is one of the focuses of the present research work that is addressed in detail in the following chapters.

The instantaneous snapshot of the velocity field depicted in Fig. II_20b helps elucidate the complexity of the turbulent flow within a group of staggered buildings. The wind field is strongly inhomogeneous, and vortical structures (with both clockwise and counterclockwise rotations) are present throughout the flow. In terms of average quantities, the velocity pattern is undoubtedly simpler since the averaging over many instantaneous realizations filters out small-scale structures in the flow pattern and emphasizes the main flow features.

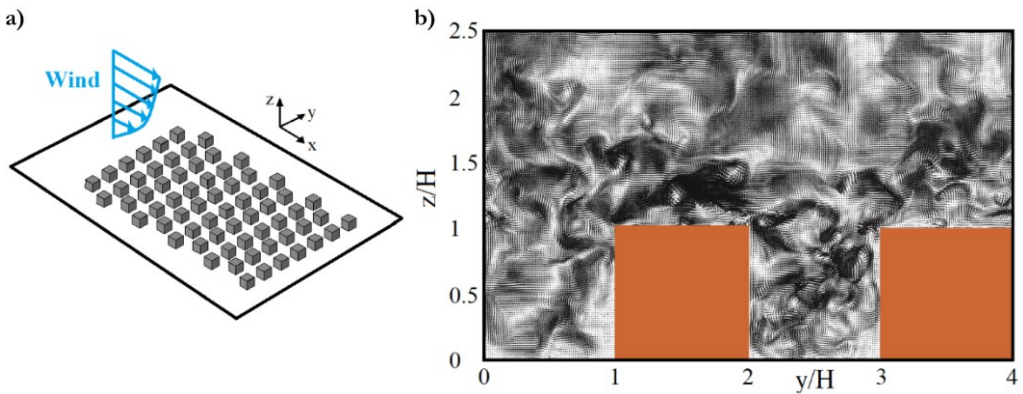


Fig. II_20 - (a) Sketch of archetypal an array of cubes usually adopted in CFD simulations and laboratory experiments and (b) instantaneous snapshot of the velocity field in a vertical y - z plane perpendicular to the approaching mean flow (which is out of the page) obtained for a staggered building array with $\lambda_p = 0.25$ by means of a DNS (modified from [98]).

Figure II_21 depicts the average velocity field and refers to the simulation of Fig. II_20, but for a vertical x - z plane –parallel to the streamwise velocity – passing through the center of the buildings [98]. The main feature of interest is the recirculation region at the bottom right-hand corner in front of the windward building. Such a vortical structure is rather persistent and is accompanied by a strong downdraft down the façade. It is worth noting the absence of a recirculation behind the leeward building. At the same time, there is a clear reverse flow near the

bottom surface between $x/H = 1$ and 2 and a strong updraft adjacent to the back façade similar to that observed for the isolated building. In addition, a recirculation vortex appears in the lower part of the canopy if one considers the vertical planes parallel to the one above (not shown). This fact is further evidence of the strong three-dimensionality of the flow (for more details, the readers may refer to [98]).

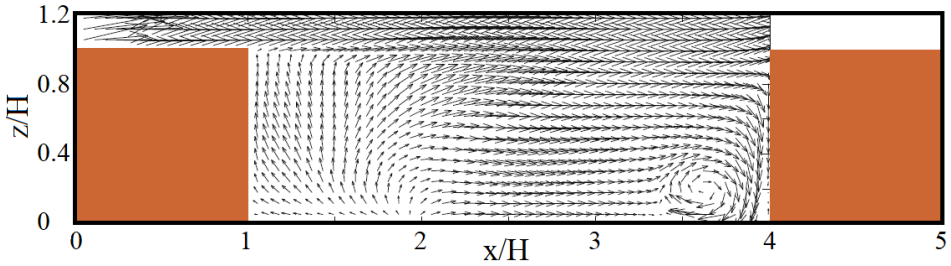


Fig. II_21 - Average velocity field in a vertical $x-z$ plane through the middle of the cubes of the array in Fig. II_20. The streamwise velocity is now directed rightward (modified from [98]).

The flow complexity is even clearer by looking at the streamlines (Fig. II_22) corresponding to the mean horizontal average velocity referred to both arrays of aligned cubes for two external wind directions (0° and 45°) and staggered cubes for a wind direction equals to 45° [99]. Streamlines are plotted at $z = 0.12H$ (i.e., close to the pedestrian level) and $0.73H$ for each configuration. The large recirculation within the canyon region behind each building and the channeling in the street aligned with the external velocity characterize the 0° -wind direction. Although the streamlines within the channeling region are similar at the two heights, the vortical structures behind the buildings are essentially three-dimensional and change considerably with height.

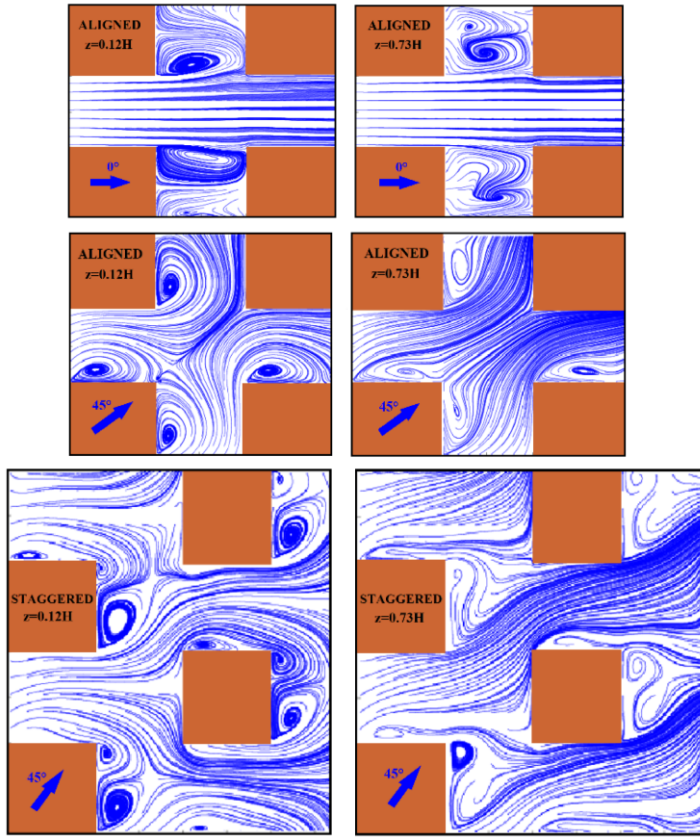


Fig. II_22 - Streamlines along horizontal planes for aligned and staggered regular arrays of cubical buildings for two directions of the approaching flow (adapted from [99]).

As shown by Kim and Baik, (2004) [100], the flow coming into the street canyon curls up around the so-called portal vortex, whose ends are located near the lower edges of the windward building (Fig. II_23a). The portal vortex is symmetric with respect to the center of the street canyon, and its horizontal axis is perpendicular to the external wind direction. For external winds not perpendicular to the façade, the horizontal size of the portal vortex changes, and a horseshoe vortex forms around the façades of the leeward building. When the incident wind angle is 45° , the flow is diagonally symmetric behind the windward building (Fig. II_23b).

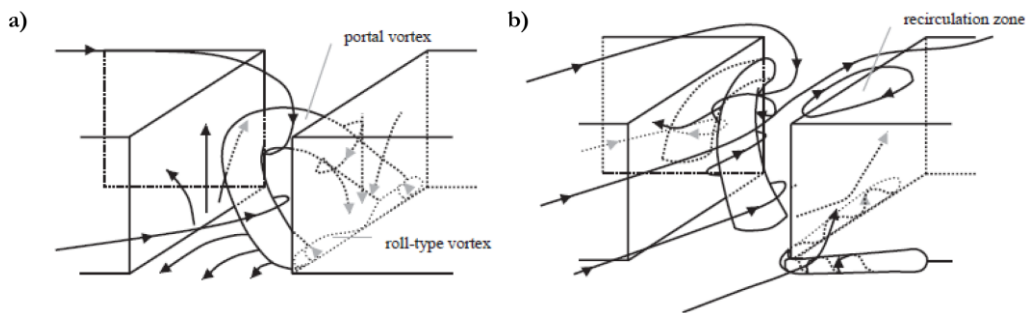


Fig. II_23 - Sketch of the mean flow circulation for external wind **a)** perpendicular and **b)** inclined of 45° with respect to the street axis (adapted from [100]).

Streamlines for the external wind of 45° show the occurrence of recirculation behind each façade. Such a feature reduces in size with height and is symmetrically situated with respect to the 45° diagonal line through the buildings. Streamlines from the two perpendicular streets upstream of the intersection come together and then diverge around the corner of the next building at the intersection. Part of them feeds into a recirculation on the leeward façade of the upstream buildings in the street perpendicular to the original flow direction, while another part channels into the far side of that same street. These flows play a considerable role in ventilation and near-source dispersion (e.g., [99,101]). The pattern of streamlines is considerably more complicated for a staggered array considering a wind direction of 45°. There is no symmetry with respect to the 45° diagonal line throughout the array, and the flow topology is substantially modified.

Albeit simplified building and urban models may help understand the fundamental mechanisms involved in the air circulation in urban areas, they may not reproduce the complexity of the wind environment in real urban areas. Furthermore, it is necessary to identify parameters that can describe and quantify the morphological characteristics of urban areas to ease the comparison and discussion of results. Hence, it is essential to investigate airflows further using real urban areas as case

studies (Fig. II_24), focusing on the dynamic relationships between density, morphology, and wind flow.

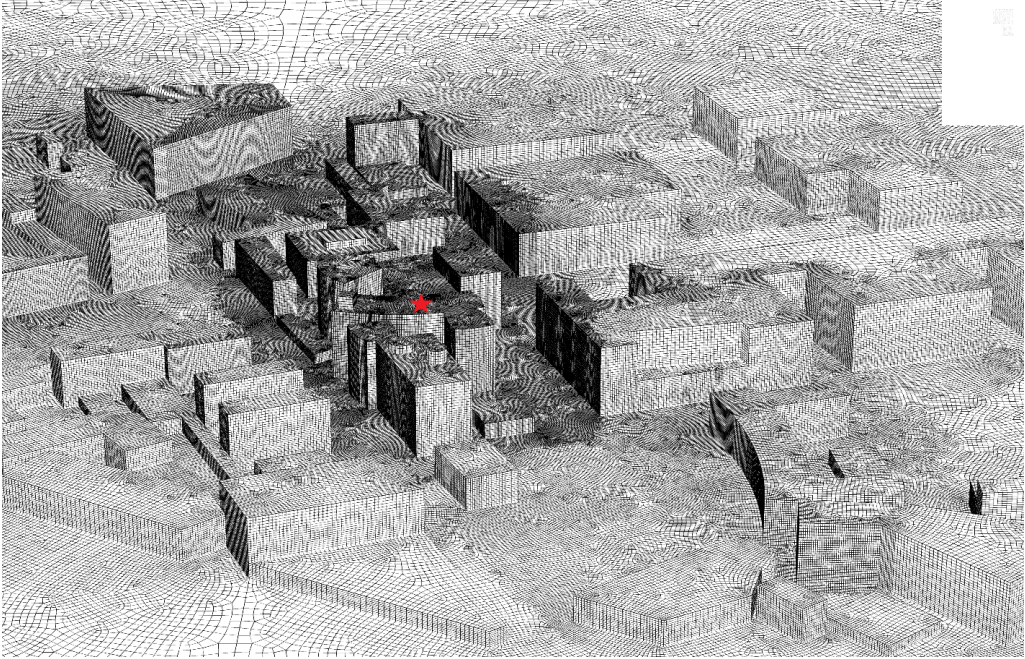


Fig. II_24 - CFD model of part of the Sapienza University of Rome. The planar area in the figure is about 1 km^2 , while the maximum building height is 32 m. The grid was generated using the surface-grid extrusion technique [102] and consists of about $26.5 \cdot 10^6$ hexahedral cells. The red star denotes the building roof where the SODAR and LIDAR described in Fig. II_1 are located.

II_5 Conclusions

The wind flows described in the previous sections are only a limited part of cases found in real cities. Vegetation (e.g., trees and green roofs), canyon asymmetries, squares, viaducts, and thermal inhomogeneity of the urban canopy layer are just some of the features generally found in cities that make the picture even more complicated and particularly difficult to generalize. Despite the continuous effort of many researchers, the progressive lowering of meteorological instrumentation costs, and the increase in computing power, the knowledge of wind circulation in cities still needs to be improved. The lack of analytical laws that provide wind speed,

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even in simple cases such as an isolated building, is just one example of the complexity of the phenomenon. This must spur the scientific community to enrich its knowledge of an important and fascinating topic such as urban fluid mechanics.

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Urban ventilation in compact cities: a review and a multidisciplinary methodology

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In the last decades, a tendency toward urban tissue densification has been observed to counteract urban sprawl. Densification may be achieved through more compact built areas, preferring the vertical to the horizontal development of buildings but avoiding bulky high-rise building blocks. This strategy significantly affects several aspects of the microclimate and produces direct and indirect effects on human health and well-being. In this regard, air pollution and heat stress constitute two increasing threats to human health and well-being that need to be faced immediately. The involved phenomena are various, intertwined, and may lead to conflicting results. Hence, regenerating existing, well-structured, and stratified urban areas by densification is not an easy challenge. Urban ventilation may favor the mitigation of detrimental effects of air pollution and heat stress on human life. Therefore, a multidisciplinary methodology is presented for embedding urban ventilation performance evaluation into urban management and planning processes. The scope is to propose a framework for urban renewal plans that is citizen-centered and aims at improving the health and well-being in existing urban areas. The methodology builds upon the performance-based approach and is supported by the conceptual framework and the literature reviews provided through the paper.

III_1 Introduction

The world population has chosen the urban environment as its habitat. Worldwide, 4.2 billion people live in cities [1] as a result of a gradual and inexorable movement of the population from rural to urban areas that started during the industrial revolution, accelerated in the 1950s, and is still ongoing despite substantial differences across continents [1] (Figure III_1). For decades, cities have been the synonym for progress, wealth, and possibilities, driving economic development and providing public services, e.g., education, transport, and healthcare [2]. Cities have represented attractive poles in human life and have become places where population, activities, and consumption are concentrated. Consequently, urban areas have severely modified and enlarged their ecological footprint and have been increasingly associated with environmental degradation, social and economic exclusion, heavy traffic, and pollution[3]. Besides this, as attractive poles, cities appear as vulnerable elements of human life, exposing most of the population, infrastructures, and activities to the threat of extreme meteorological events and climate changes, phenomena that are becoming increasingly frequent even in mild or temperate climates, e.g., in the Mediterranean basin and Europe [4,5]. The challenge towards a more sustainable and resilient built environment appears urgent, especially in existing cities that seem unprepared to tackle increasing threats due to climate changes and multifaceted stresses.

Many efforts are being made worldwide, as demonstrated, for example, by the adoption in 2015 of the 2030 Agenda for Sustainable Development by all United Nations Member States. The Agenda presents seventeen Sustainable Development Goals (SDGs) and explicitly recommends to “ensure healthy lives and promote well-being for all at all ages” (SDG #3) and to “make cities and human settlements inclusive, safe, resilient and sustainable” (SDG #11) [6]. Existing urban areas need to be regenerated, implementing their resilience and sustainability to improve the human conditions, present and future. In this regard, air pollution and heat stress

constitute two increasing threats to human health and well-being that need to be faced immediately, especially in Europe [3,7–10]. More than 74% of the European population lives in urban areas [11], and the large majority is exposed to pollutant concentrations that exceed the values recommended by the World Health Organization, despite the reduction in emissions and ambient concentrations registered in the last years [3]. It is worth noting that improvements in air quality have been registered due to measures introduced to reduce COVID-19 transmission [3]. This characteristic emphasizes the impact of nowadays lifestyle on the environment and the urgency of balancing human activity with environmental preservation [3].

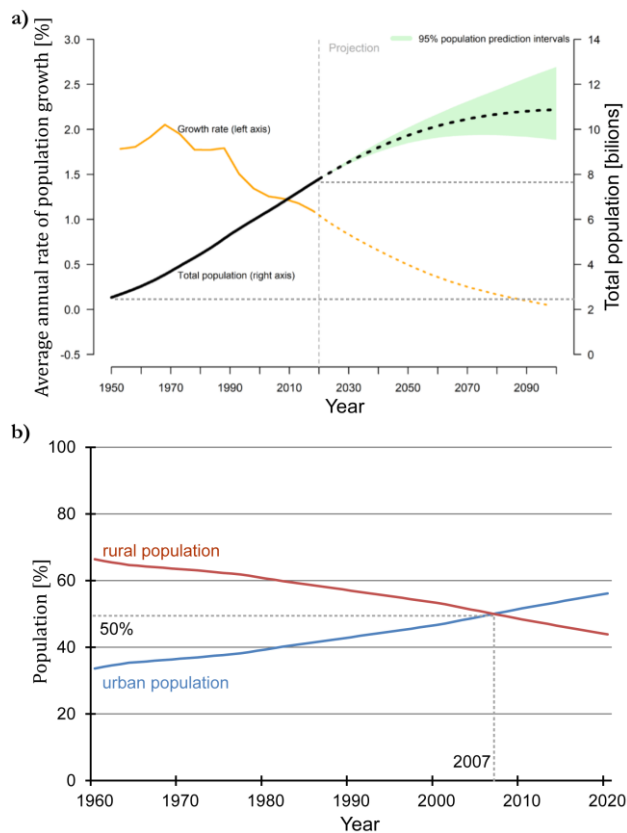


Fig. III_1 - (a) World population, modified from [12]; (b) urban vs. rural population, data from [13].

Air pollution and heat stress have been associated with poor air conditions [14–18] and linked to increased morbidity, mortality, and economic loss [3,8,19–26]. Poor air conditions significantly impact the outdoors and indoor places, worsening human health and comfort, limiting the use of open spaces, making ineffective passive solutions, e.g., building natural ventilation, and causing the increase in energy consumption for air cleaning and cooling [27]. The detrimental effects of poor air conditions can be partly mitigated by exploiting urban ventilation [15,28]. Urban ventilation represents the capacity of urban areas to introduce fresh air within their tissues and dilute pollutants and heat within their canyons. This phenomenon results from the interaction between urban areas and airflows and may improve air quality and thermal comfort. To exploit this interaction favorably, the relationship between the physical structure of urban areas, i.e., urban morphology, and local wind conditions, i.e., speed and direction, should be investigated in detail. Urban morphology becomes a passive strategy for curbing air pollution and heat stress in urban areas.

The interaction between urban morphology and airflows is a primary topic that needs to be considered in urban renewal plans since their effects on human life may be beneficial or detrimental. The character of the effects does not depend only on the characteristics of the synoptic wind as a natural phenomenon, e.g., gust, speed, and direction, but also on the features of the obstacles and environments that the wind encounters along its path. Hereunto, Givoni states that “Of all the climatic elements the wind conditions are modified to the greatest extent by urbanization” [29]. Wind may contribute to the fulfillment of requirements for indoor and outdoor thermal comfort and air quality, promote passive strategies for building ventilation, and facilitate the integration of micro-wind turbines in the urban landscape for electricity production. Therefore, adequate wind conditions within urban areas represent an environmental and economic resource to be exploited. Conversely, high wind speed, vortices, and turbulence may be responsible for wind

discomfort and nuisance for pedestrians and cause damage to buildings, infrastructures, and vegetation. It is well known that these detrimental effects are enhanced by specific characteristics of urban areas. The presence of tall buildings facing open spaces introduces high wind speed from high altitudes and vortices at the pedestrian level [30–33]. Moreover, alignments of specific morphological configurations with prevailing wind directions have been identified as responsible for accelerations in the wind speed caused by pressure short-circuiting [34]. It appears evident that these features significantly affect the use of open spaces and should be avoided. Nevertheless, if adequately investigated during the renovation planning phase, these phenomena may be exploited for locally meliorating wind conditions, improving the urban ventilation performance of urban areas.

In the framework of the global challenge towards more sustainable and resilient urban areas, it appears evident that the interaction between air flows and urban morphology is a fundamental topic to investigate, aiming at assessing the ventilation performance of urban tissues. It entails many issues and phenomena [35], at different scales, with direct and indirect repercussions on human life, health, and well-being. It appears clear that the involved phenomena are complex and multifaceted. Hence, it is necessary to reconsider the management and planning processes of urban areas, going beyond traditional approaches and towards performance-based planning, to grasp the complexity [36].

Urban ventilation is essential to curb the exposure of citizens to polluted air and guarantee thermal comfort, contributing to the challenge towards more resilient and sustainable urban areas. Despite its importance, the assessment of the urban ventilation performance, and, more in general, the study of the interaction between urban morphology and airflows, are not yet commonly embedded in urban planning and management processes, with a few exceptions. The exceptions found in the literature include procedures for conducting analyses to ensure pedestrian comfort and safety due to high wind speed, e.g., the Dutch Wind Nuisance Standard

NEN8100 [37] and the air ventilation assessment (AVA) system adopted by the government of Hong Kong in 2006 [15]. To the best of the authors' knowledge, the AVA system, commissioned after the outbreak of severe acute respiratory syndrome in Hong Kong in 2003 to improve the quality of the urban environment, is the only guideline focused on weak wind conditions. The scarcity of methodologies for evaluating urban ventilation embedded in urban planning and management may lie in the nature of the phenomena involved, complex and multifaceted, and in the consequent difficulty of carrying out these investigations that require both a high specialism and a multidisciplinary approach. Note that the attention of this paragraph is on procedures or guidelines already embedded in the urban management and planning processes. However, several studies have been conducted in the past, aiming at evaluating pedestrian wind comfort, therefore focusing on high wind speed [33,34,38–42]. Conversely, studies aiming at analyzing weak or poor wind conditions are rare. In this regard, the works by Ng [15] and Du et al. [43] for the city of Hong Kong should be mentioned.

To fill this gap and promote a new approach to the regeneration of urban areas, this paper presents a conceptual framework and a multidisciplinary methodology to embed the urban ventilation performance assessment into renewal plans of existing urban areas. Therefore, the article is structured as follows. Section III_2 describes the theoretical background focusing on the concepts of urban morphology and the performance-based approach to urban planning. Following this overview, Section III_3 outlines the conceptual framework for implementing sustainability in existing urban areas, highlighting the need for the performance evaluation of urban tissues and outlining a general workflow for urban renewal plans. Section III_4 presents an in-depth systematic review of studies conducted to analyze the relationship between urban morphology and the performances of urban areas. Then, in greater detail, Section III_5 focuses on a critical examination of the urban ventilation concept, reporting morphological parameters, investigation methods, and

performance indicators adopted in the literature. As a result of the comprehensive reviews and considerations presented in the previous sections, Section III_6 outlines the methodology applied to a significant case study, i.e., a compact urban area in Rome, Italy, to test its feasibility. Finally, Section III_7 Reports the conclusions and an outlook for future developments.

III_2 Theoretical background

“The physical dimensions of urban form may include its size, shape, land uses, configuration and distribution of open space—a composite of a multitude of characteristics, including a city’s transportation system and urban design features. However, its sustainability depends on more abstract issues—environmental (including transport), social and economic”. [44]

The sustainability and resilience of urban areas are complex concepts as they pertain to different dimensions of human life. Diverse disciplines are involved, and various aspects should be investigated using specific methods and tools. Hence, a holistic and multidisciplinary approach is essential to implement sustainability and resilience in the management and planning of urban areas. In this regard, the objective and quantitative description of the characteristics of the urban physical dimension appears as necessary but not sufficient [44]. It is fundamental to highlight and investigate the relationships between the physical dimension and the environmental, social, and economic contexts, analyzing the effects and the repercussions of these relationships on citizens’ health and well-being.

III_2.1 The performance-based approach

According to this approach, cities may be considered living organisms or open systems formed by a visible part, i.e., the physical dimension and the elements that constitute it, and an invisible part, i.e., the relationships that the diverse components establish between them and with the environment. Arguably, cities may be considered open systems because, using the definition of the “School of non-

equilibrium thermodynamics”, they receive inputs, i.e., resources, from the surrounding environment and dispose of outputs into it, determining evident stress for the environment [45]. As complex metabolic systems, cities need to adapt to changes in boundary conditions, mitigate the impacts of these changes on their constitutive elements, and anticipate possible scenarios [45]. Endorsing this vision, the physical dimension is inseparable from the processes taking place in it, the actors that live in it, and the relationships established by the different constitutive elements between them and with the environment.

Systems and processes are the keywords for a new approach applied in building design, urban planning, and urban management. This approach should be holistic, systematic, and analytic, considering various stresses often conflicting. It should be guided by clear strategies and oriented to achievable goals and objectives measured by employing performance indicators [46]. The complexity reveals the need for a change in the management and planning of urban areas, going beyond traditional approaches. Traditional planning models based on the Euclidean zoning and land use prescriptions have been proven inadequate to tackle this complex phase [47] and have been criticized for being inflexible and unable to adapt to environmental, social, and economic changes [48,49]. They are regarded as not able to consider the dynamic relationships of the physical dimension of urban areas with surroundings and functions and, therefore, the effects on citizens’ health and well-being.

Conversely, performance-based planning (PBP), or performance-based approach (PBA) to planning, involves the allocation of human activities and land uses based on quantifiable performance indicators [50] and aims to optimize land uses and resources, mitigating impacts [51]. PBP implies the passing of classic planning instruments regarded as inadequate for the task and advocates for more flexible tools that may better represent the complex, uncertain, and dynamic processes in play and are open to adaptation and transformation [52]. In this regard, modeling, as a simplified representation of the real world [53,54], proves to be an effective

tool to support PBA, allowing to investigate different phenomena, consider possible scenarios, and assess impacts ex ante [36]. Early attempts of PBP can be traced back to the early 1950s when performance standards were employed to control the negative impacts of industries, while the systematic application began in the early 1970s in the United States [51]. Nevertheless, the difficulties encountered and the level of support and effort required for implementing and applying PBP need to be considered [46,51]. However, it is already acknowledged that new paradigms and approaches need to be adopted nowadays to manage complexity. PBP reveals to be a suitable and adequate tool, and building a common base of knowledge among different disciplines seems a feasible and valuable way to overcome this issue. Hence, the quantitative description of the physical dimension of urban areas seems a fundamental first step in this direction because it allows the aggregation of results and the comparison of different scenarios. Figure III_2 shows four examples of compact urban tissues in Europe. To objectively describe similarities and differences amongst urban tissues, various morphological parameters can be used.

III_2.2 The typo-morphological approach

To quantitatively describe an urban area, it is necessary first to define the term "physical dimension" and then identify its fundamental elements. The physical dimension of an urban area is usually described in terms of urban morphology. The word morphology is composed of the two Ancient Greek words *μορφή*, *morphḗ*, meaning form, and *λόγος*, *lógos* meaning study, and means the study of the form. The term was coined by Goethe in 1785, in German *Morphologie*, to indicate comparative anatomy. By extension, urban morphology is the study of the structure of urban areas, and the term is generally used not only to denote the analyses but also the form itself. Studying urban morphology means reading and analyzing the evolution of a city, or part of it, through its physical structure. The qualitative

description is not sufficient and needs to be supported by the quantitative description of urban tissues. For this purpose, the work of the three Schools of typo-morphology, i.e., the Italian, the English, and the French Schools, is considered significant.

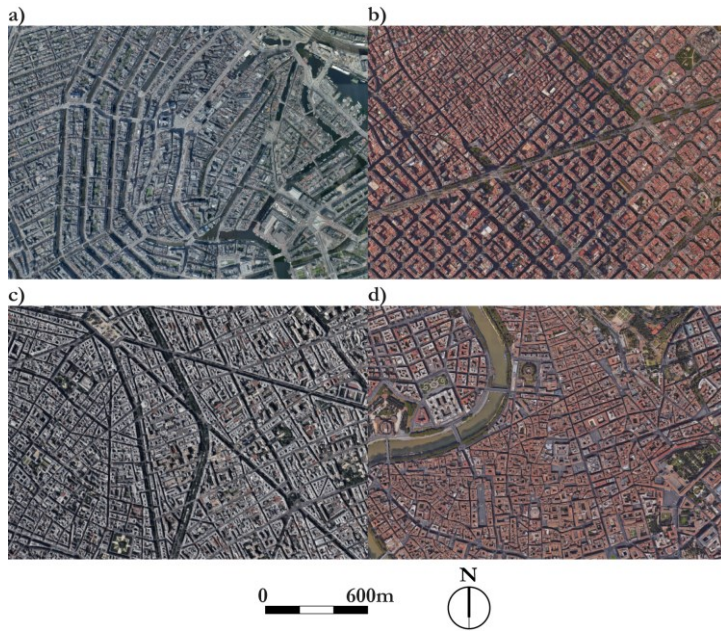


Fig. III_2 - Examples of compact urban tissues in (a) Amsterdam, (b) Barcelona, (c) Paris, and (d) Rome. Modified after Googlemap.

According to the Italian School, building type is the fundamental element of the city structure and the basis for analyzing it. The concept of building typology includes the description of the characteristics of the single building and its relations with the open space. In fact, the type determines the dimension and shape of a building and affects its location in the lot, influencing the relationship between built and open spaces. The Italian School has in Saverio Muratori its leading figure. His work was inspirational for several outstanding architects, e.g., Aldo Rossi and Carlo Aymonino, and his approach and theoretical framework to typo-morphology was continued by Gianfranco Caniggia. The English School, identified by the work of

Conzen, recognizes three fundamental components of a town plan: buildings, or more precisely their block plans, plots, aggregated in street blocks, and streets, arranged in street systems [55]. Regarding the English School, also the work by Leslie Martin and Lionel March is fundamental. Their work focused on investigating the relationships between building types and urban structures, analyzing their impact on land use efficiency [56]. Finally, the French School was established in the early 1970s as a critical analysis of the effects of the Modern Movement on the French landscape [57]. The main characteristic of this School is the focus on social repercussions. Despite differences in their approaches and aims, the three Schools may integrate into a holistic approach to urban morphology, and this is the approach adopted in the present work. A detailed description of the work of the three Schools can be found in [57,58].

III_2.3 The quantitative description of the urban environment

Building types, lots, and streets are three constitutive elements of the urban physical dimension. Consequently, the morphology of an area derives from the relations of these three components, and its description should consider their relations at different scales. The typology of the building and its locations within the lot shapes the relation between built and open areas, private and public spaces. For instance, building setbacks determine the width of urban canyons (UC), while building typologies determine if UCs are formed by only public spaces or if there are also private areas to consider, with evident impacts on the management. Therefore, the term urban morphology is employed to characterize the three-dimensional urban structure generated by a group of buildings and the open spaces entrapped between them [59]. In Figure III_3, possible relations of two building typologies, i.e., slab and pavilion, with open spaces are explored, and diverse UC configurations are presented, i.e., continuous, discontinuous, or mixed. The orientation and location of the building determine different configurations of the open spaces within the lot,

determining different UC configurations outside the lot. In Figure III_3, d refers to the distance between buildings within the same lot or island, s refers to the setback, while W refers to the distance between buildings belonging to different islands, i.e., the width of the resulting UC. At larger scales, the arrangements of the lots within the islands and the arrangements of the islands forming the different urban tissues shape districts and neighborhoods and, consequently, urban areas (Figure III_4). Hence, adopting a typo-morphological approach means adopting a multiscale approach, from the building to the neighborhood scale.

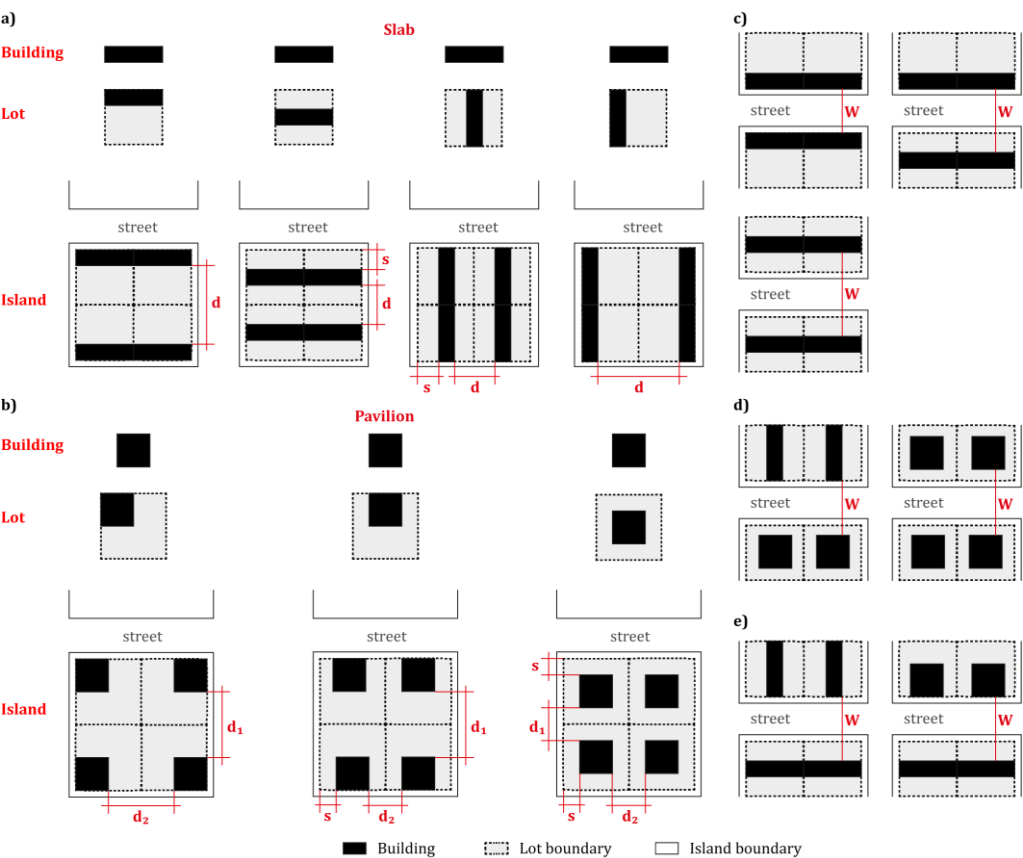


Fig. III_3 - Possible relations between two different building typologies and open spaces at different scales: **(a)** slab and **(b)** pavilion. Diverse configurations of urban canyons: **(c)** continuous, **(d)** discontinuous, and **(e)** mixed.

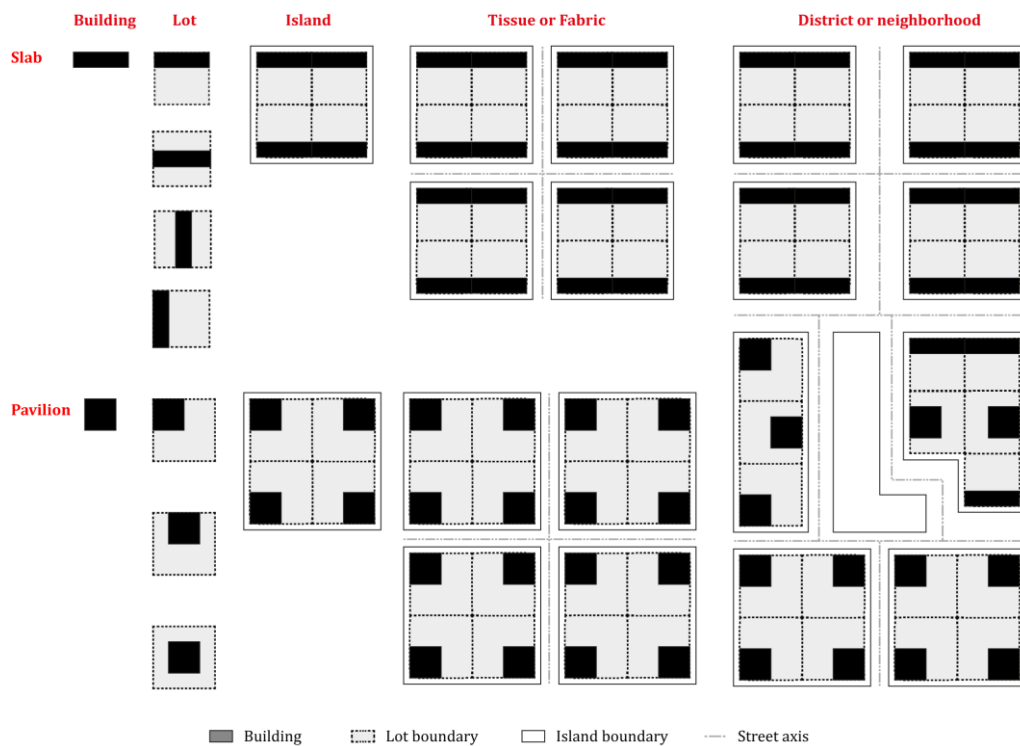


Fig. III_4 - Main observation scales or resolution levels adopted in morphological analyses.

Furthermore, morphological analyses are based on three concepts, i.e., form, time, and scale or level of resolution. The form is influenced by building types and their related open spaces. Therefore, the characteristics of interest are associated with the description of the individual buildings and the arrangement of groups of buildings, e.g., the width, length, and height of a building, the distance between buildings within and outside the same island, the street length, and layout type. The temporal factor is a primary concept because a city, as a metabolic system, changes and transforms. Performing morphological analyses means investigating the processes dictated by cultural, normative, legislative, and economic reasons that influenced the constitutive elements throughout the centuries.

Finally, the scale or level of resolution is a fundamental concept because it determines which characteristics of the three components are of interest. The

resolution levels commonly identified are building, lot, island, tissue, and neighborhood or district (Figure III_4). It appears evident that to describe the urban morphology of a specific area objectively, the parameters of all three fundamental elements and their aggregation in different levels of resolution are necessary. Note that in this way, it is possible to measure and quantify built surfaces and volumes as well as the open areas enclosed by them being private or public. From this point of view, the analytical and objective analysis of urban morphology proves to be very promising and offers opportunities and inspiration for new, detailed, and multidisciplinary analyses. Starting from specific case studies, it is possible to extrapolate parameters and indices, valid also in other contexts, that allow comparing the performances of morphologies developed in different eras and contexts. For this purpose, it is useful to introduce the concept of density.

III_2.4 The concept of density

Dealing with the quantitative description of urban morphologies, the concept of density proves to be fundamental. Density is commonly used in urban planning to describe the relationship between a specific area and the entities belonging to that area [60]. It is a key concept in urban planning and building design for managing sustainability in the long term because it helps to describe, predict, and control land uses, urban morphology, and soil consumption, the nonrenewable resource par excellence. Density proves to be a promising concept for these types of analyses because it is objective, quantifiable, and neutral; neutral because it does not involve an a priori judgment, and as a ratio, it does not entail a positive or negative meaning [61]. Nevertheless, density represents a complex concept [62] since it is context-related and defined and applied differently for different sectors, disciplines, and countries [60,63]. The main criticalities that may be encountered while measuring densities of urban areas are due to ambiguities in (i) the definition, i.e., the type of density we are interested in measuring; consequently, (ii) the indices, i.e., the

quantities that form the numerator and denominator of the ratio; and (iii) the data collection, since different disciplines and countries work with different density measures. Another issue associated with the definition of density is the presumed weak relationship between density and building type [63]. However, Berghauser Pont and Haupt have demonstrated that this problem may be eased with the use of a set of selected indices [60]. A similar conclusion has been reported by Palusci et al. [64]. Another issue that needs to be addressed is the concept of average that links density with resolution levels. Density is a ratio and, therefore, depending on the adopted scale, its value may be too blurred by statistical averages when larger scales are considered, e.g., district and region, or too specific to represent the selected area when small scales are considered [60]. In conclusion, the concept of density may be a helpful investigation and operational tool; however, it is necessary to consider the criticalities, especially in comparative and multidisciplinary studies. Consequently, it is suggested to define resolution levels, parameters, and indices preliminarily.

III_3 The Conceptual Framework

Cities face a wide range of stresses due to both natural and human agents and often appear unprepared to tackle the increasing threats due to climate changes and rapid urbanization. Implementing resilience and sustainability in the built environment by regenerating existing urban areas emerges as urgent. A resilient city is a city that responds, adapts, and continues to exist, maintaining all its characteristics despite the stresses it must face. A sustainable city ensures health and comfort to its inhabitants, present and future. The two concepts are linked and intertwined, and, arguably, it is possible to conclude that resilience is one of the characteristics a sustainable city must have.

In the last two decades, the debate about the characteristics and dimensions of the sustainable city has been central among researchers, planners, and policymakers [44]. The discussion is still ongoing since the achievement of sustainability in the

urban environment hinges upon many different factors that often lead to conflicting solutions. Furthermore, implementing sustainability means addressing site-specific issues; therefore, it is impossible to achieve a unique answer to the sustainable urban model question, valid in every climate. Nevertheless, there is a broad consensus in assuming the compact European city as a model of a sustainable city, also in stressful climates [65]. This model involves the density of urban tissues, functional mixité, social vitality, and economic diversity [66], limiting, on the one hand, the urban expansion and soil consumption—the so-called urban sprawl—and, on the other, avoiding excessive densities and overcrowding.

From an environmental point of view, the compact city is considered more sustainable because it involves fewer emissions due to individual transport and less surface area per inhabitant to heat or cool [67]. Consequently, to reduce soil consumption and optimize transport and energy supply in a district, solutions that entail the densification of urban tissues and the introduction of economic and production facilities within residential areas may be regarded as favorable during the regeneration of existing urban areas. However, these actions may significantly impact human health and well-being if not adequately investigated since the early stages. Possible consequences may be augmented production of heat and pollution, decreased solar access, and reduced wind conditions. In other words, urban ventilation in the renewed area may prove reduced and, consequently, air quality and citizen thermal comfort worsen. It is evident the need for addressing a multitude of issues since the early stages of urban renovation plans, and it is significant the role that specialist and multidisciplinary analyses play in it. Therefore, designers, planners, and policymakers need new operating methodologies for sharing knowledge from different scientific sectors, allowing a holistic approach. These methodologies should start from the analysis of the physical structure of the built environment and relate it to expected environmental performance levels,

allowing the investigation of the phenomena at different scales. Hereunto, PBP reveals to be a suitable and adequate tool.

Based on the theoretical background provided in the previous section, a general workflow consisting of six steps for the regeneration of existing urban areas is presented. The first step is to translate the agenda into quantifiable objectives. The second step involves the definition of a clear strategy. The strategy determines performances and potential risks. In turn, the achievement of certain performance levels and the reduction, or avoidance, of potential risks determine the success of a strategy in achieving the identified objectives. Key indicators should be identified to measure performance levels analytically, and evaluation procedures should be adopted. Finally, monitoring systems, providing periodic feedback, should be specified; these systems may be based on the procedures established for evaluating the strategy. The scope is to propose a framework for urban renovation plans that is citizens-centered and aims at improving human health and well-being in existing urban areas (Figure III_5). Therefore, the objective should be formulated once the site has been identified.

The choice of strategies depends on the characteristics of the specific area. Since the planning policies in many countries have been oriented recently towards more compact urban tissues, densification may be a possible strategy. As reported earlier, the densification of existing urban tissues implicates many consequences that are potentially detrimental to human health and well-being. Therefore, potential risks to human health and well-being should be identified. Figure III_5 reports some risks that may be faced while promoting denser urban tissues. Hence, performances to counteract the detrimental effects should be identified. Specifically, it is necessary to (i) identify key indicators and (ii) adopt evaluation procedures for assessing the achievement of specific performance levels. The indicators should be easily related to comfort assessment.

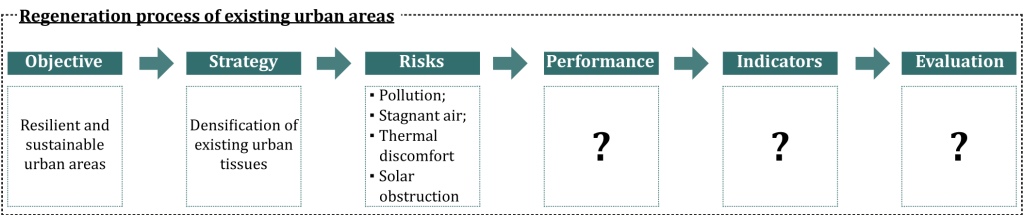


Fig. III_5 - General workflow for urban renovation plans.

The performance evaluation of urban areas appears essential, and, specifically, the investigation of the differences due to diverse morphologies emerges as fundamental. Different performances result from the many processes caused by the interaction of urban morphologies with multiple phenomena. The number and nature of the phenomena hinge upon the indicated objectives and strategies. It is necessary to assess the effects of the interaction between urban morphologies and different phenomena in terms of performance. For this purpose, it is advantageous to describe the urban morphology of the selected area using a set of morphological parameters (hereafter MPs) because employing MPs allows for comparing scenarios and results. Figure III_6 presents two possible strategies that can be adopted while regenerating the physical dimension of urban areas. The first strategy implies maintaining the same building coverage ratio, while the second aims at providing the same floor space index and volume-to-site ratio. For the definitions of the different MPs, the readers should refer to Figure III_7. The effects of the two strategies are explored for five building typologies, i.e., pavilion-towers, pavilion-palazzina, slabs, courts, and terraced houses, extrapolated from an existing compact area in Rome. Depending on the strategy, the various typologies present differences in the amount, position, and orientation of built volumes and surfaces. Differences in the built and unbuilt exchanging surfaces may cause different levels of urban tissue performances according to the phenomena of interest. Hence, to assess the performance, it is essential to identify the phenomena of interest and investigate the effects of their interactions with urban morphology.

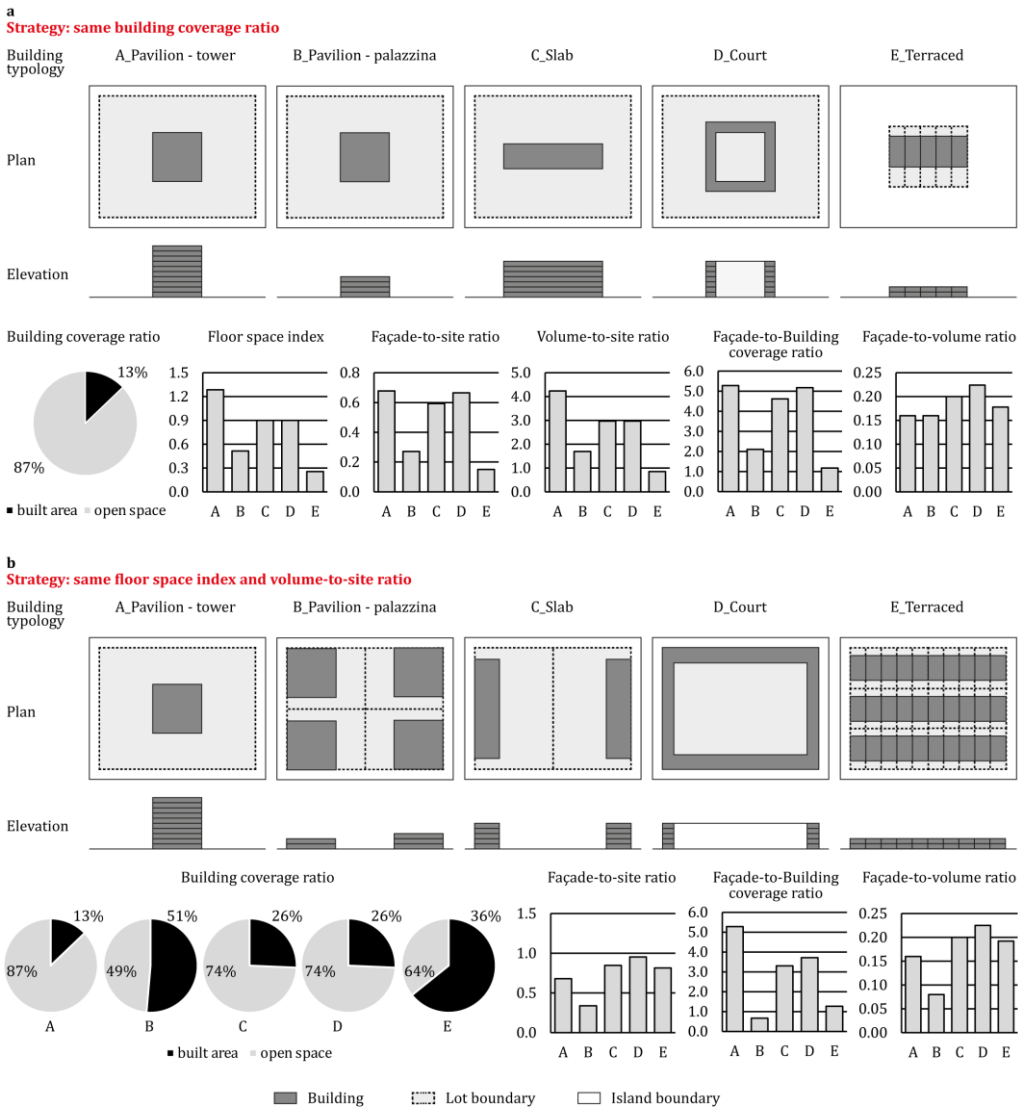


Fig. III_6 - The effects of two possible strategies to adopt while regenerating the physical dimension of urban areas are explored for five different building typologies. The diverse configurations were quantified using six MPs commonly employed in typo-morphological analyses. **(a)** Same building coverage ratio and **(b)** same floor space index and volume-to-site-ratio.

The stimulus to the quantitative description of urban areas and the evaluation of their performances may be due to the development of the geographic information system (GIS). These software tools allow for storing the spatial characteristics of urban areas and linking the spatial attributes to qualitative and quantitative data. In

this way, the physical dimension can be measured and analyzed in relation to environmental performances or linked to socio-economic forces [68–71]. Thus, the tools offer the ability to coordinate activities of fields traditionally apart and allow studying large areas [58]. Therefore, GIS tools have increasingly been used in both scientific and professional fields.

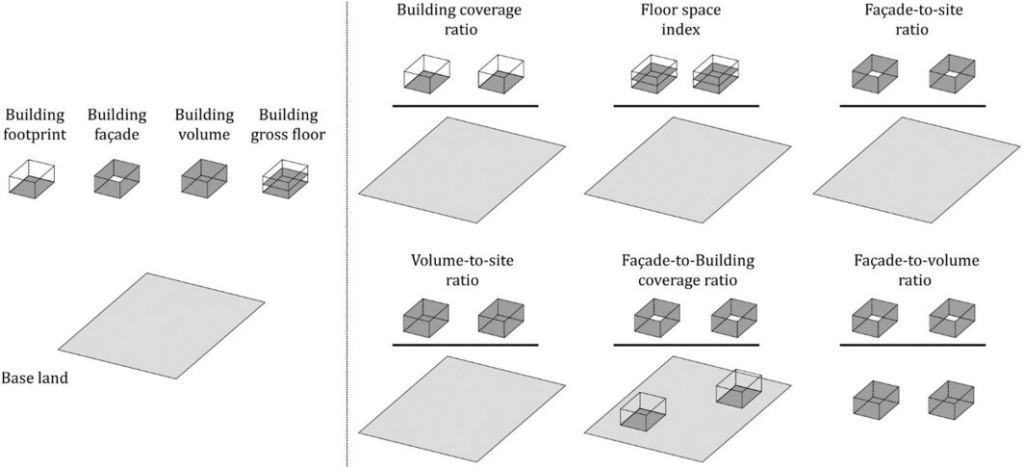


Fig. III_7 - Graphical definitions of the morphological indices employed in Figure III_6.

Since urban sustainability hinges upon many factors of different nature, the performance evaluation entails many dimensions and may be expressed using various indicators. In the following section, a systematic review of studies conducted for analyzing the relationship between urban morphology and performances of urban areas is presented.

III_4 Urban morphology and performance

The evaluation of the performance of urban tissues has gained popularity in the last few years within the scientific community (FigureIII_8). A literature review is reported in this section to provide an overview of studies in this field. The review was conducted in the Scopus database [72] using “*urban morphology*” and *performance*

combined with the Boolean operator *AND*, as terms for the search query. The identified documents should contain the specified query in the following search fields: title, abstract, or keywords. Only research papers, review papers, and book chapters published in English until 2021 have been considered. The total number of identified manuscripts is 144, and Figure III_8a reports the yearly distribution. The first works were published in 1997, and the topic has gained popularity amongst researchers in the last decade. The increased interest is particularly evident in the last three years since half of the total amount of manuscripts has been published since 2018. It is interesting to note that a similar trend may be found in the yearly distribution of published works retrieved from the Scopus database using “*urban morphology*” *AND* *sustainability* as terms for the search query (Fig. III_8b). In fact, the first work was published in 1997, and an augmented interest is evident in correspondence with 2018. This similarity may be interpreted as a sign of the increased awareness of the issues connected to urban sustainability and may also highlight the connection between the two topics, i.e., performance and sustainability, when related to urban morphology.

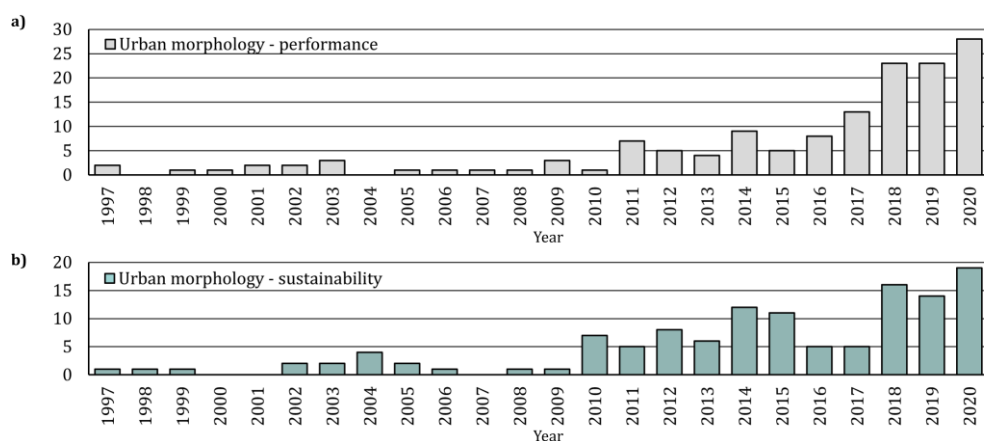


Fig. III_8 - (a) The yearly distribution of the reviewed documents; and **(b)** the yearly distribution of published documents. Legends report the search queries.

The aim of the present review is twofold: on the one hand, to identify how the performance of urban tissues has been evaluated in terms of methods, topics, and indicators; on the other hand, to analyze how urban morphology has been considered, in terms of scale and parameters. Figure III_9 outlines the review process consisting of three phases, i.e., the collection, examination, and, finally, classification. Of the 144 identified documents, 10 manuscripts were excluded because they were not accessible to the authors. The remaining 134 manuscripts were downloaded and further examined. The examination consists of two steps. Initially, only the abstract was considered to verify the relevance of the study. After the abstract screening, 5 documents were excluded because they were out of the scope of the present review, while 37 required further analyses of the adopted methodology and obtained results for the classification. After the detailed examination, another 4 documents were excluded: a manuscript was found not relevant [73], and three manuscripts were excluded because they focused on the parameterization of trees and not on the description of urban morphology [74,75]. Afterward, the remaining 125 manuscripts were examined thoroughly, focusing on methodology, results, and conclusions for (i) identifying the methodology adopted, (ii) classifying the performance evaluated, and (iii) analyzing the urban morphology parameterization. Hence, the reviewed documents were classified into 10 categories according to the topic investigated, i.e., *energy*, *microclimate*, *economics*, *assessment*, *indoor*, *morphology modeling*, *urban model*, *transport*, *design*, and *combinations* of the previous topics.

Specifically, the term *energy* has been used to characterize studies aiming at evaluating the energy performances of buildings in terms of energy consumption for cooling, energy consumption for heating, and energy production potential. The term *microclimate* has been used in this review to represent studies investigating one or more parameters that may be considered for describing the local microclimatic conditions, e.g., air temperature, solar access, and wind speed. Note that pollution

has been included in this group because its dispersion is driven by microclimatic conditions. The term *economics* has been employed to denote studies that investigate the economic performance of urban areas in both a strict sense [76–79] and a broader sense taking into account the vibrancy [80] and the livability [81,82] of urban areas. The term *assessment* has been used to identify the studies that present assessment metrics to evaluate the sustainability [83–85] and resilience [86] of urban areas. The term *indoor* identifies studies focused on the investigation of the performances in terms of indoor thermal comfort [87–89]. The expression *morphology modeling* represents studies aiming at (i) a better parameterization of the urban morphology [90–92], (ii) the classification of urban structures [93–95], (iii) data extraction from imagery [96,97], and (iv) urban area modeling [98]. The expression *urban model* has been used to characterize studies focused on the analyses of urban dynamics, i.e., urban complexity [99]; pedestrian flows [100–102]; urban intensity [103,104]; city model as polycentric cities [105,106], compact cities [107], and concentric cities [108]; urban evolution [109–118]. The term *transport* denotes studies investigating the impact of urban morphology on intersection traffic [119], goods movement [120], and multi-mode transport [121]. Finally, the term *design* indicates studies dealing with design strategies for mitigating flood risk [122], environmentally sustainable design [123], and optimized form generation [124]. It is worth noting that this classification has been proposed for sorting the large number of documents that have been reviewed and identifying the documents in line with the scope of the present manuscript. The identified topics should not be interpreted as separated but intertwined, e.g., energy and microclimate [125–131], energy and indoor [132], energy and design [133], energy and assessment [134], and microclimate and design [135].

In line with the aim of this review, it was decided to focus further analyses on documents belonging to the following topics: *energy*, *microclimate*, *indoor*, and *combinations* of at least one of the previous topics.

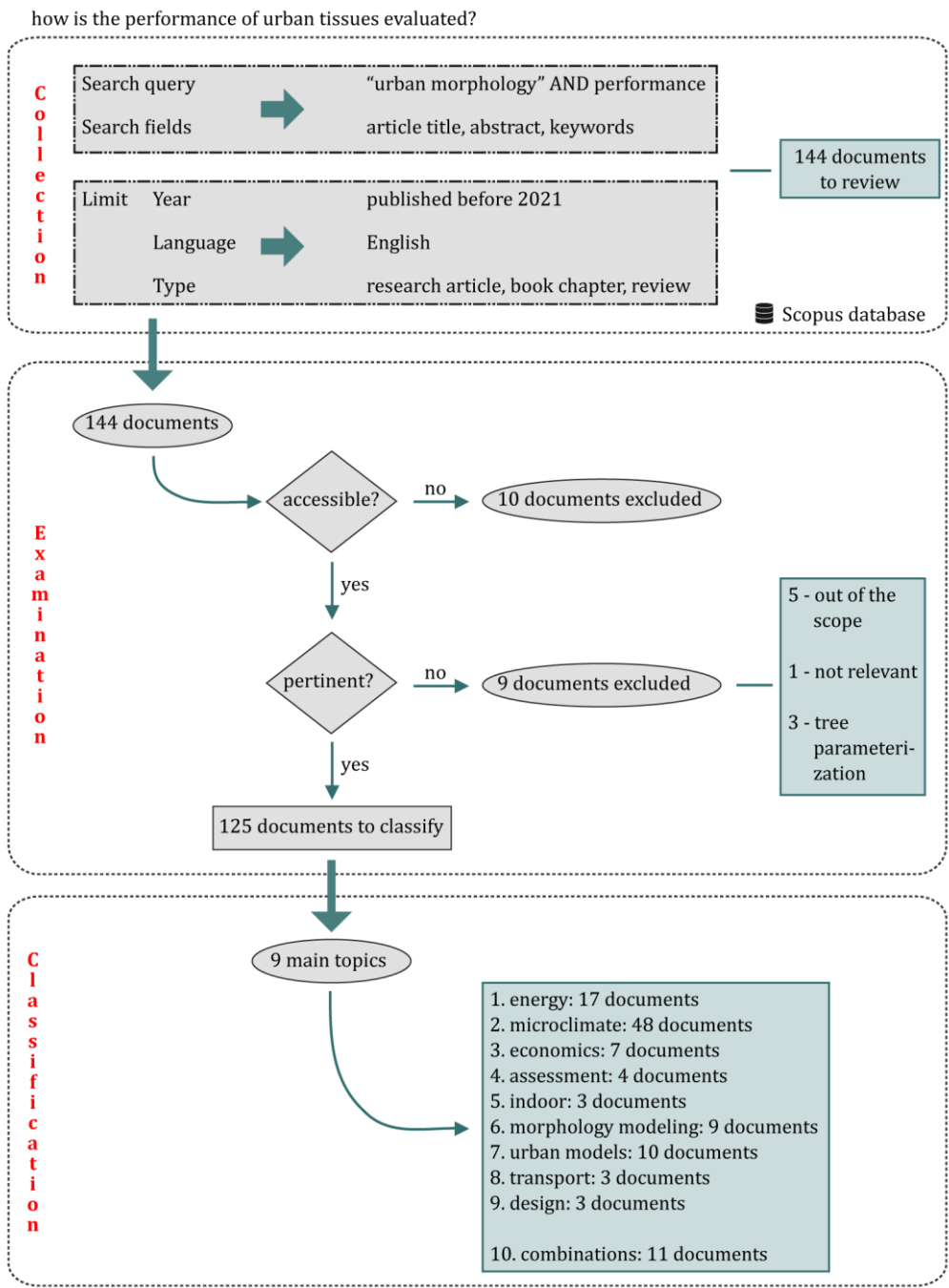


Fig. III_9 - Literature review methodology.

Table III_1 reports the selected 79 manuscripts further analyzed, highlighting (i) the reference, (ii) the authors, (iii) the topic investigated, (iv) the performance evaluated, (v) the methodology adopted, (vi) the morphology parameterization, (vii) the scale of investigation, and (viii) the document type. Regarding the studies conducted using simulations, also the employed tools have been indicated. Furthermore, the term *energy* has been used to denote documents that consider as performance both energy consumption or demand and energy production or potential. Overall, 17 documents are related to the topic *energy*, and 10 manuscripts address *combinations* when the topic *energy* is present. In addition, 3 documents entail the topic *indoor*, and a manuscript addresses the combination of *indoor* with *energy*. The remaining 49 documents involve the topic *microclimate* (48), including *combinations* when the former is present. Of these 49 manuscripts, the majority (27) investigates wind flows in urban areas in different ways. From the literature review, urban ventilation established as a popular performance to be investigated in connection with urban morphology in the last ten years. Although a new concept since the first work was published only in 2011, amongst the 79 documents analyzed, 17 manuscripts investigate the relationship between urban morphology and ventilation. Specifically, 8 documents explicitly refer to urban ventilation performance, while 9 manuscripts address pollution. Bearing the definition of urban ventilation reported in the introduction and further analyzed in the following section, studies on pollutant dispersion and concentration may be included in this topic. However, to give more information to the readers about the performance indicators employed, it has been decided to report them separately in the table. As aforementioned, the first document, aiming at evaluating urban ventilation performance, was published in 2011 [136]. This work aimed to improve the urban roughness parametrization in mesoscale models by expressing the ground coverage ratio as a function of the frontal area. The wind velocity ratio, i.e., the wind velocity in the area of interest and the wind velocity at a fixed position established as the

reference, was chosen as the performance indicator. The wind velocity ratio was selected for the performance evaluation in other studies, mainly when the chosen case studies were actual urban areas. He et al. investigated the ventilation performance of the Greater Sydney Area, performing field measurements on two sunny days in 2019 [137]. Information about urban morphology has been provided in terms of building coverage ratio, street width, and sky view factor; however, these parameters have been employed for describing the overall characteristics of the area, not for evaluating their impact on ventilation performance. Zhao et al. evaluated the ventilation in Shenyang, China, by analyzing the data from 16 weather stations [138]. In this work, the urban morphology has been described using the Local Climate Zone (LCZ) classification [139]. The aim was not to correlate LCZs to ventilation performances but rather to evaluate the suitability of this classification for ventilation studies. Yuan performed numerical simulations to assess the ventilation performance of an urban area in Hong Kong [140]. Finally, Wang et al. investigated the impact of different MPs on urban ventilation, performing numerical simulations using idealized urban models for investigating the impact of different MPs on urban ventilation [141]. The urban morphologies have been quantified using four parameters, i.e., the ground coverage ratio, the frontal area density, the plot ratio, and the building height differential.

The ventilation of urban tissues has also been assessed using indoor indices as performance indicators. Mei et al. explored the impact of building height variability, performing numerical simulations over simplified urban models using two indices, i.e., the air exchange rate per hour and the pollutant retention time [142]. Peng et al. performed numerical simulations in idealized urban models, whose morphology has been described using two parameters, i.e., the floor area ratio and the building site coverage [143]. The ventilation performance has been assessed through six indices, i.e., the airflow rate, the mean age of air, the net escape velocity, the purging flow rate, the visitation frequency, and the resident time. Finally, another indicator

used for urban ventilation performance is pollutant concentration. This indicator has been employed in two articles belonging to pollution in the performance category. In the first study, published in 2012, the pollutant transport from the ground level to the urban atmospheric boundary layer of idealized two-dimensional UC was explored by conducting wind tunnel experiments and numerical simulations and evaluating the scaled overall pollutant removal coefficient [144]. In the second work, the ventilation performance of four design scenarios has been investigated by conducting numerical simulations using simplified models of residential blocks in Port Said city, Egypt [145]. The ventilation performance has been assessed by evaluating PM_{10} concentrations, while urban morphology has been quantified using several parameters, i.e., the absolute rugosity, the occlusivity factor, the plot area ratio, the volume area ratio, the plan area density, and the frontal area density. Unfortunately, the definition of the different morphological parameters is not provided. Urban ventilation has also been addressed at a larger scale, i.e., the city scale, for improving urban morphology parametrization in mesoscale models implementing a new method for calculating the frontal area density from annual wind probability data [146]. Finally, additional 10 manuscripts refer to the urban wind environment in different ways:

- Investigating how to improve the urban canopy models coupled with mesoscale models to enhance the simulation of the wind speed and air temperature in complex urban environments, i.e., using high-spatial-resolution urban fraction [147]; developing a database for Beijing based on several parameters, i.e., the building height characteristics, the building plan area fraction, the frontal area density, the height-to-width ratio, and the sky view factor, [148]; implementing observational information of the sky view factor [149]; proposing a categorization of the building height based on the fractal dimension [150]; suggesting a formulation for the drag coefficient [127]; corroborating the causality between the accuracy of the

parameterized urban morphometry and the reliability of the results of urban boundary layer simulations [151];

- Evaluating the performance of the adopted simulation tools for analyzing the performance of two design scenarios in terms of solar irradiance, wind airflows, building indoor temperatures, and energy demand [128];
- Applying parametric design optimization processes over conventional urban design processes to achieve more sustainable urban environments [135];
- Providing a critical review of the properties influencing energy and airflows in urban neighborhoods [126];
- Stressing the importance of identifying which urban morphology characteristics have the most significant impact on thermal comfort and how to mitigate the urban heat island effect [152].

Main Findings

The literature review provided in this section focuses on two aspects:

- The evaluation of performance in terms of methods, topics, and indicators.
- The parameterization of morphology in terms of scale and parameters.

The following main conclusions may be drawn for each of the analyzed aspects. Regarding performance, the most popular topics are *energy* and *microclimate*, and, in this regard, urban ventilation has gained popularity, especially in the last few years. Ventilation is a fundamental topic to be addressed and involves a variety of phenomena [35]. The methods adopted for conducting the investigations are various, i.e., numerical simulations, laboratory experiments, and field measurements. Moreover, three main indicator categories may be identified, i.e., the mean velocity ratio, the pollutant concentration, and indoor indices.

Although it is widely recognized that urban morphology is fundamental in determining the performance of urban tissues [153], studies conducted using actual

urban areas are rare due to the difficulties in modeling the phenomena and the high degree of specialization required [154]. Moreover, it emerges that tools for investigating the phenomena at the neighborhood scale are too specialized, and often they do not allow information exchange [155]. It is considered necessary to provide a critical literature review regarding urban ventilation studies to identify morphological parameters, investigation methods, and performance indicators applicable to the neighborhood scale in compact areas.

Table III_1 - Overview of studies aiming at evaluating the performance of urban tissues belonging to the topics: *energy*, *microclimate*, *indoor* and *combinations* of the previous.

#	Refs	Authors	Year	Topic	Performance	Method	Tool	Morph.	Scale	Type
1	[156]	Palme et al.	2020	energy	cooling demand	sim.	BES	no	lot	art.
2	[157]	Othman and Alshboul	2020	microcl.	out. thermal comfort	sim.	Envimet AND Rayman	yes	island	art.
3	[158]	Ronchi et al.	2020	microcl.	cooling capacity	sim.	InVEST	yes	city	art.
4	[159]	Battisti	2020	microcl.	out. thermal comfort	sim.	Envimet AND Rayman	no	island	art.
5	[160]	Uçlar and Buldurur	2020	energy	heating consumption	stat. analysis	-	yes	neighb.	art.
6	[131]	Natanian et al.	2020	comb.1	energy performance +out.thermal comfort+ solar access	sim.	Rhino+Grass hopper+plugins	yes	neighb.	art.
7	[161]	Leng et al.	2020	energy	heating consumption	sim.+statanalysis	EnergyPlus	yes	neighb.	art.
8	[162]	Apreda et al.	2020	microcl.	air temp.	sim.	Envimet	yes	island	art.
9	[137]	He et al.	2020	microcl.	urb. ventilation+ out. thermal comfort	meas.+sim.	Rayman	yes	neighb.	art.
10	[163]	Poon et al.	2020	energy	solar energy potential	sim.	Rhino+Grass hopper+plugins	yes	neighb.	art.
11	[164]	Liu and Morawska	2020	microcl.	surface temp.	sim.	WRF	yes	city	art.
12	[89]	Sadeghi et al.	2020	indoor	ind. comfort	meas.+ sim.	EnergyPlus	no	-	art.
13	[138]	Zhao et al.	2020	microcl.	urb. ventilation	meas.	-	yes	neighb.	art.
14	[165]	Nikoloudakis et al.	2020	microcl.	air temp.	mod + meas.	-	yes	city	art.
15	[166]	Yuan et al.	2020	microcl.	air temp.	sim.	ANSYS Fluent	yes	neighb.	art.
16	[167]	Carpio-Pinedo et al.	2020	microcl.	solar access	mod.	-	no	island	art.
17	[145]	Hassan et al.	2020	microcl.	pollution	sim.	ANSYS Fluent	yes	island	art.
18	[168]	Salvati et al.	2020	energy	energy demand	sim.	UWG+ TRNSYS	yes	neighb.	art.
19	[169]	Zonato et al.	2020	microcl.	air temp.	mod.+sim.	WRF	yes	city	art.
20	[170]	Chokhachian et al.	2020	microcl.	air temp. +solar access ind./out.	sim.	Rhino+Grass hopper+plugins	yes	neighb.	art.
21	[171]	Yoseph	2020	microcl.	ind. comfort	sim.	Revit 2015- Ecotect+Grass hopper+plugins	no	island	book

#	Refs	Authors	Year	Topic	Performance	Method	Tool	Morph.	Scale	Type
22	[130]	Javanroodi and Nik	2019	comb.1	energy performance	sim.	ANSYS Fluent+Energy Plus	yes	neighb.	art.
23	[172]	Xu et al.	2019b	microcl.	out. thermal comfort	sim.	OpenFOAM+Rhino+Grasshopper+plugins	yes	neighb.	art.
24	[173]	Ghassoun et al.	2019	microcl.	pollution	meas.+mod.	-	yes	city	art.
25	[174]	Xu et al.	2019a	microcl.	out. thermal comfort	sim.	Rhino+Grasshopper+plugins	no	neighb.	art.
26	[147]	Shen et al.	2019	microcl.	wind speed+air temp.+humidity	sim.	WRF	yes	city	art.
27	[175]	He et al.	2019	microcl.	urb. ventilation	rev.+meth.	-	yes	neighb.	art.
28	[176]	Chatterjee et al.	2019	microcl.	air temp.	sim.	Envimet	yes	neighb.	art.
29	[177]	Salvati et al.	2019	microcl.	air temp.	sim.	UWG	yes	neighb.	art.
30	[142]	Mei et al.	2019	microcl.	pollution	sim.	OpenFOAM	yes	neighb.	art.
31	[148]	X. He et al.	2019	microcl.	air temp.+wind speed	sim.	WRF	yes	city	art.
32	[143]	Peng et al.	2019	microcl.	urb. ventilation	sim.	ANSYS Fluent	yes	neighb.	art.
33	[88]	Claude et al.	2019	indoor	mold growth	sim.	EnergyPlus	yes	building	art.
34	[129]	Javanroodi et al.	2018	comb.1	energy performance	sim.	Fluent+Rhino+Grasshopper+EnergyPlus	yes	neighb.	art.
35	[178]	Li et al.	2018	microcl.	CO ₂ emissions	mod.	-	no	city	art.
36	[179]	Amaral et al.	2018	energy	energy performance	rev.	-	no	-	rev.
37	[87]	Chan and Liu	2018	indoor	ind. comfort	survey	-	yes	neighb.	art.
38	[180]	Cody et al.	2018	energy	energy performance	sim.	IESVE	yes	building	art.
39	[149]	de Moraes et al.	2018	microcl.	wind speed+surf. temp.	sim.	TEB	yes	city	art.
40	[181]	Moraitis et al.	2018	energy	solar energy potential	mod.	-	yes	nation	art.
41	[182]	Costanzo et al.	2018	energy	energy performance	sim.	Rhino+Grasshopper+plugins	no	neighb.	art.
42	[134]	García-Pérez et al.	2018	comb.4	global warming potential	stat. analysis	-	yes	city	art.
43	[183]	Hammerberg et al.	2018	microcl.	air temp.	sim.	WRF	yes	city	art.
44	[140]	Yuan	2018	microcl.	urb. ventilation	sim.	ANSYS Fluent	no	neighb.	book
45	[146]	Yuan	2018b	microcl.	urb. ventilation	sim.	MM5/CALMET	yes	city	book
46	[184]	Pili et al.	2018	energy	solar energy potential	mod.	GIS	no	city	art.

#	Refs	Authors	Year	Topic	Performanc e	Method	Tool	Morph.	Scale	Type
47	[185]	Pacifici et al.	2017	microcl.	air/surf. temp.+ humidity+ illuminance	meas.	-	yes	neighb.	art.
48	[186]	Thouron et al.	2017	microcl.	pollution	sim.	WRF+ POLAIR3D	yes	city	art.
49	[187]	Shi et al.	2017	energy	form generation	rev.	-	yes	-	rev.
50	[188]	Saratsis et al.	2017	microcl.	solar access	sim.	UrbanDaylight- DAYSIM	yes	island	art.
51	[189]	Palme et al.	2017	energy	cooling demand	sim.	UWG+ TRNSYS	yes	neighb.	art.
52	[150]	Li et al.	2017	microcl.	air temp.+wind speed	sim.	WRF ²	yes	city	art.
53	[141]	Wang et al.	2017	microcl.	urb. ventilation	sim.	PALM	yes	neighb.	art.
54	[190]	Perišić et al.	2017	microcl.	pollution	mod.	-	no	city	art.
55	[191]	Demuzere et al.	2017	energy	energy balance	sim.	ULSMs TERRA URB, CLM, SURFEX and SUEWS	yes	city	art.
56	[132]	Braulio- Gonzalo et al.	2016	comb.2	energy performance + ind. comfort	sim.	Design Builder+Energy Plus	yes	neighb.+ city	art.
57	[192]	Perišić et al.	2016	microcl.	solar access	sim.	Radiance	yes	island	art.
58	[193]	Guo et al.	2016	microcl.	surface temp.	mod.	-	yes	city	art.
59	[194]	Rodríguez Algeciras et al.	2016	microcl.	out. thermal comfort	sim.	RayMan	yes	island	art.
60	[195]	Taki and Alabid	2016	energy	ind. comfort	survey+sim.	EnergyPlus	no	building	book
61	[196]	Jurelionis and Bouris	2016	energy	energy consumption	sim.	CFD*	yes	neighb.	art.
62	[128]	Gros et al.	2016	comb.1	wind speed+ surf. temp.+ ind. temp.+ cooling demand	sim.	EnviBatE+ SOLENE- Microclimate+ SATURNE	no	neighb.	art.
63	[127]	Gutiérrez et al.	2015	comb.1	air temp.+wind speed	sim.	WRF ²	yes	city	art.
64	[126]	Srebric et al.	2015	comb.1	wind speed+ energy consumption	rev.	-	yes	-	rev.
65	[135]	Taleb and Musleh	2015	comb.5	wind speed+ solar irradiation	sim.	CFX+Grass hopper	yes	neighb.	art.
66	[197]	Oertel et al.	2015	microcl.	out. thermal comfort	meas.+sim.+ survey	RayMan Pro	yes	neighb.	art.
67	[198]	Sarralde et al.	2015	energy	solar energy potential	mod.	GIS	yes	neighb.	art.

#	Refs	Authors	Year	Topic	Performance	Method	Tool	Morph.	Scale	Type
68	[199]	Pay et al.	2014	microcl.	pollution	sim.	CALIOPE Air Quality Forecast System	no	city	art.
69	[200]	Bueno et al.	2014	microcl.	air temp.	sim.	UWG	yes	neighb.	art.
70	[201]	Hofman et al.	2014	microcl.	pollution	meas.+sim.	AURORA+MI MOSA4	yes	city	art.
71	[125]	Zhun Min Adrian et al.	2013	comb.1	solar radiation+ energy consumption	meas.+sim.	IESVE	yes	neighb.	art.
72	[151]	Chan et al.	2013	microcl.	wind speed + TKE	sim.	MM5	yes	city	art.
73	[152]	Pattacini	2012	microcl.	wind speed	sim.	Envimet	yes	neighb.	art.
74	[144]	Leung et al.	2012	microcl.	pollution	meas.+sim.	Fluent	yes	island	art.
75	[202]	Gros et al.	2011	microcl.	solar radiation	rev.	-	yes	-	rev.
76	[136]	Ng et al.	2011	microcl.	urb. ventilation	sim.	MM5/ CALMET	yes	city	art.
77	[133]	Vahabzadeh Manesh et al.	2011	comb.3	energy consumption	sim.	*	yes	neighb.	book-rev.
78	[203]	Salat	2009	energy	heating consumption	sim.	APUR	yes	neighb.	art.
79	[204]	Al-Maiyah and Elkadi	2007	microcl.	solar access	sim.	TOWNSCOPE	no	island	art.

*The Authors did not mention explicitly the employed software tool.

Abbreviations: Regarding the topic: microcl. microclimate; comb. = combination; comb. 1 = energy + microclimate; comb. 2 = energy + indoor; comb. 3 = energy + design; comb. 4 = energy + assessment; comb. 5 = microclimate + design. Regarding the performance: ind. = indoor; out. = outdoor; surf. = surface; temp. = temperature; urb. = urban; TKE = turbulent kinetic energy. Regarding the method: meas. = measurements; meth. = methodology; mod. = models; rev. = review; sim. = simulations; stat. = statistical. Regarding the scale: neighb. = neighborhood. Regarding the type: art. = article; rev. = review.

III_5 Urban ventilation

“The outdoor temperature, wind speed and solar radiation to which an individual building is exposed is not the regional “synoptic” climate, but the local micro-climate as modified by the “structure” of the city, mainly of the neighborhood where the building is located. ... However, special details of the individual buildings can have significant impact on the exposure conditions and comfort of pedestrians in the streets. ... the actual wind speed and turbulence in the streets, can vary significantly over very short distances, depending on some design details of the building along the street” [29].

III_5.1 Definition

Although studies of wind effects on the built environment established as a branch of civil engineering in the early 1960s [205], it is in the last two decades that the investigation of the interactions between airflow and urban morphology has gained popularity within the scientific community. Figure III_10 reports the yearly distribution of manuscripts available in the Scopus database published between 1960 and 2021.

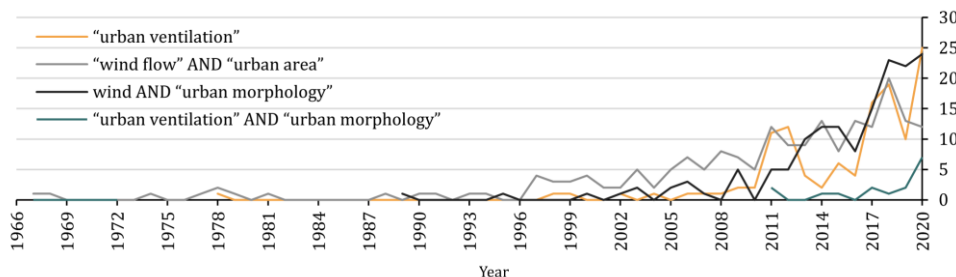


Fig. III_10 - The yearly distribution of published documents. Legends report the search queries.

Only research papers, review papers, books, and book chapters published in English have been considered. The terms used in the search query are: (i) “urban ventilation”, (ii) “wind flow” AND “urban area”, (iii) wind AND “urban morphology”, and (iv) “urban ventilation” AND “urban morphology”. The upward trends indicate the increased popularity of the topics, particularly notable in the

second decades of the 2000s. Particularly evident is the increase in the popularity of urban ventilation in the last four years. The reasons for such popularity may be identified in: (i) the growing awareness among public opinion of the urgency of sustainability in the urban environment; (ii) the increasing concern about the effects on human health of exposure to high levels of pollutant concentrations [206] and poor wind conditions in the built environment [15]; and (iii) the progress made in the fields of computational power and instrument availability.

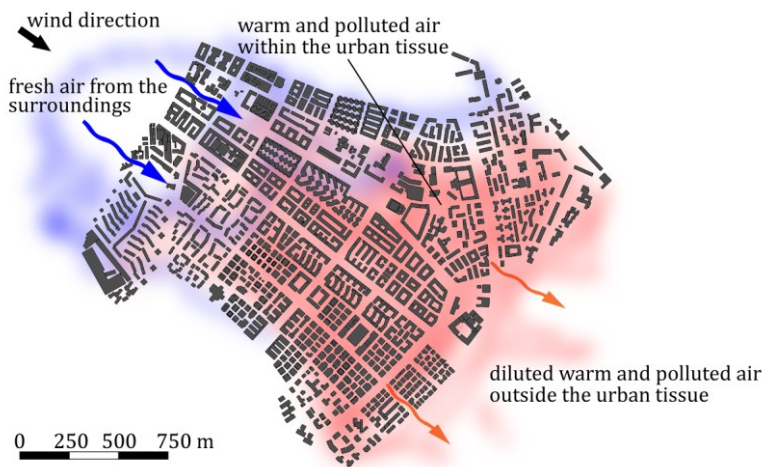


Fig. III_11 - Graphical representation of the concept of urban ventilation.

Addressing urban ventilation means considering cities as living organisms that breathe, introducing clean and fresh air within their tissues diluting in this way heat and pollution trapped in the urban canyons (Figure III_11). Carrying on the analogy with other branches of science, e.g., anatomy and biology, terms like *breathability* introduced by Neophytou and Britter [207], and *inhale and exhale effects* introduced by Hang et al. [16] have started being used in the scientific literature for describing the urban ventilation and outdoor air exchange. Since urban ventilation results from the interaction between urban areas and airflows, it is essential to thoroughly investigate the relationship between urban morphology and local wind conditions.

In this regard, many studies have been conducted, and, although characterized by different approaches, methodologies, and parameters, a common theoretical background may be identified. The hypothesis is that urban tissues are polluted while the air coming from rural or marine surroundings is clean [208].

This hypothesis appears relevant and applicable to the reality of our cities, which are the places where people, activities, and structures concentrate. In fact, urban areas inevitably alter the radiative, thermo-hygrometric, and aerodynamic characteristics of the environment where they are located [209]. The consequence is a reduction in wind speed within and right above the urban tissues. It is a well-known phenomenon that contributes to the Urban Heat Island (UHI) effect and produces a reduction in the ability to remove heat and pollutants from urban canyons [14], compromising the beneficial effects of urban ventilation. In other words, an urban area exerts resistance on the air mass, reducing its velocity and, consequently, the ability to wash out urban canyons. Since buildings are sharp-edged bluff bodies, the driving mechanism in the interaction between buildings and airflows is the *form drag*. Hence, the aerodynamic response of an urban area is influenced by its *form*, its morphology, which depends on (i) the characteristics of individual buildings, (ii) their mutual arrangements, and (iii) the characteristics of the area at larger scales. It is evident that an accurate description of urban morphology plays a primary role in urban ventilation investigations.

III_5.2 Morphological parameters

Given the importance of urban morphology, many efforts have been devoted to identifying the parameters that could represent the aerodynamic response of urban areas at the neighborhood scale. Initially, urban morphology was described in wind engineering applications and pollutant dispersion studies employing parameters representative of urban roughness [210]. The most common parameters are the aerodynamic roughness length, z_0 [211–213], the displacement length, d [212,214],

the zero-plane displacement height, z_d [210,215–218], the drag coefficient, $c_d(z)$ [213,215,216,218,219], the exponent p of the power-law wind profile [212], the frontal area density, λ_f [220], the plan area density, λ_p [215,217,219], the layout pattern, i.e., aligned or staggered [215,219], and the building height or height variation [215,219]. Apart from the last four parameters that depend only on the physical characteristics of urban areas, the others have been derived from empirical relations obtained by conducting wind tunnel experiments [220], mainly using idealized and simplified urban configurations, i.e., arrangements of cube-like buildings. Albeit useful to describe the overall effects of urban morphology on wind conditions, these parameters are highly sector-based and do not ease the knowledge sharing between two specialistic sectors, i.e., wind engineering and urban planning. Other parameters commonly used in these studies are the height-to-width ratio H/W , or UC aspect ratio, where H is the mean building height and W is the distance between two opposing buildings, and the length-to-height ratio, where L is the length of the canyon and H is the mean building height [221]. The former was commonly used for considering the effect of building density on flow regimes [209,215,222,223]. Finally, attempts have been made to obtain the aerodynamic parameters using morphometric methods in real cities [220]. Figure III_12 reports examples of the abovementioned studies.

As the topic's popularity grew, many efforts have been made to analyze the effects of urban morphology on urban ventilation. The morphological parameters adopted for the investigations are various and depend on the phenomena under investigation and the scale of interest. Excluding studies focused only on single buildings as beyond the scope of the present research, three different urban models may be identified, i.e., two-dimensional (2D) and three-dimensional (3D) UCs and 3D urban arrays. Urban models are selected to investigate the effects of certain morphological parameters on specific phenomena at the relevant scale [224,225].

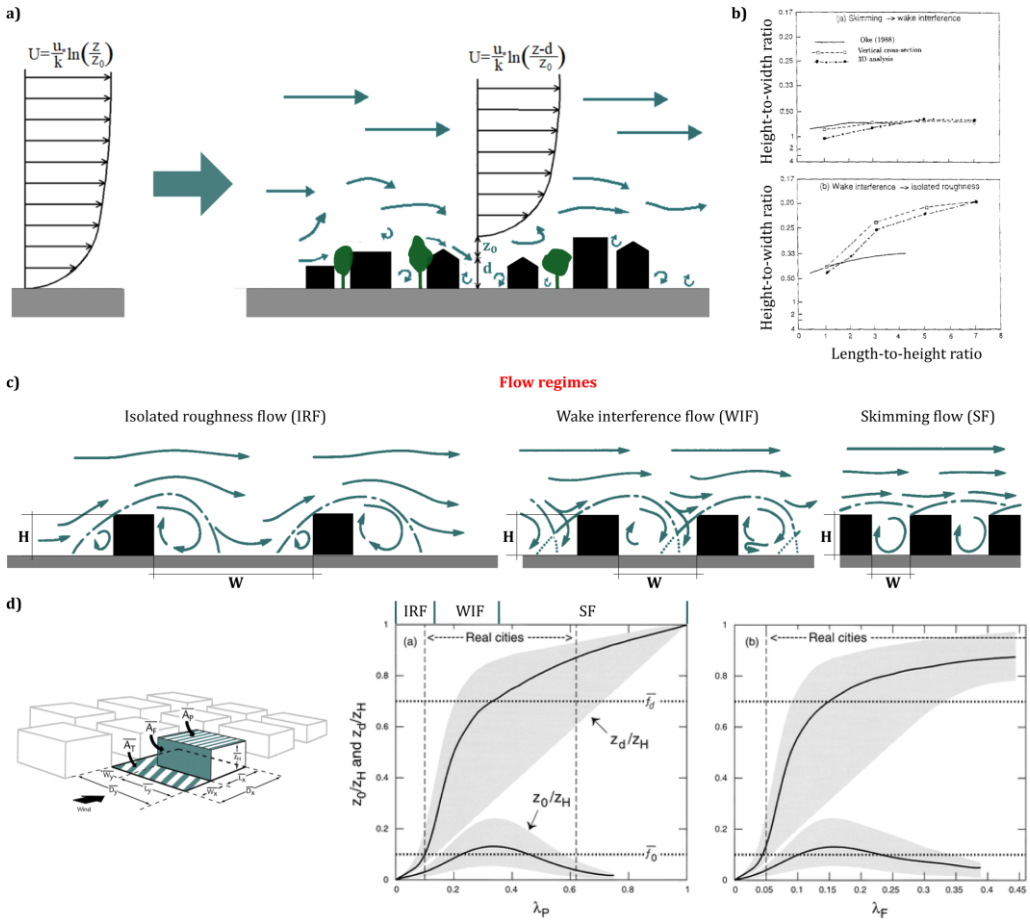


Fig. III_12 - Examples of morphological parameters used in wind engineering applications and pollutant dispersion studies: **(a)** z_0 and d ; **(b)** relation between height-to-width ratio and length-to-height ratio of UCs from [221]; **(c)** flow regimes, modified after [222]; and **(d)** parameters of interest, modified after [220].

Therefore, studies performed using 2D UCs mainly aim at investigating the impact of the UC aspect [223,226–228], the roof shape [229,230], and the height or height variation [229,231] (Figure III_13). Studies performed using 3D UCs are mainly focused on the UC aspect ratio [232], the roof shape [233], the height or height variation [234], the L/H or UC length-to-height ratio [221,235], and the orientation of the UC compared to the direction of the approaching wind [234] (Figure III_14).

2D urban canyon

Aspect ratio

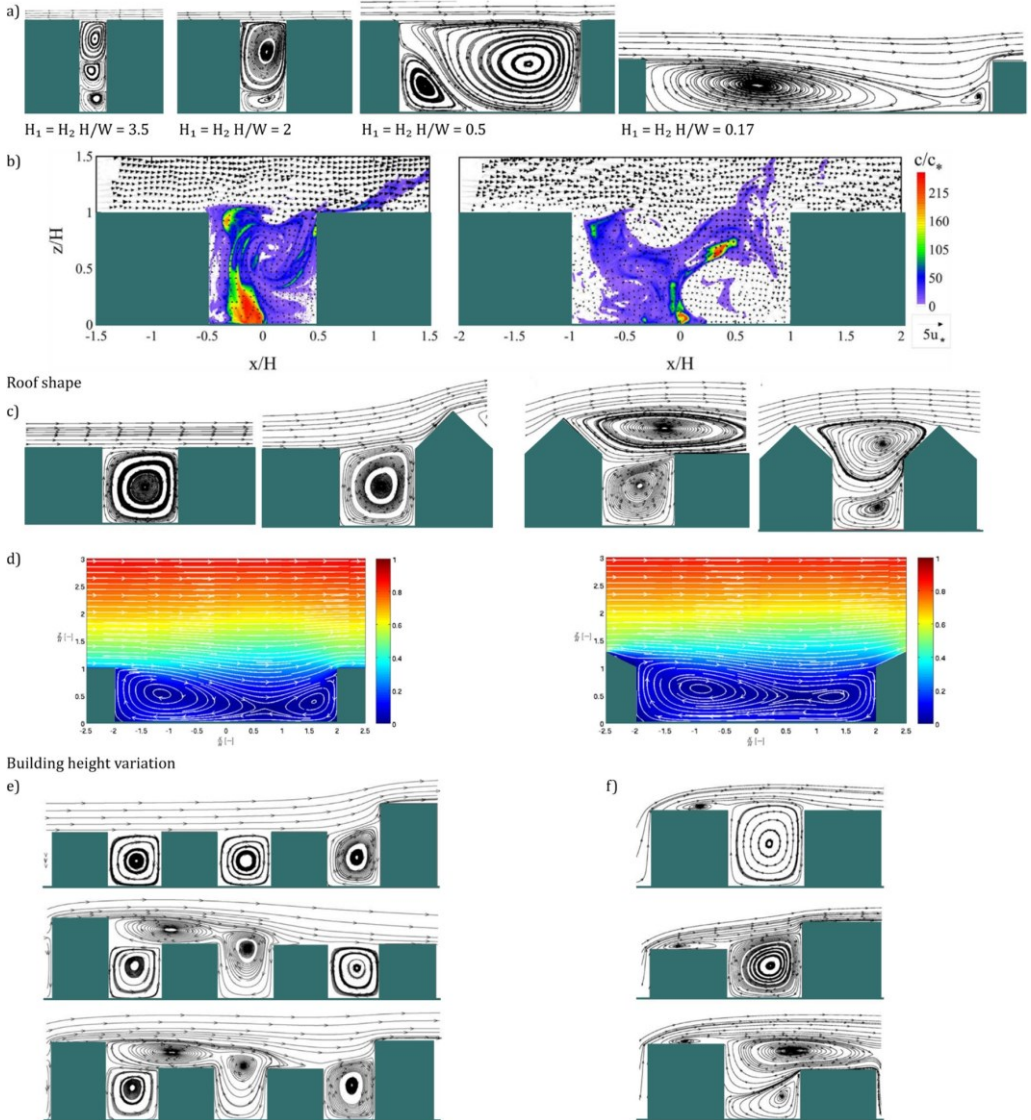
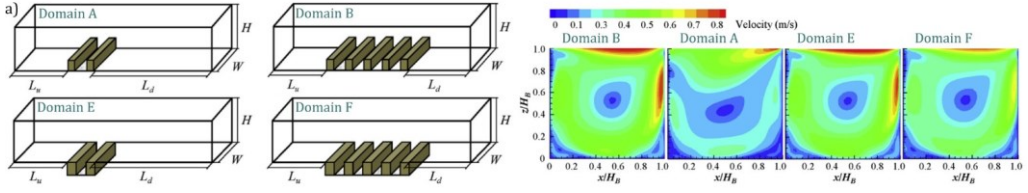


Fig. III_13 - Examples of studies using 2D urban canyon models for investigating the impact of (a) the aspect ratio on streamlines, modified from [226]; [228]; (b) the aspect ratio on instantaneous velocity (vectors) and concentration (colors) fields for aspect ratio equal to 1 and 2, modified from [228]; (c) the roof shape on streamlines, modified from [229]; (d) the roof shape on the mean wind velocity ratio and streamlines, modified from [230]; (e) the building height variation on streamlines, modified from [229]; and (f) the building height variation on streamlines, modified from [231].

3D urban canyon

Aspect ratio



Roof shape

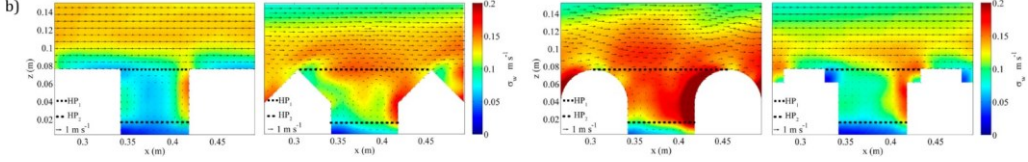
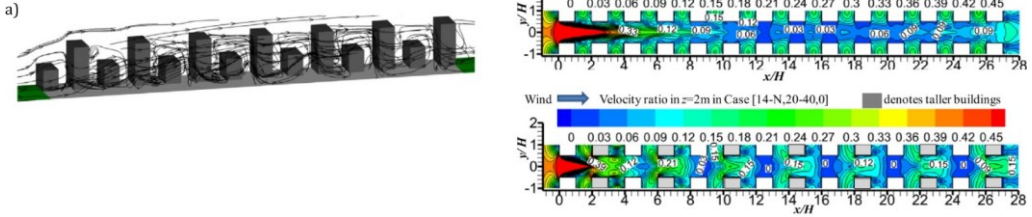


Fig. III_14 - Examples of studies using 3D urban canyon models for investigating the impact of (a) the aspect ratio on wind velocity, modified from [232]; and (b) the roof shape on the time-averaged velocity (vectors) and vertical turbulence intensity (contours), modified from [233].

3D urban arrangement

Height variation



Orientation

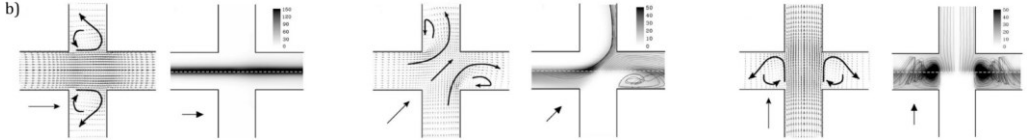


Fig. III_15 - Examples of studies using 3D urban arrangement models for investigating the impact of (a) the height variation on 3D streamlines and the velocity ratio, modified from [241]; and (b) the orientation on velocity field and pollutant concentration, modified from [250].

Finally, studies performed using 3D urban arrays generally aim at investigating the effects of the UC aspect ratio [236,237], L/H [237], array layout types [238], building height or building height variation [237,239–241], plan area density λ_p [219,242–247], frontal area density λ_f [242,243,245,246,248,249], and orientation [27,250,251] (Figure III_15). Note that this classification has been proposed only

for the sake of clarity. Single MPs should not be regarded as exhaustive to represent the investigated phenomena. In many studies, various MPs have been considered. A comprehensive overview of morphological parameters used in urban ventilation studies may be found in [64].

Studies aiming at assessing the impact of morphological parameters on urban ventilation are usually performed on idealized case studies. The idealized urban models are composed of simplified building geometries, usually comprising cubes or rectangular parallelepipeds, grouped to typify the area of interest. Albeit useful for investigating specific features of the phenomenon, idealized urban models may not represent the complexity of actual urban areas. Hence, investigations of the relationship between urban morphology and ventilation in actual urban tissues are of paramount importance. However, studies that aim at investigating correlations between MPs and urban ventilation performances are rare [64,252–254]. Each of the previous studies focused on sets of MPs: the plan area density and the floor space index [252]; the plan area density, the sky view factor, the tree view factor, and the green plot ratio [253]; the plan area density, the mean building height, the maximum building height, the standard deviation of the building height, and the façade area ratio [254]; and the plan area density, the mean building height, the root mean square of the building heights, the median of the building heights, the area-weighted mean building height, the volume density, and the façade area density [64]. Actual urban areas are used as case studies mainly for describing phenomena in specific contexts or verifying the accuracy of computational setups [41,143,262–270,224,255–261].

III_5.3 Investigation methods

Urban ventilation is a phenomenon belonging to the so-called urban physics, i.e., an applied discipline, inherently multidisciplinary, aiming to investigate the physical processes in urban areas [17]. Overall, these processes can be described as heat and

mass transfers in outdoor and indoor urban environments studied at different observation scales [17]. Variables and parameters in play are various and intertwined, ranging from the human scale, less than 1 m, to the meteorological microscale, up to 2 km (Figure III_16a). Therefore, the complexity characterizing urban physics studies is evident and affects methods and tools available for the investigations that are usually highly specialized and little interconnected. Focusing on the investigation of urban ventilation, the main phenomena of interest are (i) turbulence, (ii) building wakes, (iii) plumes, (iv) heat transfer, (v) convective flows, and (vi) advective flows (Figure III_16b). The investigation methods usually employed to analyze these phenomena are three: (i) in situ measurements [253], (ii) laboratory measurements [242,252,271], and (iii) numerical simulations [64,142,143,254]. This feature is supported by the outcomes of the literature review presented in Section III_4. Each method offers advantages and disadvantages that should be carefully considered, before starting the investigation, to select the appropriate approach and tool [224].

Regarding in situ measurements, the main advantage is that they can capture the complexity of the phenomena under investigation since the boundary conditions are real; however, this characteristic also determines the main disadvantages of the method. Firstly, measurements are not performed in a controlled environment, and, therefore, they are subject to meteorological conditions and cannot be replicated. Secondly, the measurements are usually performed point by point, especially for air temperatures and wind speed and direction, due to the specific characteristics of the instruments (e.g., thermometers, Light Detection and Ranging, and anemometers). Hence, it is not possible to have data for the entire area under investigation. Using many instruments simultaneously could provide an amount of data sufficient to be representative of larger areas. Nevertheless, this affects the cost of the campaign and requires careful calibration of the devices to ensure consistency

of the results. Finally, in situ measurements are possible only for existing case studies; consequently, they cannot be used for parametric or feasibility studies.

Another investigation method is represented by laboratory measurements that are usually performed using wind tunnels or water channels. Laboratory measurements allow a high control over the boundary conditions and may be employed for conducting parametric studies and analyses preliminary to the construction phase. However, the most common techniques involve measurements performed point by point. Despite the existence of techniques that allow obtaining information on planes or entire volumes, e.g., Particle Image Velocimetry (PIV) and Laser-Induced Fluorescence (LIF), these methods are not yet frequently used because of the costs and the limitations for complex geometries due to the mutual obstructions caused by building models. Finally, another issue is the adherence to the so-called similitude theory, i.e., the geometric, kinematic, dynamic, and thermodynamic similarities, that need to be considered when experiments with scaled models are conducted.

Finally, numerical simulations prove to be a powerful investigation method because they may overcome the main disadvantages of the previous methods. Numerical simulations provide detailed information about all simulated variables in the entire computational domain, allow full control over the boundary conditions, and can also be performed for parametric and feasibility studies. Nevertheless, this method presents potential disadvantages typical of numerical techniques. Consequently, scrupulous attention must be paid to building the model, generating the computational grid, selecting the turbulence model, and setting the boundary conditions that need to be realistic to obtain meaningful results. In this regard, several guidelines have been developed in the last fifteen years to assist researchers and professionals [272–275]. Nevertheless, it is fundamental to stress the necessity to conduct validation studies of the computational settings prior to the actual investigation to verify the reliability of the results. In this case, there are guidelines helpful for identifying validation metrics [276] and grid-convergence procedure

[277]. Regarding numerical simulations, urban ventilation is usually investigated employing two approaches, i.e., Large Eddy Simulation (LES) and Reynolds-averaged Navier–Stokes (RANS) approaches. Although the LES approach yields more accurate results, the RANS approach is still widely used in both research and engineering practice [278]. In fact, despite the remarkable progress achieved in computational power, LES simulations are still computationally expensive and, at the moment, hardly embedded into the design process. In Figure III_16b, the wide range of atmospheric phenomena that can be simulated using the RANS approach is reported.

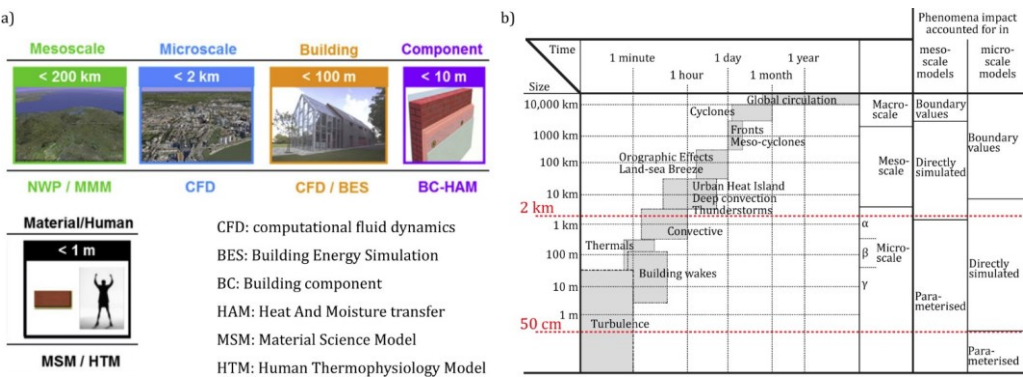


Fig. III_16 - (a) Schematic representation of the spatial of interest in urban ventilation studies highlighting their typical maximum horizontal length scales and models, modified from [17]; and **(b)** spatial and temporal scales of atmospheric phenomena and their parameterization in RANS model, modified from [279].

III_5.4 Performance indicators

Regardless of the investigation method adopted, urban ventilation performance is assessed using different indicators. Initially, the aerodynamic response of urban areas has been evaluated in terms of drag coefficient to assess the resistance exerted by buildings on wind flows [215,216,282,283,218,219,242,248,249,271,280,281] and pressure coefficient to estimate the load induced by wind flows on building surfaces [215,223]. Recently, two new indicators have been introduced for considering the

resistance exerted on airflows, i.e., the friction factor [283] and friction coefficient [230]. Another approach adopted to investigate urban ventilation is to focus on the exchange between in-canyon and above-canyon areas [245,260,284]. For this purpose, Bentham and Britter introduced two models: the spatially and temporally averaged advection velocity within the urban canopy, constant across the height of the canyon, U_C , and the spatially averaged exchange velocity between in-canopy and above-canopy flow, U_E [285]. Similarly, indicators like flow rate [286] and pollutant flux or pollutant transport rates [240,287] have been used to quantify the exchange of the area of interest with the surroundings. In addition, the evaluation of pollutant performance of urban areas [288–291]. Pollutant concentrations can be evaluated both on surfaces and as the bulk concentration in the whole canyon [223]. Nevertheless, disadvantages in analyzing pollutant concentration distributions have been pointed out, as pollutant concentrations are dependent on the location and the type of the source [292]. Specifically, Bady, Kato, and Huang remarked on the necessity to set indices for evaluating air quality [292]. For this purpose, indices developed for indoor ventilation studies started being used since a similarity between the processes involved in urban and indoor ventilation [293] has been recognized. Generally, the indices used in these analyses are the Visitation Frequency (VF), the Purging Flow Rate (PFR), the average staying time (TP), the age of air (τ), and the air exchange rate (ACH). VF represents the average frequency with which pollutants generated in the local domain return to the local domain after being transported outside; PFR is the effective airflow rate required to remove the pollutant from the local domain; TP represents the time the pollutant takes from once entering into or being generated in the domain until its leaving; and τ represents the time a particle of external air takes to replace a particle of air in a specific location inside the domain. Incidentally, Hang et al. proposed using the concept of the local age of air adapting the homogeneous emission method, originally developed for indoor experiments using the tracer gas techniques

[293,294], to overcome the disadvantages related to the dependence on the pollutant source and for focusing the causes of the concentration [208]. The work by Huang et al. [295] represents the first attempt in English at employing VF, PFR, TP, and ACH for evaluating ventilation within an actual urban area in Japan. In the last years, many studies using ventilation indices have been performed to analyze the impact of urban morphologies on ventilation [16,27,287,296–301,234,236,237,240,241,264,284,286]. It is worth noting that most of the studies employing ventilation indices have been performed using idealized urban models. This characteristic is due to the difficulties encountered in applying the indices in actual urban areas, where morphologies are often irregular and inhomogeneous, and boundaries are difficult to define. To overcome these issues, a new index has been introduced recently, i.e., the air delay τ_d [264]. A complete review of ventilation indices is provided by Peng et al. [302]. Finally, another indicator for evaluating urban ventilation is the spatially averaged wind velocity ratio (mWVR). This indicator has proven useful in both idealized [238,239,241,243,303,304] and actual urban areas [64,252–254]. Moreover, this indicator is very useful because it has also been used for studying pedestrian comfort related to low wind speed [43], for evaluating computational settings [232], and for supporting optimization procedures [305–308]. It is worth noticing that the abovementioned parameters may be used in combination.

Main Findings

From the literature review provided in this section, the following main conclusions may be drawn for each of the analyzed aspects, i.e., morphological parameters (MPs), investigation methods, and performance indicators.

Regarding the MPs, the main features to consider for describing a single building are the building plan area or footprint (A_B), the shape, the building height (H_B), the building volume (V_B), the building façade area (S_B), and the orientation in relation

to wind direction. From the viewpoint of urban arrangements, the morphological characteristics to consider are the layout type, the orientation in relation to the wind direction, the mean building height (H_{MB}), building height variation (σ_B), the plan area density (λ_p), and frontal area density (λ_f). Note that λ_f is the ratio between the total projected area of building vertical surfaces facing the approaching wind direction and the total land area; therefore, it is possible to compute this parameter only when information about the direction of the approaching wind is available. Since urban ventilation studies conducted using actual case studies employ the façade area density (λ_{fac}), it has been decided to replace λ_f with λ_{fac} . Figure III_17 reports the graphical definitions of the MPs selected for conducting urban ventilation investigations in actual urban areas.

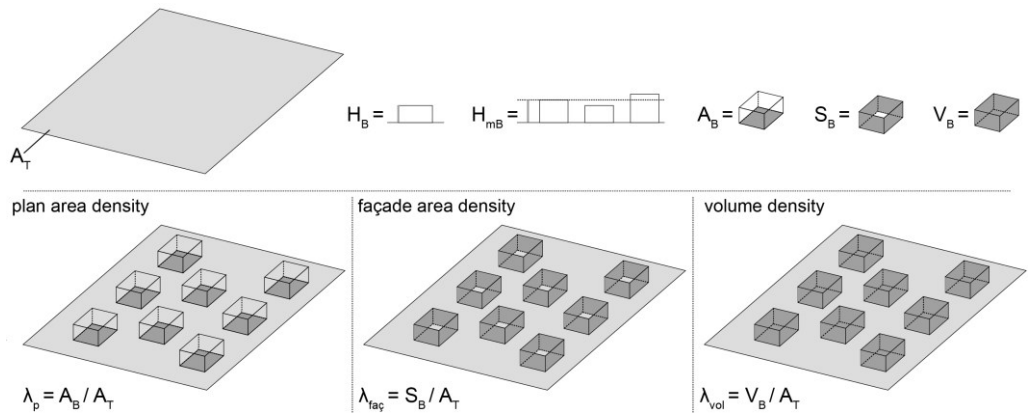


Fig. III_17 - Graphical definitions of the morphological parameters identified as relevant to characterize urban areas in urban ventilation performance studies.

Regarding the investigation method, it is possible to claim that numerical simulations performed using the RANS approach represent a valid and versatile method for investigating the relationship between urban ventilation and urban morphology. Regarding the performance indicator, mWVR proves to be a versatile indicator. Therefore, it has been identified as useful for investigating the impact of morphological parameters on urban ventilation in actual urban areas. Finally, it is

also suggested to employ τ because it may provide information about the level of entrapment of exhausted air within the UCs. This index may be valid for comparing different scenarios.

III_6 Urban Ventilation Performance Assessment Methodology

Air pollution and heat stress constitute two increasing threats to human health and well-being that need to be faced immediately. Urban ventilation may favor the mitigation of detrimental effects of air pollution and heat stress on human life. In the last decades, a tendency towards urban tissue densification may be observed to counteract the indefinite development of low-density urban areas into natural surroundings and implement sustainability in the urban environment. Urban tissue densification may be achieved through more compact built areas, preferring the vertical to the horizontal development of buildings. This strategy affects the urban wind environment and may reduce urban ventilation performances significantly, compromising its beneficial effects. Hence, regenerating existing, well-structured, and stratified urban areas by densification is not an easy challenge. Therefore, a multidisciplinary methodology is presented in this section for embedding urban ventilation performance evaluation into urban management and planning processes. This methodology builds upon the performance-based approach and is supported by the conceptual framework and the literature reviews provided through the paper.

Figure III_18 reports the workflow for urban renewal plans that aim at improving urban ventilation performance. The potential risks associated with the densification of urban tissues are pollution, stagnant air, and thermal discomfort. Consequently, adequate levels of urban ventilation have been identified as the desired performance. The mean wind speed ratio, the mean wind field, i.e., mean wind speed and direction, and the age of air have been identified as valid performance indicators to assess ventilation performance and, therefore, the success of the

planned strategy. The evaluation may be carried out by comparing different scenarios, highlighting, for instance, the improvements achieved compared to the current state. In addition, regulations and comfort criteria may be employed. Besides the standards mentioned in the introduction, several wind comfort criteria may be found in the literature [252,309–311]. In this regard, Table III_2 reports the criteria for highlighting wind speed ranges that cause thermal discomfort. These criteria appear particularly effective in the case of compact urban areas, where low wind conditions are usually found. Finally, the proposed procedure may be used for both monitoring the ventilation performance and identifying possible hot spots during heatwaves in the area of interest.

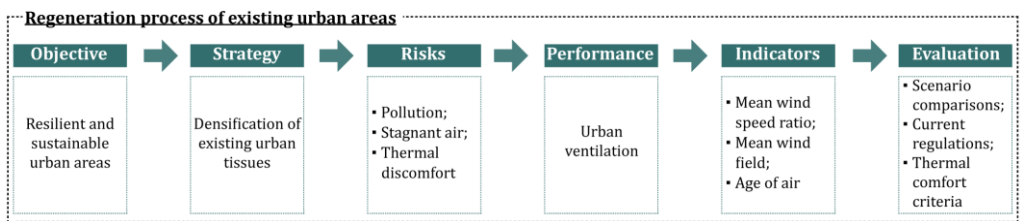


Fig. III_18 - Workflow for urban renewal plans that aim at improving urban ventilation performance.

Table III_2 - Criteria for assessing wind-induced discomfort considering temperature effect at the pedestrian level [252].

	Daily mean temperature (°C)		
	< 10	10 - 25	> 25
Daily mean wind velocity range causing thermal discomfort due to insufficient wind speed (m/s)	-	-	<0.7
Daily mean wind velocity range realizing acceptable wind environment (m/s)	< 1.3	< 1.5	0.7 – 1.7
Transition range of daily mean wind velocity from acceptable wind to strong wind (m/s)	1.3 – 2.0	1.5 – 2.3	1.7 – 2.9
Daily mean wind velocity range causing strong wind-induced discomfort (m/s)	> 2.0	> 2.3	> 2.9

After the workflow description, it is possible to present the multidisciplinary methodology for assessing urban ventilation in existing urban areas (Fig. III_19). This methodology consists of three phases: the physical structure quantification, the wind environment simulation, and the performance evaluation. In III_19, an additional preliminary step comprising area selection and data collection has been reported. The data to collect pertain to urban morphology and microclimatic conditions, including air quality reports. This information is fundamental for generating 2D and 3D models of the area and setting the boundary conditions for the numerical simulations. In this regard, data measured at a nearby airport or rural surroundings are essential. It is worth noting that data collection is crucial since the availability and genuineness of the data affect the results of the investigations. However, it has been described as an additional preliminary phase to remark on the need for available databases. These databases should be comprehensive, reliable, and fully accessible by planners and policymakers to guarantee the homogeneity of the data and the reliability of the results.

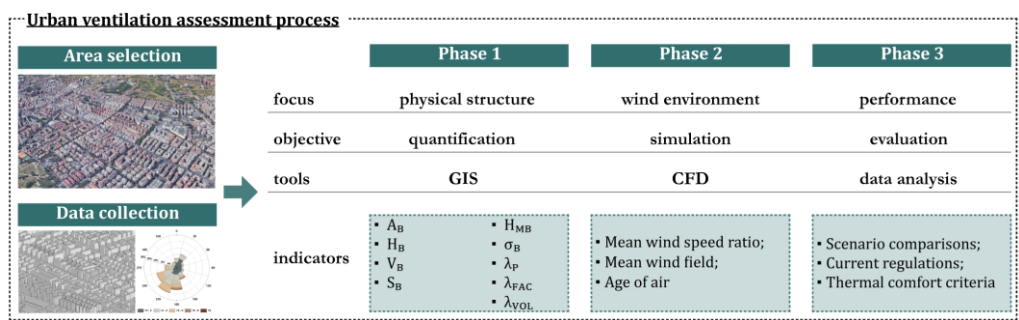


Fig. III_19 - Phases forming the process for the assessment of the ventilation performance of an urban area.

Once the data related to the physical structure have been collected, it is possible to create the GIS model of the area if this is not available. In this regard, national and international efforts and resources have been devoted recently to creating databases and GIS models. A GIS model is advantageous for performing morphological

analyses, calculating MPs, and storing data of different nature, i.e., qualitative and quantitative. This phase is also significant for setting effective strategies considering the climatic conditions. As concluded in Section III_5, the MPs of interest are plan area density, area-weighted mean building height, volume density, and façade area density. It is suggested to consider also other parameters related to building height, e.g., the mean building height, the root mean square of the building heights, and the median of the building heights. Albeit employed mainly in studies conducted using idealized urban models, these parameters have been regarded as relevant in the literature. Figure III_20 reports examples of morphological analyses performed using GIS software. The compact area selected for the study is the Tuscolano–Don Bosco district in Rome, Italy. The investigations have been carried out using the open-source GIS software QGIS [312]. The open-source GIS software proves to be very useful because it allows for:

- Checking the feature topologies on point, line, and polygon layers automatically by setting specific rules.
- Cleaning topology errors automatically.
- Adding missing details and features.
- Extracting information from raw data.
- Combining information for calculating MPs employing algorithms and scripts.

These characteristics offer the ability to study vast areas and handle a large amount of data, making the methodology particularly valuable for policymakers. In this work, the primary data have been retrieved from the open database provided by the regional authority [313]. The selected MPs have been calculated from three sets of data: the building footprint area, the elevation above sea level of the foot and the top of every building, and details on the street network. Furthermore, information about the building construction age and building typology has been added by the authors.

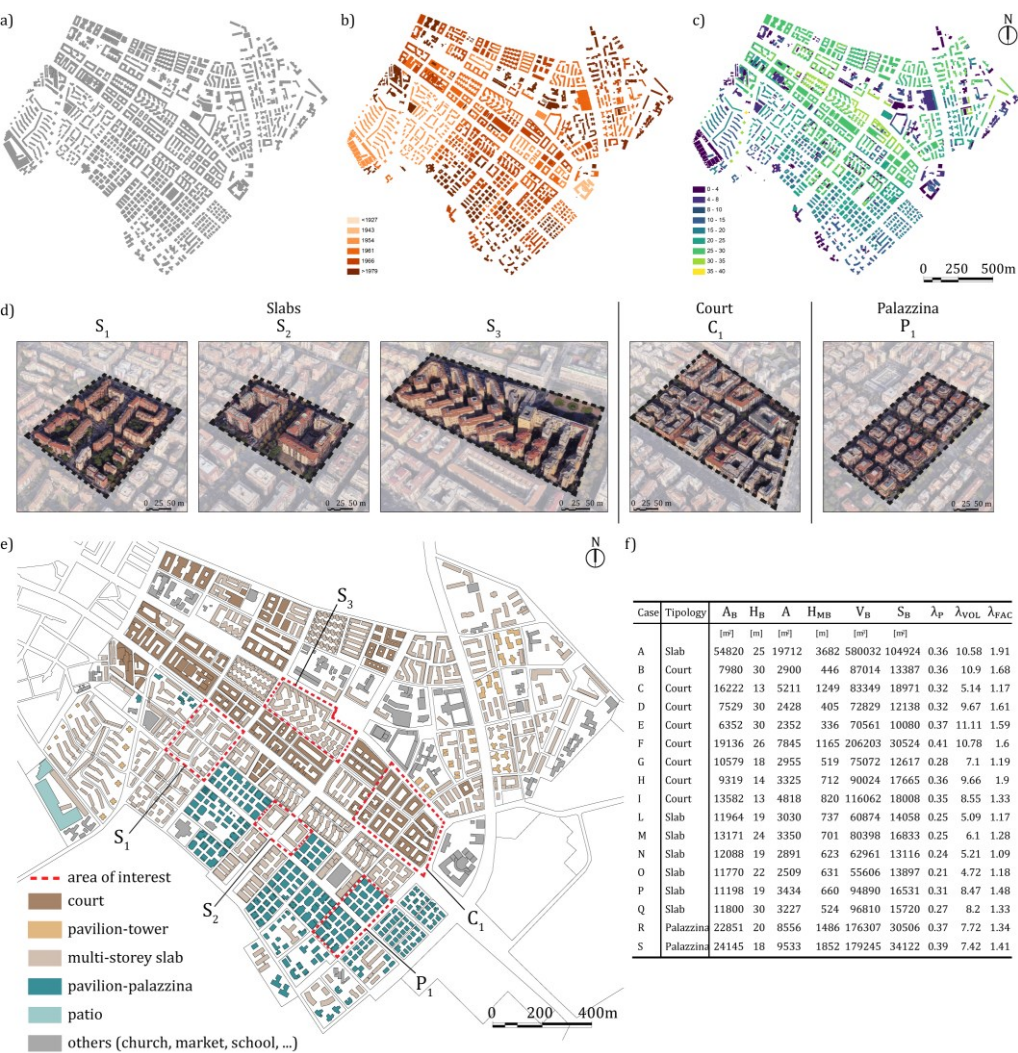


Fig. III_20 - Examples of morphological analyses performed using GIS tools: **(a)** building plan, **(b)** building age, **(c)** building height, **(d)** perspective views of specific morphologies, **(e)** typologies, and **(f)** morphological parameters.

Once information about urban morphology and microclimatic conditions have been collected and checked, it is possible to start the second phase, i.e., the wind environment simulation. In the previous section, it has been reported that 3D RANS simulations prove to be a valid investigation method. Therefore, starting from the 2D GIS model, the computational domain and the grid should be

generated. Meticulous attention should be paid because the accuracy of the results depends, amongst many other factors, on the resolution and quality of the grid. Nevertheless, these characteristics influence the computational cost of the simulations. Therefore, a compromise between the simplification of the model and the feasibility of the simulations should be reached. Figure III_21 shows the high-resolution grid generated for evaluating the ventilation performance of the selected case study. After the grid generation, it is possible to define the computational setup and solver setting. To accurately represent the surroundings of the area of interest while setting inflow and boundary conditions, a land-use map [314] may be used for estimating the aerodynamic roughness length according to the Davenport–Wieringa roughness classification [212]. Once the computational setup has been defined, it is possible to perform the simulations and compute the selected performance indicators.

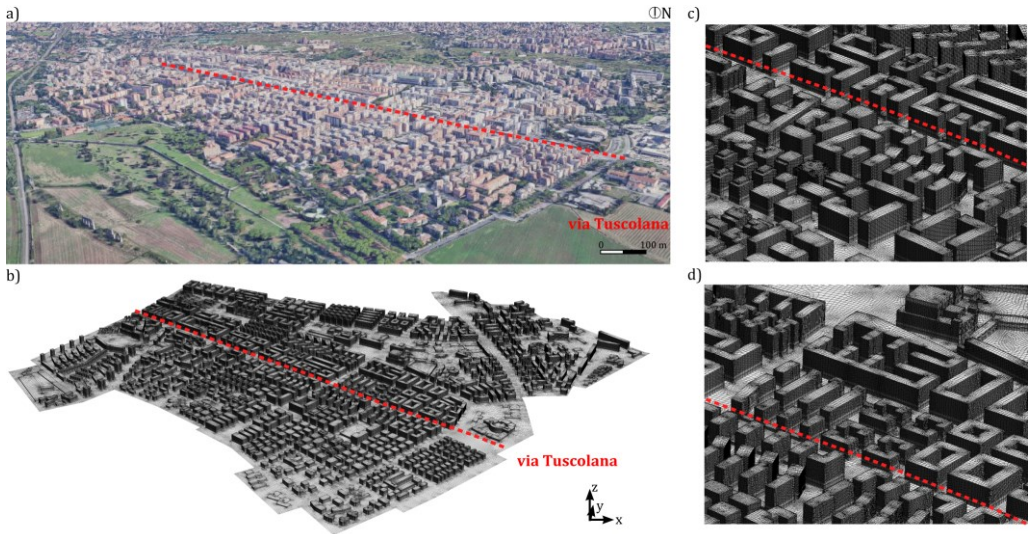


Fig. III_21 - Perspective view of (a) the area of interest (modified from Google Maps), (b) the computational grid, (c) enlargement of the computational grid and (d) enlargement of the computational grid. The total cell count is about 86 million. Modified after [64].

Finally, phase three entails performance evaluation using data analysis. This phase may be conducted using datasheets or creating scripts in programming and numeric computing platforms, e.g., MATLAB, that can process data automatically. Afterward, results may be processed employing GIS software to generate maps that ease monitoring and may also be used by non-specialists.

III_7 Conclusions

Albeit essential for curbing heat stress and pollution in existing urban areas, the investigation of urban ventilation is not yet commonly embedded into the management and planning of urban areas. Through literature review and discussion, this paper proposes a workflow for urban renewal plans that aim at improving urban ventilation performance and builds up a multidisciplinary methodology for assessing urban ventilation performance in existing urban areas. The methodology consists of three main phases: the physical structure quantification, the wind environment simulation, and the performance evaluation. Regarding the physical structure, morphological parameters valid for its quantification and tools for data aggregation are provided. Regarding the wind environment, 3D RANS simulations are suggested as valid methods for analyzing the wind environment and computing the performance indicators. Regarding the performance evaluation, three possibilities have been indicated.

The proposed methodology may be applied to both research and professional purposes. As a research tool, this methodology may be used for investigating the correlation between urban ventilation and morphology, improving prediction models for estimating ventilation performances without running simulations. In addition, the methodology may be employed for implementing comfort criteria and regulations that are scarce in the case of weak wind conditions. As a professional tool, this methodology may be applied: (i) in case of renewal plans, for assessing the achievement of objectives and prioritizing actions, and (ii) in case of urban

management, for identifying areas exposed potentially to poor air conditions, and, therefore, vulnerable to pollution and heat stress.

Further developments may imply the integration of the methodology into generation and optimization design processes. Finally, the methodology may be further improved by employing transient simulations for solar radiation and heat transfer calculation. Nevertheless, preliminary results suggest that this may significantly affect the computational cost and time of the simulations, undermining the integration of the analyses into the urban management and planning processes.

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Urban ventilation in compact cities: impact of morphological parameters

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Impact of morphological parameters on urban ventilation in compact cities: The case of the Tuscolano-Don Bosco district in Rome, 2022 *Science of the Total Environment* 807, 150490.

Air pollution and heat stress are major concerns associated with the liveability, resilience, and sustainability of cities. They directly affect health and comfort and are associated with augmented morbidity and mortality and an increase in the energy demand for building ventilation, air cleaning, and cooling. Nevertheless, the detrimental effects of poor air quality may partly be mitigated by increased urban ventilation. This strategy is closely related to the level of urbanization and urban morphology. Therefore, detailed investigations on the impact of different morphologies on urban ventilation are of paramount importance. Computational Fluid Dynamics simulations have been widely used during the last decades to investigate the effects of urban morphology on urban ventilation. However, most of these studies focused on idealized building arrangements, while detailed investigations about the role of real urban morphologies are scarce. This study investigates ventilation in a compact area in the city of Rome, Italy. 3D steady-state Reynolds-averaged Navier-Stokes simulations are performed to analyze the impact of Morphological Parameters (MP) on urban ventilation. The results show a considerable worsening of urban ventilation with increasing building density with a reduction in the mean wind velocity up to 62% experienced at the pedestrian level (z_p). Correlations between five MPs, e.g., plan area density, area-weighted mean building height, volume density, façade area density, and non-dimensional mean velocity at pedestrian level and at 10 m height are evaluated, and simple models are obtained using linear regression analysis. Among the selected MPs, the building façade density shows a remarkable correlation with the non-dimensional mean velocity at z_p ($R^2 = 0.82$). Such correlations can be valuable tools for practitioners and urban designers, particularly during the first stage of planning, for highlighting areas potentially vulnerable to poor air conditions without running computationally expensive simulations.

IV_1 Introduction

Nowadays, more than 55% of the world's population lives in urban areas [1], and this number keeps growing due to the increase in the number, size, and density of cities [2], which are enlarging their environmental footprint. Consequently, the challenge towards more sustainable and resilient built environments has become urgent, especially in existing cities. Many efforts are being made worldwide. In this regard, the adoption in 2015 by all United Nations Member States of the 2030 Agenda for Sustainable Development is significant. In the Agenda, seventeen Sustainable Development Goals (SDGs) have been identified to guarantee prosperity. The third and the eleventh goals explicitly state that it is necessary to “ensure healthy lives and promote well-being for all at all ages” and to “make cities and human settlements inclusive, safe, resilient and sustainable” [3].

Currently, air pollution and heat stress are two major concerns [4–9] directly associated with the livability, resilience, and sustainability of cities. In Europe, more than 74% of the population lives in urban areas [10], and over 90% of the urban population is exposed to air pollution [11]. Air pollution and heat stress have been linked to augmented morbidity and mortality [12–17]. However, the detrimental effects of air pollution and heat stress can – at least partly – be mitigated by increased urban ventilation [6]. Urban ventilation represents the capacity of a built area for introducing fresh air within its tissues and diluting pollutants and heat within its canyons. This phenomenon is closely related to the level of urbanization and the urban morphology, i.e., the form and the structure of the urban area, the physical characteristics of the buildings, and their mutual arrangement. Conversely, urban morphology can be used as an effective tool in renovation plans for improving urban ventilation.

For this purpose, two in-depth analyses are of paramount importance: detailed investigations of the impact of different morphologies on urban ventilation; and the identification of parameters and indicators that can describe the various

characteristics of the urban morphology quantitatively. To be able to evaluate the impact of morphological parameters on urban ventilation, investigations are generally conducted at the street scale, less than ~ 100 to 200 m, and at the neighborhood scale, up to 1 or 2 km, depending on the features of interest [18]. Given the complexity of the phenomenon, the majority of the studies performed in the past used simplified models of actual urban areas.

The simplified models are generic urban geometries selected based on the phenomenon under investigation. A review of morphological parameters used for generic urban geometries in urban ventilation studies is provided in Section IV_2.1. Albeit useful for investigating the contribution of specific parameters, these simplified models may not reproduce the complexity of the built environment. Exploring the relationship between urban ventilation and morphology has gained popularity in the literature in the past two decades; however, detailed investigations on the role of real urban morphologies are still required. Works conducted using actual urban areas as case studies are, in fact, very rare [19–21]. Section IV_2.2 provides a review of urban ventilation studies for actual urban areas along with the methodology and morphological parameters. Other previous studies with numerical simulations in actual urban areas were performed; however, their aim was rarely to provide simplified models or guidelines generalizing the results. In fact, the simulations were usually conducted for: describing phenomena in specific case studies such as pollutant dispersion and reduction [22–29], and urban microclimate [9,30–33], or for verifying the accuracy of CFD [34,35], and assessing the sensitivity of boundary conditions [36] and computational domains [37].

Given the lack of studies investigating the impact of real urban morphologies, this paper presents Computational Fluid Dynamics (CFD) simulations of the impact of the urban morphology on the ventilation within an area of the city of Rome, Italy, i.e., the Tuscolano-Don Bosco district. Urban morphology is described by a set of seven Morphological Parameters (hereinafter MPs) and their combinations,

common amongst practitioners, policymakers, and designers. This choice is motivated by the necessity of linking two specialist sectors: on the one hand, wind engineering and, on the other hand, building design and urban planning. Urban ventilation is expressed in terms of the mean wind speed ratio that, in the past, proved to be a useful indicator for this kind of analysis [19–21,38–41]. An overview of indicators commonly employed in urban ventilation studies is provided in Section IV_2.3. Relations between each MP and the spatially averaged mean wind speed ratio at pedestrian level and 10-m height are discussed, and correlations obtained using linear regression analysis are provided. CFD is used for this investigation because it allows full control over the boundary conditions and provides information on the flow within the entire domain without suffering from potential problems due to similarity requirements [42].

IV_2 Literature review on morphological parameters and performance indicators

This section reports a review of studies on urban ventilation highlighting: the morphological parameters used for generic configuration (Section IV_2.1), the morphological parameters used for actual urban areas (Section IV_2.2), and the performance indicators (Section IV_2.3).

IV_2.1 Literature review of morphological parameters for generic urban geometries

Simplified models are usually composed of generic building geometries forming idealized urban structures. They are usually represented by 2D and 3D urban canyons (UCs) and 3D urban arrays composed of aligned or staggered elements. The simplified model types are selected based on the features of the phenomenon at the local scale under investigation. An overview of morphological parameters used in urban ventilation studies for generic urban configurations is presented in

Table IV_1. In studies performed using 2D UCs, the different urban morphologies are often parameterized using the so-called UC aspect ratio (H/W or height-to-width ratio), hereinafter referred to as AR [43–51], the roof shape [45,49], and the height or height variation [44–46]. Regarding the 3D UCs, besides the AR [7,52–56]; the roof shape [57], the height or height variation [54,58]; the L/W or UC length-to-width ratio [7,54]; and the L/H or UC length-to-height ratio [52,53] are often considered in the parameterization. Moreover, the orientation of the UC compared to the direction of the approaching wind is another important parameter [54]. Finally, in studies using 3D urban arrays, the focus is on: AR [59,60], L/H [60], array layout types [39,61–64], building footprint density expressed in terms of plan area density λ_p (i.e., the ratio between the total area of building footprints and the total land area) [39,59–61,63–70], building height or building height variation [38,60,63–65,69,71–73], frontal area density λ_f (i.e., the ratio between the total projected area of building vertical surfaces facing the approaching wind direction and the total land area) [61,64,65,67,69,74,75], orientation [38,40,72,73,76–78], and canopy roof cover [78].

Table IV_1 - Overview of morphological parameters used in urban ventilation studies for generic urban configurations.

Idealized model types	Morphological parameters	Refs
2D urban canyons	aspect ratio	Sini et al., (1996) [43]; Xie et al., (2005a)[44]; Xie et al., (2005b) [45]; Xiaomin et al., (2006) [46]; Cheng et al., (2008) [47]; Ho et al., (2015) [48]; Badas et al., (2017) [49]; Di Bernardino et al., (2017) [50]; Di Bernardino et al., (2018) [51]
	roof shape	Xie et al., (2005b) [45]; Badas et al., (2017) [49]
	building height or height variation	Xie et al., (2005a) [44]; Xie et al., (2005b) [45]; Xiaomin et al., (2006) [46]
3D urban canyons	aspect ratio	Hunter et al., (1990) [52]; Hunter et al., (1992) [53]; Hang et al., (2010a) [54]; Hang et al., (2010b) [55]; Hang et al., (2012a) [7]; Ai and Mak, (2017) [56]
	roof shape	Llaguno-Munitxa and Bou-Zeid, (2018)[57]
	building height or height variation	Hang et al., (2010a) [54]; Nardecchia et al., (2018) [58]
	length-to-width ratio	Hang et al., (2010a) [54]; Hang et al., (2012a) [7]
	length-to-height ratio	Hunter et al., (1990) [52]; Hunter et al., (1992) [53]
	orientation	Hang et al., (2010a)[54]
3D urban arrays	aspect ratio	Hang et al., (2011) [59]; Hang and Li, (2011) [60]
	length-to-height ratio	Hang and Li, (2011)[60]
	array layout types	Cheng and Castro, (2002) [61]; Coceal et al., (2006) [62]; Kanda, (2006) [63]; Hagishima et al., (2009) [64]; Hu and Yoshie, (2013) [39]
	plan area density λ_p	Cheng and Castro, (2002) [61]; Kanda, (2006) [63]; Santiago et al., (2008) [67]; Hagishima et al., (2009) [64]; Buccolieri et al., (2010) [68]; Hang et al., (2011) [59]; Hang and Li, (2011) [60]; Hu and Yoshie, (2013) [39]; Razak et al., (2013) [69]; Cantelli et al., (2015) [70]; Chen et al., (2017) [65]; Di Bernardino et al., (2020a) [66]
	building height or height variation	Kanda, (2006) [63]; Hagishima et al., (2009) [64]; Yim et al., (2009) [38]; Hang and Li, (2011) [60]; Hang et al., (2012b) [71]; Razak et al., (2013) [69]; Lin et al., (2014) [72]; Hang et al., (2015) [73]; Chen et al., (2017)[65]
	frontal area density λ_f	Cheng and Castro, (2002) [61]; Santiago et al., (2008) [67]; Hagishima et al., (2009) [64]; Razak et al., (2013) [69]; Chen et al., (2017) [65]; Ikegaya et al., (2017) [74]; Di Bernardino et al., (2020b) [75]
	orientation	Soulhac et al., (2009) [76]; Yim et al., (2009) [38]; Amicarelli et al., (2012) [77]; Hang et al., (2013) [78]; Lin et al., (2014) [72]; Hang et al., (2015) [73]; Ramponi et al., (2015) [40]
	canopy roof cover	Hang et al., (2013) [78]

IV_2.2 Literature review of morphological parameters for actual urban areas

Despite the possibility of investigating specific parameters, the simplified models only partially represent the complexity of actual urban areas where different building typologies coexist within the urban tissues. A detailed investigation of the ventilation in actual urban areas is therefore necessary. To the best of the authors' knowledge, there are only a few studies that have investigated the effects of urban morphologies on wind conditions thoroughly using real case studies. Among the others, Kubota et al., (2008) [19] carried out wind tunnel experiments for 22 cases representing actual residential neighborhoods in Japan, Yang et al., (2013) [20] conducted field measurements in 10 residential sites in Shanghai, China and Tschritzis and Nikolopoulou (2019) [21] performed numerical simulations for 24 cases taken from the Greater London area. Specifically, Kubota et al., (2008) [19] studied the correlation between building density and spatially averaged wind velocity at the pedestrian level. The building density was expressed in terms of gross building cover ratio (equivalent to λ_p) and gross floor area ratio (the ratio between the total area of building levels and the total land area). As for the ventilation, the wind velocity ratio, i.e., the ratio between the wind velocity measured at the height of interest, in this case the pedestrian level, and that at a reference height, was used for the assessment. Focusing separately on detached and apartment buildings, they found a strong correlation between λ_p and the wind velocity ratio for values of λ_p between 0.1 and 0.34. Yang et al., (2013) [20] instead analyzed the correlation between the pedestrian-level wind velocity ratio and the urban density, quantified by λ_p , the sky view factor, the tree view factor, and the green plot ratio. They concluded that the pedestrian-level wind velocity ratio is significantly correlated with the density of the urban sites, highlighting the necessity to test their results under a more strictly controlled experimental environment. Finally, Tschritzis and Nikolopoulou (2019) [21] analyzed the correlation between urban morphology and

pedestrian wind comfort. They quantified the urban morphology using four parameters: the mean building height, the maximum building height, the standard deviation of the building height, and the façade area ratio. The pedestrian wind comfort was evaluated using wind comfort criteria by performing numerical simulations for eight wind directions. Among the different morphological indicators, the façade area ratio has a dominant impact on the mean wind speed ratio and the percentage of outdoor space that is comfortable for certain activities.

IV_2.3 Literature review of performance indicators in urban ventilation studies

In the last decade, the spatially averaged wind velocity ratio (wVR) has been proven as a useful indicator for evaluating urban ventilation. Among different purposes, it has been used for:

- investigating the relevance of different morphological parameters or building characteristics in aligned and staggered buildings arrays [39,69,72,79–81];
- analyzing the pedestrian comfort related to low wind speed [41];
- evaluating computational settings [56];
- supporting optimization procedures [82–85].

Besides spatially averaged wind velocity ratios, other indicators and methodologies have been employed for investigating the aerodynamic response of urban areas through:

- the description of the exchange between in-canopy and above-canopy flows [65,86,87];
- the analysis of pollutant concentration fields [88–91];
- the evaluation of drag and pressure coefficient [63,64,67,92–94];
- the application of indices mainly developed for indoor ventilation studies [95] and eventually modified for outdoor investigations, e.g., air

exchange rate, visitation frequency, residence time, purging flow rate, age of air, etc. [7,34,40,47,54,55,59,60,68,71–73,78,95–105].

IV_3 Description of the case study

To evaluate the impact of morphological parameters on urban ventilation, a large compact area in Rome is selected, i.e., the Tuscolano-Don Bosco district. The Tuscolano-Don Bosco district is chosen as an example of a compact city in a Mediterranean climate. Details of the meteorological conditions typically observed in the Roman area can be found in Monti and Leuzzi (2005) [106]; Pelliccioni et al., (2015) [107]; Di Bernardino et al., (2021a) [108]. This section introduces the characteristics of the Tuscolano-Don Bosco district, including information about the building typologies and urban morphologies present in the area, and describes the parameters used for the morphological analyses.

IV_3.1 Area of interest

The Tuscolano-Don Bosco district in Rome is chosen as a case study for investigating the impact of urban morphology on ventilation. The Tuscolano-Don Bosco district can be considered representative of a compact city in the Mediterranean area in terms of its morphological and typological characteristics. The district is located in the South-East part of Rome (41°51'25.1" N 12°33'43.5" E), 6 km from the city center (identified with the Colosseum in Fig. IV_1a), and around 5 km from the Ciampino airport (Fig. IV_1a). Apart from an original nucleus dating back to the early 20th century, the neighborhood quickly developed in the aftermath of the World War II to respond to the urgent need for housing. Consequently, the district became one of the most densely populated in the city, with about 10,000 people per km² [109], with an average λ_p above 0.3. The boundaries of the area of interest within the district are well defined (Fig. IV_1b): on the North by Centocelle park, on the North-East by Torre Spaccata park, on

the East by the commercial-administrative pole of Cinecittà, on the South degli Acquadotti park, and on the West by the railway and the Quadraro neighborhood.

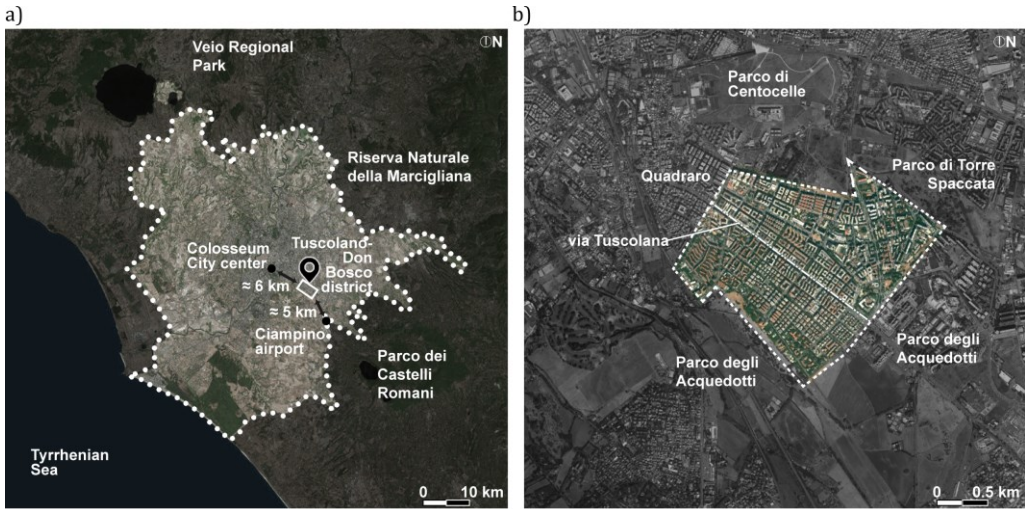


Fig. IV_1 - (a) Map of Rome, including the Tuscolano-Don Bosco district location (white rectangle), (modified from Geoportale Italiano); and **(b)** detailed map with indication of the urban area modeled explicitly in the computational domain (white dotted line), (modified from Google Earth 2009).

The district developed according to an orthogonal grid along the main street, via Tuscolana, which represents the backbone of the entire district (Figs. IV_1b-2). The longitudinal axis of this street is oriented at an angle of 40° to the South. Therefore, it is possible to identify two sub-areas: one in the North and the other in the South of via Tuscolana. The former is characterized by higher buildings, larger public spaces (squares and boulevards), and longer UCs compared to the latter (Figs. IV_2a). Moreover, the urban morphologies in the northern area are more compact, with a predominance of towers and courtyards. Furthermore, the presence of podiums hosting commercial activities occupying the first 4-8 m of the buildings is very common in this area. The morphologies belonging to the southern area, instead, can be referred to as open with a prevalence of multi-story slabs, pavilions, and “palazzina”, a characteristic building typology of Rome similar to the

pavilion but with fewer stories. Overall, the district is mainly composed of narrow streets with $0.7 < AR \leq 2.5$. The building height varies significantly according to the different typologies within the district; the mean height is above 20 m, while its maximum is about 40 m. A scarce presence of vegetation is registered. All the above-mentioned morphological characteristics are typical of the so-called Mediterranean compact city [110].

In order to conduct a detailed and systematic investigation, it has been decided to analyze the airflow in portions of the area of interest, hereinafter called areas of investigation (AIs). The constraints imposed for the selection of the AIs are (i) circular shape; (ii) the presence of at least one row of buildings around the AI for every wind direction analyzed [111,112]; (iii) a sufficient number of cases “randomly” chosen, from a morphological point of view, i.e., the AIs should present inhomogeneous morphologies. Since very long urban canyons (above 200 m long) are present in the northern sub-area, it has been decided to work with AIs of 300 m (total number of AIs equal to 12) and 250 m radius (total number of AIs equal to 19) in order to avoid that the urban canyon length will interfere significantly with the results. The centers of the AIs are aligned on orthogonal grids (one for 250 m and one for 300 m radius AIs) and generally placed every 200 m both longitudinally and transversally. Figure IV_2 shows a grey-scale map of building heights, including the locations of every AI center: red cross for 250 m radius AIs and iced blue for 300 m radius AIs.



Fig. IV_2 - (a) Map of the height [m] of the buildings modeled in the domain with the locations of the center of the AIs; plan view of the 31 AIs considered in the study with **(b)** 300 m radius and **(c)** 250 m radius.

IV_3.2 Urban morphological parameter

The calculation of the MPs describing real cities is a nontrivial task because of the complexity of the urban textures [113–116]. Since this study aims at assessing the impact of the urban morphology on the ventilation within a real compact urban area, the first step of the investigation is the identification of MPs and their combinations, able to describe the different morphologies and quantify the building density and the vertical structures of cities. Among the MPs generally employed in urban canopy studies, it is chosen not to use directional parameters because this study aims at providing a prediction model to be used in the early stage of the design. Therefore, MPs used by practitioners and urban planners, which are usually non-directional, seem to be the best choice. Specifically, the MPs used in this study are: the plan area density λ_p , the mean building height (H_m), the root mean square of the building heights (H_o), the median of the building heights (H_{med}), the area-weighted mean building height (H_{aw}), the volume density λ_{vol} (i.e., the ratio between total building volume and total land surface) and the façade area density $\lambda_{faç}$ (i.e., the ratio between total building vertical surfaces and total land area). Figure IV_3 presents the building characteristics of interest and some of the MPs used in the present study. Note that the façade density $\lambda_{faç}$ is different from the frontal area density λ_f because the former is the ratio between the building façade area and the land area, while the latter is the ratio between the projected area of building façades facing the wind and the land area. H_{aw} has been introduced as a possible alternative to more consolidated parameters such as H_m , H_o , and H_{med} to take the presence of the podiums that characterize the area of interest better into account. The morphological analyses have been carried out using two versions of the open-source GIS software QGIS [117], namely v. 2.14 and 3.2.3. The primary data are the open data provided by the regional authority [118] and consist of information about the footprint area and the elevation above sea level of the foot and the top of every building. The quality of the raw data has been checked for the entire

modeled area, and, when necessary, field surveys have been conducted. The raw data have been processed to extract information about land area, building footprint area, and building height. Then, several algorithms and scripts have been used to combine the basic information in order to calculate the selected morphological parameters.

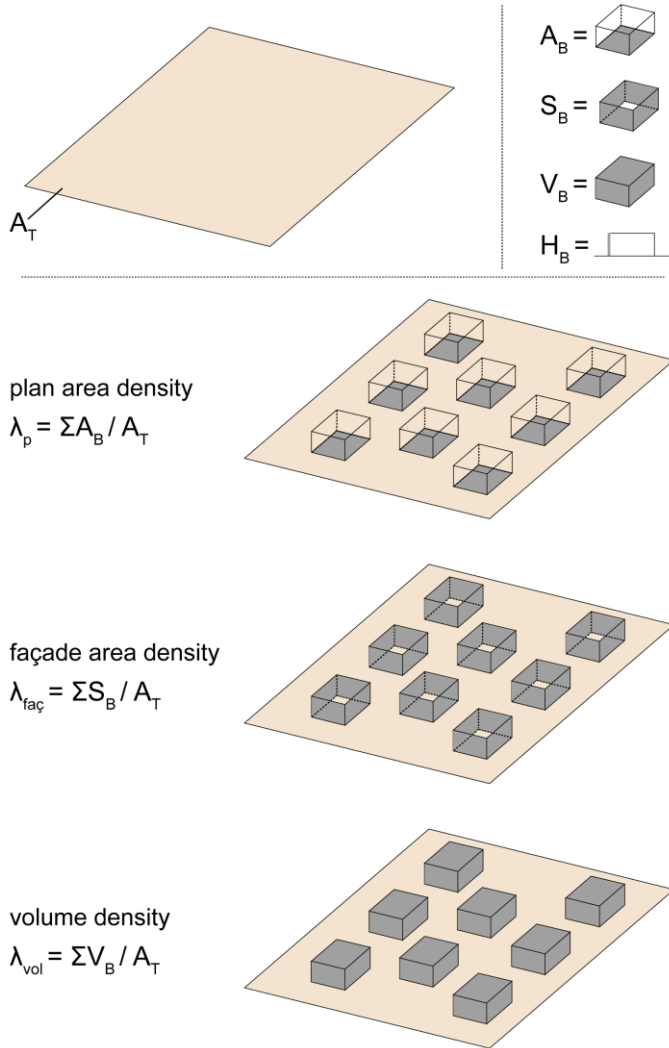


Fig. IV_3 - Building characteristics and main morphological parameters used for characterizing the urban area: A_T : total area, A_B : building footprint area, S_B : building façade area, V_B : building volume, and H_B : building height.

Table IV_2 reports the values of the 7 MPs calculated for the 31 AIs. Note that λ_p ranges between 0.25 and 0.38, which is suggested by Oke as a suitable range to exclude the worst effects in terms of not providing shelter and not facilitating pollutant dispersion inside UCs [119]. It is possible to divide the AIs into three groups based on the position of their centers in relation to via Tuscolana, i.e., N=North, S=South, T=on via Tuscolana. The presence of via Tuscolana and larger squares and boulevards in the northern area is evident by analyzing λ_p for each group. The average values of λ_p are 0.32 for the N-group, 0.35 for the S-group, and 0.34 for the T-group; the maximum values are 0.37, 0.38, and 0.37, respectively, while the minimum values are 0.25, 0.32, and 0.26, respectively. Regarding H_m , the average values are 17.8 for the N-group, 18.7 for the S-group, and 18.3 for the T-group. Therefore, the S-group presents the highest value. Conversely, considering the average values of H_w , the T-group shows the highest value. In fact, the average values are 22.5 for the N-group, 22.2 for the S-group, and 23.5 for the T-group. The discrepancy between H_m and H_w may be due to podiums hosting commercial activities along via Tuscolana and in the northern area. This feature may also be confirmed by analyzing H_o , the average values of which are 10.2 for the N-group, 8.3 for the S-group, and 9.8 for the T-group.

Table IV_2 - List of the morphological parameters calculated for each AI: radius of the AI (r), position of the AI center in relation to via Tuscolana (N=North, S=South, T=on via Tuscolana), number of buildings ($\#_B$), plan area density (λ_P), mean building height (H_m), root mean square of the building heights (H_σ), the median of the building heights (H_{med}), area-weighted mean building height (H_{aw}), volume density (λ_{vol}), and façade density ($\lambda_{faç}$).

AIs	r [m]	Center	$\#_B$	λ_P	H_m	H_σ	H_{med}	H_{aw}	λ_{vol}	$\lambda_{faç}$
A ₁	300	N	149	0.34	15.87	10.33	18.00	23.27	7.93	1.49
B ₁	300	N	159	0.35	17.16	11.21	21.00	24.66	8.63	1.63
C ₁	300	N	146	0.33	17.70	11.62	21.00	25.10	8.36	1.54
D ₁	300	N	133	0.33	18.59	10.90	21.00	23.07	7.66	1.41
E ₁	300	N	131	0.32	17.21	10.44	21.00	22.03	7.05	1.29
F ₁	300	N	104	0.30	17.72	11.66	18.00	21.23	6.43	1.17
G ₁	300	N	95	0.29	18.49	9.16	21.00	19.59	5.61	1.02
H ₁	300	S	180	0.32	18.80	8.01	21.00	21.28	6.76	1.44
I ₁	300	S	223	0.34	19.10	8.69	21.00	23.91	8.17	1.78
J ₁	300	T	218	0.35	19.20	9.69	21.00	24.82	8.76	1.80
K ₁	300	T	188	0.37	18.20	10.80	21.00	24.38	8.97	1.69
L ₁	300	S	241	0.36	18.44	9.48	21.00	23.53	8.44	1.70
A ₂	250	N	106	0.37	14.92	10.87	10.00	23.24	8.49	1.55
B ₂	250	N	117	0.35	15.76	11.31	10.00	24.58	8.62	1.65
C ₂	250	N	93	0.33	17.87	12.07	24.00	25.55	8.45	1.56
D ₂	250	N	80	0.32	18.56	11.13	21.00	25.07	7.95	1.44
E ₂	250	N	79	0.32	16.73	9.78	18.00	21.07	6.78	1.24
F ₂	250	N	76	0.30	18.04	9.52	24.00	22.71	6.82	1.25
G ₂	250	N	68	0.30	17.07	9.87	16.50	17.09	5.05	0.91
H ₂	250	N	80	0.27	17.99	7.89	21.00	16.73	4.49	0.93
I ₂	250	N	79	0.25	21.00	8.41	24.00	19.87	4.91	1.01
J ₂	250	S	109	0.32	18.25	8.08	21.00	20.60	6.56	1.30
K ₂	250	N	148	0.33	19.17	8.56	21.00	23.90	7.97	1.71
L ₂	250	N	142	0.36	20.81	9.46	24.00	25.47	9.25	1.85

AI _s	r [m]	Center	# _B	λ_P	H _m	H _{σ}	H _{med}	H _{aw}	λ_{vol}	$\lambda_{fa\grave{c}}$
M₂	250	T	148	0.37	18.20	11.04	21.00	24.86	9.23	1.83
N₂	250	T	124	0.36	16.98	10.92	21.00	24.01	8.65	1.62
O₂	250	T	114	0.26	18.80	6.52	21.00	19.53	5.06	1.12
P₂	250	S	201	0.35	18.85	8.15	21.00	22.82	7.92	1.78
Q₂	250	S	183	0.36	18.62	9.46	21.00	23.55	8.46	1.72
R₂	250	S	162	0.38	18.95	9.24	21.00	22.11	8.48	1.64
S₂	250	S	170	0.36	18.69	5.54	19.50	19.70	7.14	1.38

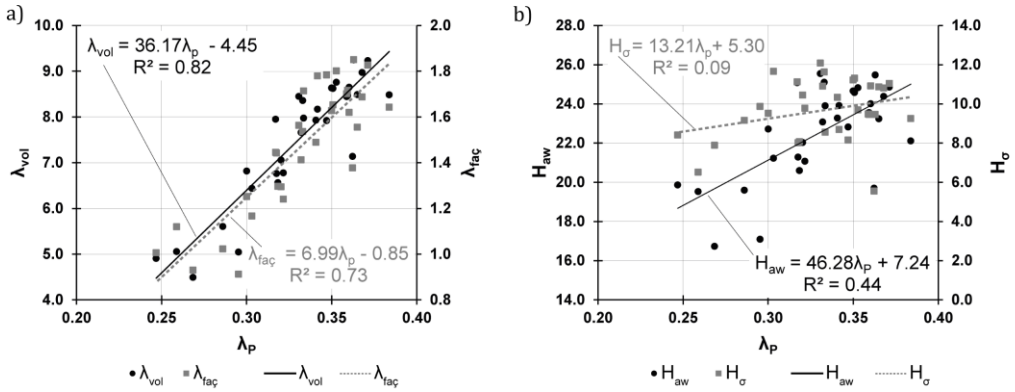


Fig. IV_4 - (a) Volume density (λ_{vol} , black circles) and façade density (λ_{fac} , grey squares) as a function of plan area density (λ_P); **(b)** area-weighted mean building height (H_{aw} , black circles) and root mean square of the building height (H_σ , grey squares) as a function of plan area density (λ_P).

Figure IV_4a shows the relations λ_P - λ_{vol} and λ_P - λ_{fac} , which highlight interesting characteristics of the building typologies of the Tuscolano-Don Bosco district. The two relations exhibit a strong correlation and monotonically increasing trends. The strong correlations and the absence of outliers are a consequence of the building characteristics as dictated by the different typologies present in the AIs, which are typical of the compact Mediterranean city. The increasing trends are the signature of the absence of typologies like skyscrapers or malls, which would result in low values of λ_P for large values of λ_{vol} and λ_{fac} or large values of λ_P for low values of λ_{vol} and λ_{fac} , respectively. These typologies, present in many contemporary cities, are not typical of the Mediterranean compact city. Therefore, it is possible to conclude that the chosen MP relationships can quantitatively and qualitatively describe the different morphologies present in the area of interest. Specifically, they not only report quantities about the building density, volume, and façade but can also provide insights into the building typologies present in the area as they correlate information regarding three densities, i.e., plan area density, λ_P , volume density, λ_{vol} , and façade area density, λ_{fac} . Another important characteristic to consider is the building height. This characteristic, if quantified using a set of indices like in this case, can provide information about the characteristics of the area, as explained

above. However, unlike building volume and building façade, the building height is usually regulated by codes, and therefore correlations with the plan area density may be low, like in this case (Fig. IV_4b).

IV_4 CFD simulations

The present study investigates the ventilation in a large compact area in Rome, the Tuscolano-Don Bosco district, performing 3D steady-state Reynolds-averaged Navier-Stokes simulations. This section presents details about the computational domain and grid, the imposed boundary conditions, and the chosen solver settings.

IV_4.1 Computational geometry and grid

The computational domain is built according to the best practice guidelines [8,112,120,121]. Consequently, the height of the domain is equal to $6H_{max}$, where $H_{max} = 40$ m is the height of the tallest building in the area. Furthermore, special care is given to allow the full development of the wake region irrespective of the wind direction. Therefore, the plan area of the computational domain is $5000 \text{ m} \times 5000 \text{ m}$, while the height is 240 m (Fig. IV_5a).

Over 1,500 buildings belonging to the area of interest are modeled explicitly. The computational grid is generated using the surface-grid extrusion technique presented by van Hooff and Blocken (2010) [122], which allows a large control of the grid quality. The grid consists of only hexahedral cells to avoid possible convergence problems associated with steady RANS simulations when second-order discretization schemes are used [8]. The non-conformal grid technique with a 1:2 ratio [123] is applied in order to provide a detailed representation of the buildings and limit the number of grid cells. Consequently, the domain is divided into three parts (Fig. IV_5b), where the core, region $\mathcal{A}$, represents the area of interest. Here, the buildings are modeled explicitly, i.e., with their actual shape and size, with high resolution down to details of 0.5 m (Fig. IV_5b), while small façade

and roof details are not included. Moreover, other urban elements, such as sidewalks, gardens, barriers, etc., are implicitly modeled by means of the corresponding values of the aerodynamic roughness length, z_0 [124], converted to equivalent sand grain roughness height, k_s [121]. In regions *B* and *C*, the grid is coarser, but the growth ratio remains below 1.3 as recommended by the guidelines, e.g., [112,120]. All the urban elements, buildings included, are modeled implicitly using z_0 .

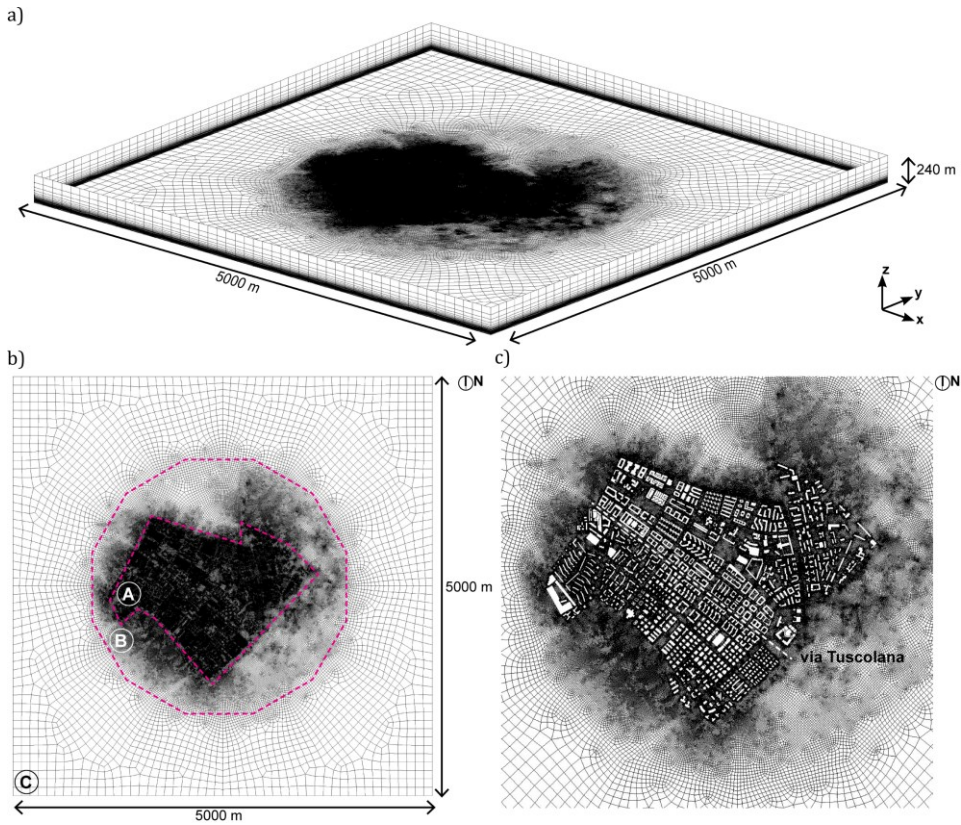


Fig. IV_5 - (a) Axonometric view of the computational grid; **(b)** top view of the computational grid with non-conformal interfaces highlighted; **(c)** top view of the area of interest at 3 m height. The total cell count is about 86 million.



Fig. IV 6 - Perspective view of: (a) the area of interest (modified from Google Maps); (b) the computational grid and (c) its enlargement. The total cell count is about 86 million.

In accordance with the recommendations by Franke et al., (2007) [120] and Tominaga et al., (2008) [112] regarding the evaluation of the pedestrian wind environment, the pedestrian level (1.8 m) is above the third cell layer. The resulting grid consists of about 86 million hexahedral cells (Fig. IV_5, 6). Note that a separate grid independence analysis for the case study grid is not performed, but instead, in line with the vast majority of CFD studies for large urban areas (e.g., [24,26,30–32,34,35,37,125–130]) and in agreement with the published best practice guidelines for such simulations, the grid resolution and grid topology of the case study are based on:

- General best practice guidelines for grid generation [131,132], such as those on cell orthogonality and wall-adjacent cell faces that should be either perpendicular or parallel to the adjacent wall;
- Specific best practice guidelines for studies on wind flow around buildings [112,120,121], such as the minimum grid resolution of 10 cells along every building edge and across every passage between adjacent buildings;
- The grid resolution as resulting from the sub-configuration study (see Appendix A), where a grid independence analysis was performed.

IV_4.2 Boundary conditions

Since the simulations refer to neutral atmospheric conditions, the classical logarithmic law (e.g., [133]) for the vertical profile of the wind velocity, U , is used at the inlet:

$$U(z) = \frac{u_*}{\kappa} \ln \left(\frac{z+z_0}{z_0} \right) \quad \text{IV_1}$$

while Eqs. (A.3) and (A.4) are employed to set k and ε , respectively. The simulations are performed for 12 wind directions, equally spaced every 30° , starting from North (0°). A wind speed of 3 m/s at 10 m height is imposed at the inlet. The aerodynamic

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roughness length z_0 is estimated based on the Davenport-Wieringa roughness classification [124] for each wind direction according to the land use map [134]. Three different values of z_0 are used to model the urban area upwind of the domain: 0.25 m, 0.5 m, and 1.0 m. At the top of the domain, a symmetry boundary condition is applied, while zero static gauge pressure or symmetry boundary conditions are imposed at the domain sides, depending on the wind direction. For the bottom of the domain and the building surfaces, the standard wall functions by Launder and Spalding (1974) [135] with roughness modification by Cebeci and Bradshaw (1977) [136] are used. Specifically, four different classes are considered to model the urban surface: open ($z_0 = 0.03$ m), rough ($z_0 = 0.25$ m), very rough ($z_0 = 0.50$ m), and closed ($z_0 = 1.00$ m). The corresponding values of the roughness parameters, i.e., the sand-grain roughness height k_s (m) and the roughness constant C_s , are determined using their consistency relationship with the aerodynamic roughness length z_0 derived by Blocken et al. (2007) [121]:

$$k_s = \frac{9.793 \times z_0}{C_s} \quad \text{IV_2}$$

Smooth wall conditions are imposed at the building surfaces ($k_s = 0$ and $C_s = 0.5$).

IV_4.3 Solver settings

The same solver settings as in the validation study are applied. The validation study is reported in Appendix A. The 3D steady RANS equations are solved in combination with the realizable k - ε model [137] using Ansys Fluent 16.2 [138]. For pressure-velocity coupling, the SIMPLE algorithm is used, and second-order discretization schemes are applied. Finally, every simulation is run for 12,000 iterations and is terminated when the scaled residuals do not show any further reduction with an increasing number of iterations. The following minimum values are reached: 10^{-5} for continuity and ε , 10^{-4} for k , and 10^{-7} for x -, y - and z -velocity.

IV_5 Results and discussion

This section analyzes the relationships between the spatially averaged mean wind velocity ratio and the urban MPs considering the 12 wind fields simulated as described in section IV_4.2. Two non-dimensional mean wind velocity ratios are used for the analysis, i.e., $\gamma_p = U_p/U_{ref}$ and $\gamma_{10} = U_{10}/U_{ref}$. Here, U_p and U_{10} are the values at the pedestrian level ($z_p = 1.8$ m) and half of the average UC height ($z_{10} = 10$ m), respectively, while U_{ref} is the mean velocity magnitude set at z_p at the inlet plane. Both ratios, which quantify the reduction in wind velocity caused by the urban canopy, are spatially averaged over each of the 31 AIs and then averaged over the 12 simulations (one for each wind direction imposed at the inlet). As mentioned earlier, this choice is due to the fact that MPs used by practitioners and urban planners are not directional. Furthermore, the averaging procedure should minimize unwanted effects associated with the directional (and, therefore, local) characteristics of the AIs.

Note that the non-dimensional wind velocity, when employed for investigating the relationship between urban morphology and urban ventilation in idealized urban textures, is usually estimated considering only one building typology. However, using a simplifying assumption, such as idealized urban textures with only one building typology, may not be acceptable in actual urban areas like the one considered in the present analysis, where the 31 AIs show different morphological characteristics.

IV_5.1 Model comparison with Kubota et al.'s experiments

Initially, some of the results are compared with those by Kubota et al., (2008) [19], who conducted a series of experiments in the wind tunnel at the Niigata Institute of Technology for 22 case studies representing 270×270 m² actual urban areas referring to major Japanese cities. The wind velocity was measured at approximately 50 points placed uniformly around the buildings in each area. Figure IV_7 shows

γ_p as a function of λ_p for all the 31 AIs in the present study (red solid squares: 300-m radius; red open squares: 250-m radius) and for the apartment-house types from Kubota et al., [19] (black crosses). The first characteristic to highlight is that γ_p decreases monotonically with λ_p , i.e., there is an overall decrease in mean velocity for larger building densities. The γ_p trend emerging from the present CFD study is in good agreement with that found by Kubota et al., (2008) [19], even though the data show a less strong correlation probably due to the higher level of inhomogeneity of the urban morphology in the present study, as indicated by the coefficient of determination (R^2). This agreement supports the CFD results and the methodology adopted in this work. Note that 250-m and 300-m cases exhibit similar behavior. This suggests that the λ_p - γ_p relationship is independent of the AI radius used for its determination.

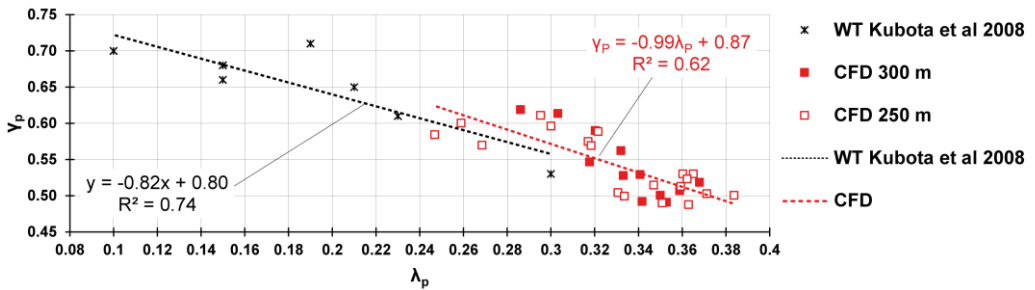


Fig. IV_7 - γ_p versus λ_p . Solid and open red squares refer to γ_p obtained for the 31 AIs using the CFD data, while crosses denote γ_p based on wind-tunnel experiments by Kubota et al., (2008) [19].

IV_5.2 Impact of morphological parameters on γ_p and γ_{10}

The urban ventilation is explored by analyzing γ_p and γ_{10} , computed for 300-m and 250-m radii, as a function of λ_p , H_{av} , λ_{vol} , λ_{fac} , and λ_{fac}/λ_p . Figure 8 shows the relationships between each MP and γ_p and γ_{10} . For each MP- γ_p and MP- γ_{10} relation, a simple model obtained using linear regression analysis is derived, indicating the correlation between the two variables by means of R^2 .

Figure IV_8a compares γ_p and γ_{10} as a function of λ_p . γ_p decreases monotonically with increasing λ_p , ranging from 0.62 to 0.49 with 0.54 as a mean value. This suggests that pedestrians experience, on average, a mean wind speed reduced by a factor of 0.54 with respect to the undisturbed velocity outside the city. On the other hand, γ_{10} falls in the 0.50-0.80 range, with 0.60 as a mean value and a larger deviation, above 37%. However, for $\lambda_p > 0.33$, the two wind speed ratios tend to converge, i.e., $U_p \sim U_{10}$ for denser urban tissues and narrower canyons. Another salient feature is the abrupt reduction in γ_p and γ_{10} observed for $\lambda_p = 0.33$, where the latter seems to represent a sort of threshold value. In fact, λ_p no longer plays a significant role for $\lambda_p > 0.33$ (at least for the considered λ_p range). Note that for $\lambda_p < 0.33$, the data points are mainly placed above the trend line, while the opposite happens for $\lambda_p > 0.33$. This characteristic will be discussed further in the next subsection. The models derived for λ_p - γ_p and λ_p - γ_{10} are:

$$\gamma_p = -0.99\lambda_p + 0.87 \quad \text{IV_3}$$

$$\gamma_{10} = -1.99\lambda_p + 1.26 \quad \text{IV_4}$$

with $R^2 = 0.62$ and $R^2 = 0.63$, respectively. As already found by Kubota et al., (2008) [19], there is a strong linear relationship between λ_p and γ_p . The results reported in the present work show that a strong linear relationship also exists between λ_p and γ_{10} .

The impact of the building height variation on urban ventilation is assessed using H_m , H_σ , H_{med} , and H_{av} . Among these four MPs, the latter shows the strongest correlation with both γ_p and γ_{10} . For this reason, only the results related to H_{av} are displayed in Fig. IV_8b, while the results related to H_m , H_σ , and H_{med} can be found in Appendix B. However, among the five key MPs in this section, λ_p , H_{av} , λ_{vol} , λ_{fac} , and λ_{fac}/λ_p , H_{av} is the one that shows the weakest correlation, especially at the

pedestrian level ($R^2=0.48$). Therefore, it has been decided not to report the models shown in Fig. IV_8b.

The dependence of the reduction in mean wind velocity ratio is apparent also for increasing λ_{vol} for both the pedestrian level and the 10-m height (Fig. 8c). γ_p decreases as the volume density increases and, for large values of λ_{vol} , γ_p and γ_{10} tend to converge onto 0.5. The models derived for λ_{vol} - γ_p and λ_{vol} - γ_{10} are:

$$\gamma_p = -0.03\lambda_{vol} + 0.74 \quad IV_5$$

$$\gamma_{10} = -0.05\lambda_{vol} + 1.01 \quad IV_6$$

with $R^2 = 0.68$ and $R^2 = 0.75$, respectively.

Fig. IV_8d reports the values of γ_p and γ_{10} as a function of λ_{fac} . A remarkable correlation for both λ_{fac} - γ_p and λ_{fac} - γ_{10} relations is observed. The two trends decrease monotonically as λ_{fac} increases and converge onto 0.50 for $\lambda_{fac} \sim 1.8$. R^2 is 0.82 and 0.89 for γ_p and γ_{10} , respectively. The fact that the best correlation occurs for λ_{fac} may be explained by considering the nature of this parameter, which carries information on both the building height and the perimeter of the building footprint. This finding is in line with the results of previous studies [21] and corroborates the methodology adopted in this work. The models derived for λ_{fac} - γ_p and λ_{fac} - γ_{10} are:

$$\gamma_p = -0.14\lambda_{fac} + 0.74 \quad IV_7$$

$$\gamma_{10} = -0.29\lambda_{fac} + 1.03 \quad IV_8$$

Finally, Figure IV_8e shows the dependency of γ_p and γ_{10} on λ_{fac}/λ_p . The corresponding models are:

$$\gamma_p = -0.06 \frac{\lambda_{fac}}{\lambda_p} + 0.82 \quad IV_9$$

$$\gamma_{10} = -0.14 \frac{\lambda_{fac}}{\lambda_p} + 1.23$$

IV_10

and present a significant correlation being $R^2 = 0.63$ and $R^2 = 0.76$, respectively.

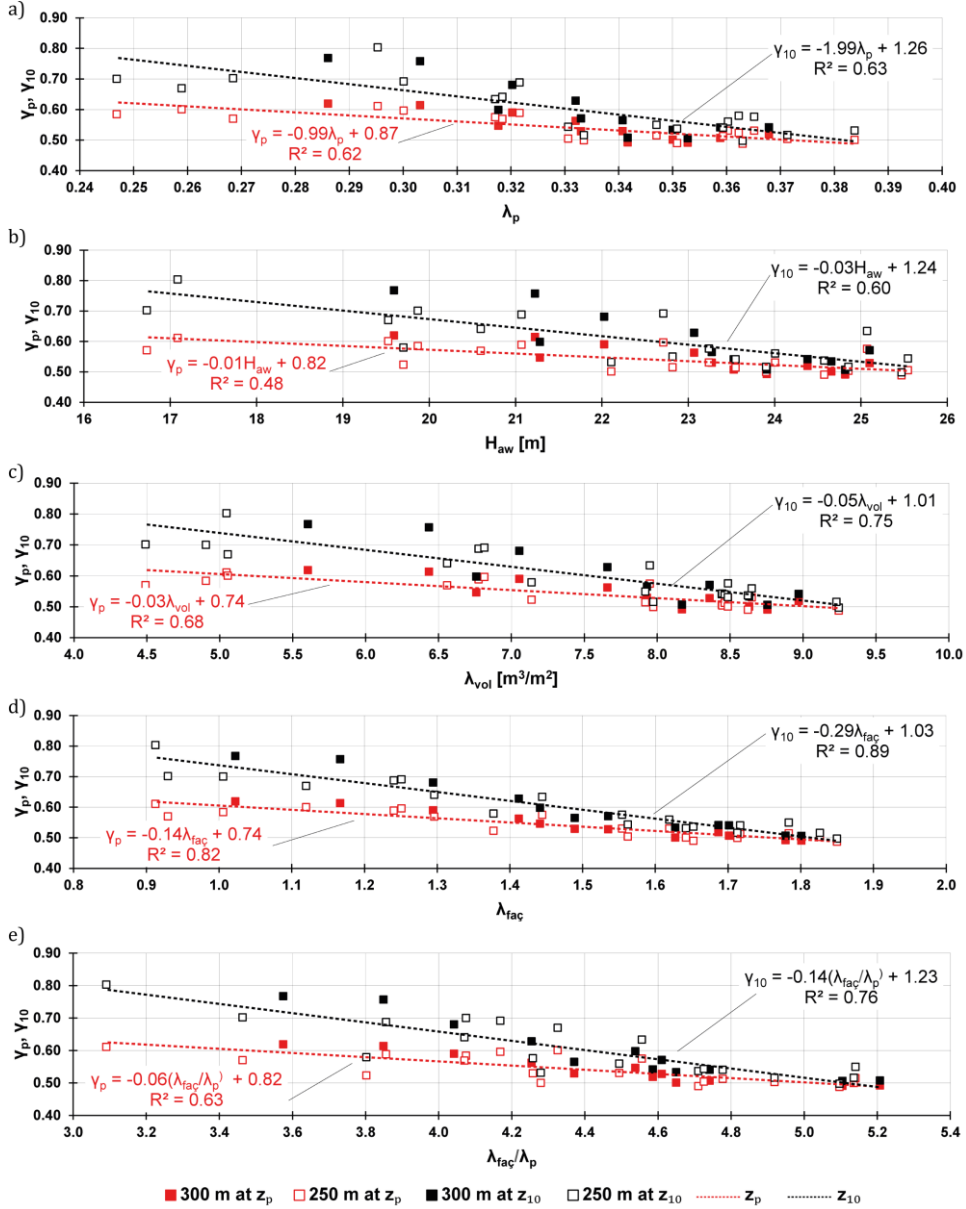


Fig. IV_8 - γ_p and γ_{10} as a function of: (a) plan area density, λ_p ; (b) area-weighted mean building height, H_{aw} ; (c) volume density, λ_{vol} ; (d) façade density, λ_{fac} and (e) λ_{fac}/λ_p .

Overall, four main general observations are made:

- γ_p and γ_{10} clearly depend on all five morphological parameters.
- γ_p and γ_{10} do not depend on the AI radius.
- γ_p and γ_{10} decrease monotonically with increases in the morphological parameters.
- γ_p and γ_{10} tend to share the same value for denser urban tissues, suggesting that the impact of the height on the velocity ratio inside the canyon vanishes.

IV_5.3 Further discussion

Focusing only on the impact of λ_p on γ_p and γ_{10} , three different behaviors in this relation can be distinguished (Fig. IV_9). A first plateau can be identified around $\gamma_p = 0.6$ at pedestrian level ($\gamma_{10} = 0.73$ at $z = 10$ m) for $\lambda_p \leq 0.31$, while a second plateau with $\gamma_p = 0.52$ ($\gamma_{10} = 0.54$) occurs for $\lambda_p \geq 0.34$. Therefore, it is possible to conclude that while for $\lambda_p \leq 0.31$, the difference between γ_p and γ_{10} is significant, for larger λ_p , the difference becomes small, i.e., the height does not play a large role anymore. Around $\lambda_p = 0.33$, an abrupt decrease of γ_p and γ_{10} as a function of λ_p takes place. Therefore, $\lambda_p = 0.33$ might be interpreted as a critical value for the flow regime. This hypothesis is corroborated by the fact that $\lambda_p = 0.33$ is close to $\lambda_p = 0.35$, i.e., the value of the plan area density that is usually considered as the limit between the wake-interference flow (WIF) and the skimming flow (SF) regimes [113]. Previous studies have demonstrated that in the WIF regime, the interaction between the buildings becomes evident (Lee and Soliman, 1977 [92]; Hussain and Lee, 1980 [93]; Oke, 1987 [139]; Oke, 1988 [119]). In fact, the buildings are close enough to each other so that their wakes and the vortices around their sharp edges cannot develop fully and interact with each other. Conversely, it has been demonstrated that in the SF regime, the building density is so large that approaching wind enters into the

canyons with difficulties [93]. In the latter case, the flow skims over the roofs, and stable vortices form in the space between buildings. As a result, in the SF regime, outer and inner flows are decoupled to a large degree, and vertical exchanges of mass and momentum are low. Therefore, the minimal difference between γ_p and γ_{10} for $\lambda_p \geq 0.34$ may be explained as the consequence of the SF regime.

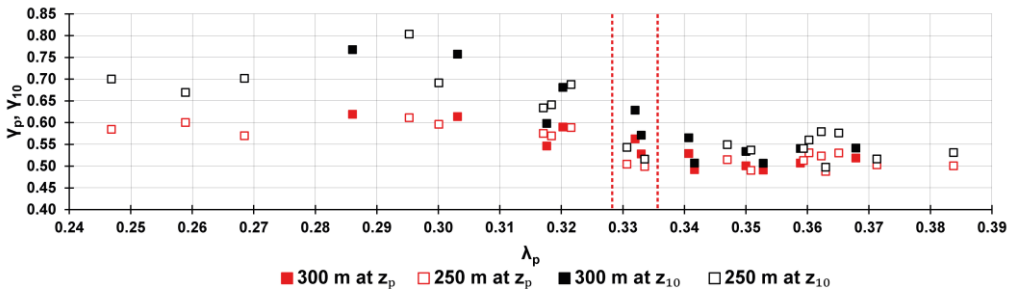


Fig. IV_9 - γ_p versus λ_p . The dashed lines identify the possible range of variation of the critical value for the flow regime change, i.e., from the WIF to the SF regimes.

IV_6 Limitations and future work

The scope of this investigation is the analysis of the impact of morphological parameters on urban ventilation in real compact urban areas. The study is subjected to a number of limitations, which may be addressed in future research:

- Isothermal steady-state RANS simulations are performed to conduct the investigations. The inclusion of thermal effects obtained by modeling solar radiation, long-wave radiation, convection, and conduction should provide additional insights into the phenomenon. Unsteady RANS simulations may be used in a future study to investigate the diurnal variation of temperature and extend the study into the realm of thermal microclimate.
- The focus of this investigation is on real compact urban areas, which are characterized by a range of λ_p between 0.25 and 0.4 (e.g., [69,103,140]). Future analyses should consider a λ_p range wider than that considered in this

work (0.25–0.38) to investigate a wider variety of cases and to extend the range of building densities of the models provided.

- Guided “random” cases without taking into account the different building typologies have been considered in the present analysis. A further step could be to consider only areas of interest with homogeneous morphologies, also quantifying the role played by the single morphologies and building typologies in urban ventilation.
- The goal of the study is to provide simple linear models for evaluating the urban ventilation performance at the early stages of the urban planning and building design processes. The urban ventilation performance has been evaluated using the spatially averaged wVR that, in the last decade, has been proven as a useful indicator in both idealized [69] and actual urban areas [19]. Nevertheless, further developments of the present work may be conducted using the other indicators and methodologies as presented in the literature review.

IV_7 Summary and conclusion

This paper presents a study based on isothermal RANS simulations to investigate the impact of urban morphology on ventilation within a compact area in Rome, Italy. The investigated area is the Tuscolano-Don Bosco district representative of a compact city with a Mediterranean climate. Within the area, 31 AIs complying with three requirements are selected. The requirements imply constraints about the dimensions and the locations of the AIs. Morphological analyses have been carried out using the open-source GIS software QGIS. A set of seven MPs common amongst practitioners, policymakers, and designers are employed to characterize the AIs quantitatively. This choice is motivated by a more general scope of the present study: an attempt to integrate different disciplines, i.e., on the one hand,

building design and urban planning, and, on the other hand, wind engineering, in order to ease the management of the urban environment complexity. The AIs show different morphologies and a range of λ_p between 0.25 and 0.38. These values are in line with those found in the literature and corroborate the choice of Tuscolano-Don Bosco as a case study. Among the MPs, the relations λ_p - λ_{vol} and λ_p - $\lambda_{faç}$ present strong correlations, i.e., $R^2 = 0.82$ and $R^2 = 0.73$, respectively, and may be used to characterize urban areas since they not only report quantities about the building density, volume and, façade but can also provide insights into the building typologies. Regarding the building height, a set of indices, e.g., the mean building height (H_m), the root mean square of the building heights (H_o), the median of the building heights (H_{med}), and the area-weighted mean building height (H_{aw}), may provide information about the characteristics of the area. However, the building height usually is regulated by codes, and, therefore, correlations with other MPs may be low, as in the present case. As indicators for evaluating the ventilation, two non-dimensional mean wind velocities are employed, i.e., $\gamma_p = U_p/U_{ref}$ at pedestrian level and $\gamma_{10} = U_{10}/U_{ref}$ at half of the average UC height. These mean velocities are spatially averaged over each of the 31 AIs and the 12 wind directions considered for the simulations. They can be interpreted as the reduction in mean wind velocity caused by the urban canopy.

The following main conclusions can summarize the work:

- There is a clear dependency of the ventilation indicators on the selected morphological parameters; therefore, simple models obtained using linear regression analysis are derived for each MP- γ_p and MP- γ_{10} relation.
- There is a strong correlation between the building density, λ_p , on the one hand, and γ_p and γ_{10} , on the other hand. The same holds for the volume density, λ_{vol} , and γ_p and γ_{10} , while a remarkable correlation is found for $\lambda_{faç}$ - γ_p and $\lambda_{faç}$ - γ_{10} .

- Among the four MPs related to the height of the buildings, the area-weighted mean building height, H_{aw} , shows the strongest influence on urban ventilation. Nevertheless, its influence is the weakest compared to the other selected MPs: λ_p , λ_{vol} , λ_{fac} , and λ_{fac}/λ_p .
- $\lambda_p = 0.33$ might be interpreted as a critical value for the flow regime change, i.e., from the WIF to the SF regimes.

Finally, the present methodology is proven to be suitable for evaluating the ventilation performance for urban areas characterized by different morphologies, dimensions, and locations. The MPs adopted seem promising to be embedded in the wind environment description, in particular at the pedestrian level. In fact, once the reference velocity is known (e.g., the one measured at the airport weather station closest to the considered site), the linear equations for γ_p yield an estimate of the mean wind speed at the pedestrian level without any need to run the simulation. This characteristic makes the parameters suitable for urban ventilation assessment in the early stages of the design process. Therefore, the provided linear models can be valuable tools for practitioners, urban designers, and policymakers, particularly during the first stage of urban regeneration planning, for highlighting areas potentially vulnerable to poor air conditions without running computationally expensive simulations.

A. Appendix

A.1 Sub-configuration validation

Validation is fundamental to demonstrate the accuracy and reliability of CFD results. In the present work, the “sub-configuration validation procedure” has been employed. This procedure entails the identification of simplified test cases that include the salient features of the actual problem of interest [120,141,142]. Since the focus of the study about the actual urban area is on mean wind velocity at different heights within urban canyons, the validation study should be performed using sub-configurations that provide experimental results at several locations at different heights within the urban canyon. For this purpose, the work by Soulhac et al., (2009) [76] is selected.

A.2 Wind-tunnel experiments

The CFD validation study is carried out using the wind tunnel (WT) measurements provided by Soulhac et al., (2009) [76], who performed an experimental investigation on the complex flow patterns within street intersections. The experiments were conducted in the closed-circuit atmospheric boundary layer WT of the Laboratoire de Mécanique des Fluides et d’Acoustique (LMFA) at the Ecole Centrale de Lyon, France. The WT has a rectangular cross-section of 3.7 m in width and 2.5 m in height with a length of 14 m. The urban geometrical model used in the experiments was composed of 16 parallelepipeds ($0.5\text{ m} \times 0.5\text{ m}$ in plan and height, H , equal to 0.1 m) placed with a constant spacing ($S = 0.1\text{ m}$) and representative of an urban arrangement where streets intersect each other orthogonally (Fig A_1a). This configuration generated UCs with $AR = 1$ and length $L = 5H$. The 1:200 reduced-scale building models corresponded to buildings of $100\text{ m} \times 100\text{ m} \times 20\text{ m}$ in full scale. Therefore, the modeled urban arrangement could be considered representative of the real case study in terms of $AR (= 1)$, mean

building height ($= 20$ m), size of the islands, and orthogonal arrangement. Irwin spires and roughness elements distributed over the upstream fetch of the test section were used in order to generate a neutrally stratified, turbulent boundary layer. The approach-flow profile of the mean velocity was nearly logarithmic:

$$U(z) = \frac{u_*}{\kappa} \ln \left(\frac{z-d}{z_0} \right) \quad A_1$$

where $\kappa = 0.42$ is the von Karman constant, z the vertical coordinate, $u_* = 0.27$ m/s the friction velocity, $d = 0.02$ m the displacement height, and $z_0 = 0.0027$ m the aerodynamic roughness length.

The velocity components along the streamwise and vertical (z -axis) directions were measured at five transversal (y -axis) locations ($y_1 = -0.6H$, $y_2 = -0.8H$, $y_3 = -1.4H$, $y_4 = -2.2H$, $y_5 = -3H$) along the second canyon using a two-component Laser Doppler Anemometry system (Fig A_1a, b). Further details on the experimental setup and flow characteristics can be found in Soulhac et al., (2009) [76].

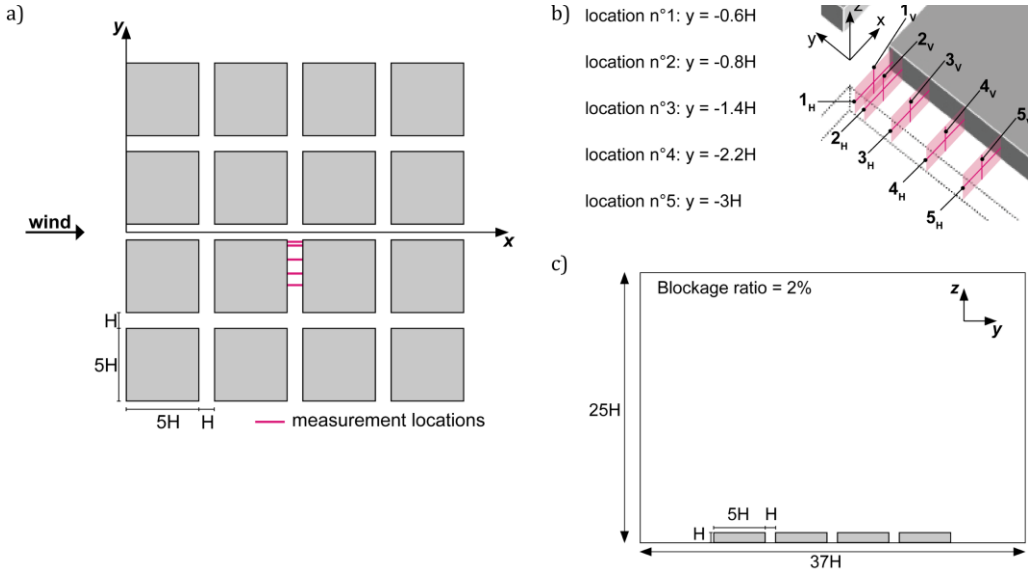


Fig. A_1 - (a) Planar view of the model set up, (b) parallel view of part of the model with the measurement locations, and (c) wind-tunnel cross section.

A.3 Computational model and grid-convergence study

The computational domain has dimensions $L_D \times W_D \times H_D = 4.3 \times 3.7 \times 2.5 \text{ m}^3$. The cross-section of the domain is equal to the cross-section of the WT in accordance with the experimental setup (Figs. A_1a, c). Therefore, the domain height is $25H$. The roughness elements distributed over the floor of the wind tunnel upwind of the parallelepipeds are not modeled explicitly, and the inlet and outlet planes were located $5H$ upwind and $15H$ downwind of the city model, respectively, according to best practice guidelines [112,120] (Fig. A_2a).

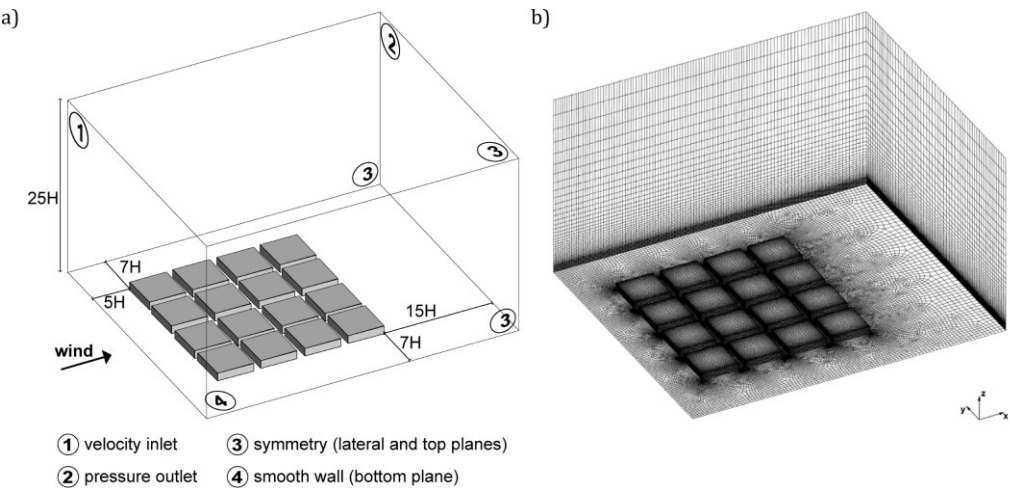


Fig. A_2 - (a) Computational domain with indication of boundary condition types and (b) computational grid (basic case).

Table A_1 - Characteristics of the three grids for the grid-convergence study.

	linear scale factor	number of cells			
		building edge (plan)	building height	building separation	total
Coarse	$/ \sqrt{2}$	28	11	11	1,040,358
Basic	-	40	16	16	3,093,542
Fine	$\times \sqrt{2}$	57	23	23	6,324,237

For the grid-convergence study, three computational grids are generated according to the best practice guidelines [8,112,120,143] and using the surface grid extrusion technique [122]. The basic grid is built with 40 cells along every building edge in plan view and 16 cells along the building height and building separation for a total of about 3×10^6 hexahedral cells. The coarse and the fine grids are generated by the application of $1/\sqrt{2}$ and $\sqrt{2}$ linear factors to the grid resolution, respectively. The characteristics of the grids are listed in Table A_1, and the resulting grids are shown in Figs. A_3a-c.

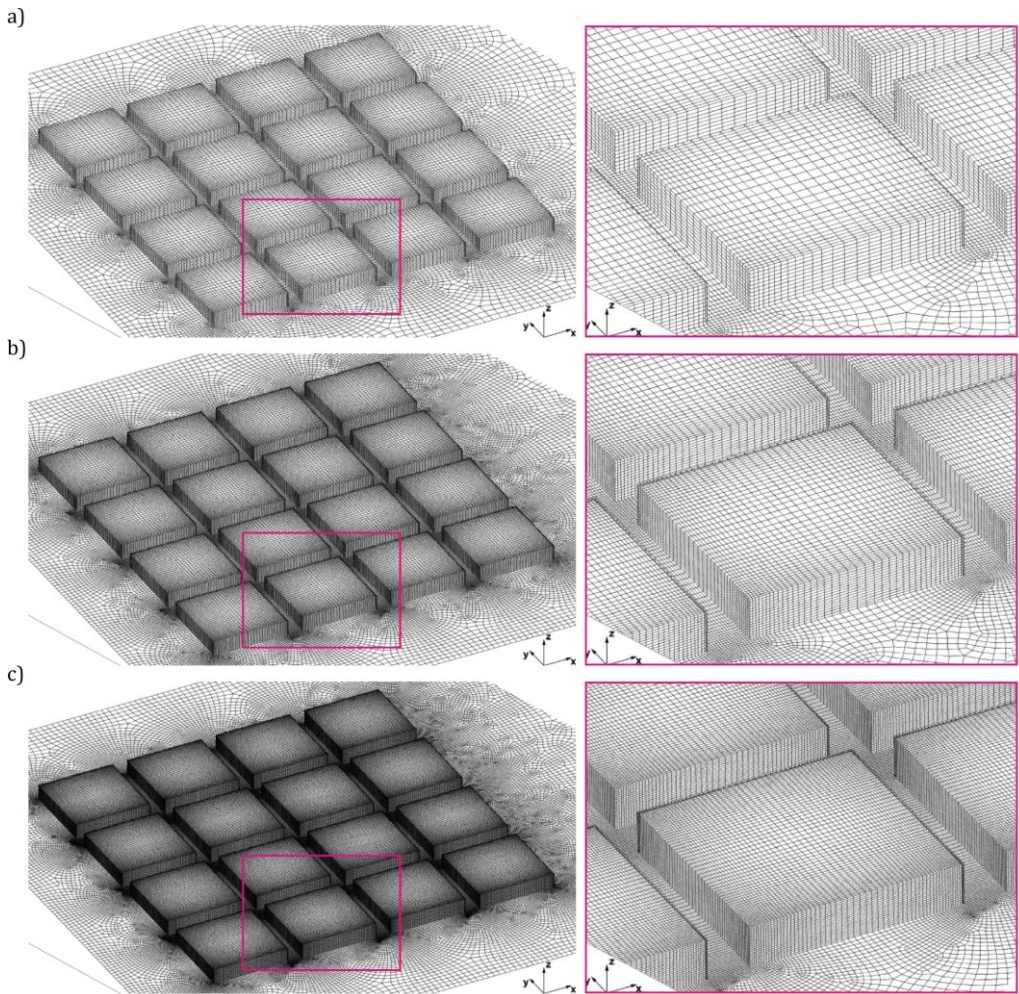


Fig. A_3 - (a) Coarse, (b) basic and (c) fine computational grid used for the sensitivity test.

Figure A.4 compares the results on the three grids in terms of the non-dimensional mean streamwise, U_x/U_H , and vertical, U_z/U_H , velocity components. U_H is the mean, streamwise velocity at $z = H$. These comparisons are conducted along five vertical profiles (Fig. A_4b-f) and five horizontal lines (Fig. A_4h-l). The vertical lines (1_v, 2_v, 3_v, 4_v, and 5_v) belong to the central vertical plane passing through the main axis of the urban canyon of interest, while the horizontal lines (1_H, 2_H, 3_H, 4_H, and 5_H) are placed at $z = 0.5H$. It is apparent that the basic and the fine grids provide similar results along all five lines. Nevertheless, slight deviations of U_x/U_H and U_z/U_H occur at location y_1 close to the top of the canyon, and at locations y_3 and y_4 close to the leeward façade, respectively. Conversely, significant deviations for both U_x/U_H and U_z/U_H occur between the coarse and the basic grids at different positions. In order to provide a quantitative error estimation, the grid-convergence index (GCI) is used [144]:

$$GSI_{basic} = F_s \times \left| \frac{r^p \times \left(\frac{U_{basic}}{U_H} - \frac{U_{fine}}{U_H} \right)}{(1-r^p)} \right| \quad A_2$$

where $r = \sqrt{2}$ is the linear grid refinement factor, $p = 2$ is the formal order of accuracy and refers to the second-order discretization schemes used for the simulations, while $F_s = 1.25$ is the safety factor, recommended when three grids are considered [144]. The GCI values obtained for both U_x/U_H and U_z/U_H averaged over all data points along the ten lines are listed in Table A_2. Overall, the deviations are well below 5% along all the ten lines except at y_1 for U_x/U_H and at y_3 for U_z/U_H , where the deviations are close to 6%. A further refinement of the grid has been conducted by applying a scale factor of $\sqrt{2}$ on the number of cells on every edge of the fine grid for a total number of hexahedral cells above 14×10^6 . The results show slight improvements at every position of about 1%. Since this improvement is not significant compared to the increase in computational time, it

is concluded that the basic grid provides nearly grid-independent results, and it is retained for the validation study.

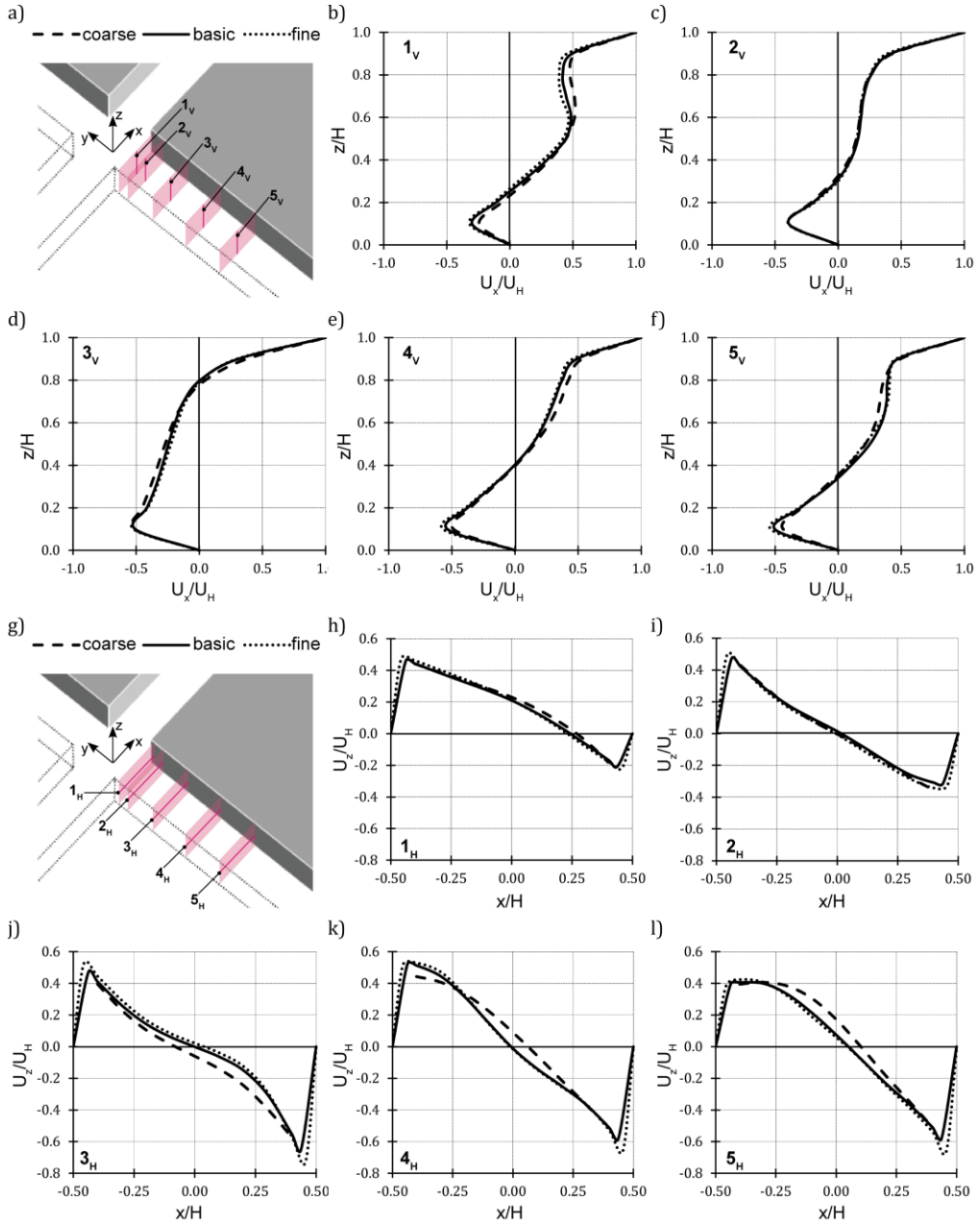


Fig. A_4 - (a, g) Part of the computational model showing the five measurement locations; vertical (b-f) and horizontal (h-l) profiles of U_x/U_H and U_z/U_H computed using the three grids at five different positions in the second canyon perpendicular to the wind direction.

Table A_2 - Grid Convergence Index (GCI) evaluated for the basic grid. Averages of U_x/U_H and U_z/U_H over all data points along the ten lines.

GCI_{basic}	y_1	y_2	y_3	y_4	y_5
	-0.6 H	-0.8 H	-1.4 H	-2.2 H	-3 H
U_x/U_H	0.06	0.02	0.03	0.03	0.04
U_z/U_H	0.02	0.05	0.06	0.02	0.04

A.4 Boundary conditions and solver settings

The vertical profiles of mean wind speed, U , turbulence kinetic energy, k (m^2/s^2), and turbulence dissipation rate, ε (m^2/s^3), are imposed at the inlet plane. In particular, Eq. (V_1) is used for U , while k and ε are given by:

$$k(z) = \frac{(u_*)^2}{\sqrt{C_\mu}} \quad \text{A}_3$$

$$\varepsilon(z) = \frac{(u_*)^3}{\kappa(z+z_0)} \quad \text{A}_4$$

where $C_\mu = 0.09$ is a constant. At the top and lateral sides of the domain, symmetry boundary conditions, i.e., zero normal velocity and zero normal gradients of all variables, are applied (Fig. A_2a). At the outlet section, zero static gauge pressure is imposed. Moreover, for the bottom and building surfaces, the standard wall functions by Launder and Spalding (1974) [135] with roughness modification by Cebeci and Bradshaw (1977) [136] are used imposing zero roughness height, i.e., $k_s = 0$ and $C_s = 0.5$.

The CFD simulations are performed by applying the 3D steady RANS equations with the realizable (RE) k - ε model closure [137] using Ansys Fluent 16.2 [138]. Although LES, when applied with care, is intrinsically superior to steady RANS, the latter approach is still most widely used in building simulation studies such as those

on urban ventilation [145]. The SIMPLE algorithm is used for pressure-velocity coupling, while second-order discretization schemes are applied for both the convection and viscous terms of the governing equations. The choice for the realizable k - ε turbulence model is based on the recommendations by Franke et al. (2004) [146] and earlier successful validation studies with this model [31,32,142,147–150]. The simulations are terminated when the scaled residuals do not show any further reduction with an increasing number of iterations. The following minimum values are reached: 10^{-5} for continuity, 10^{-8} for x -, y -, z -velocity, and k , and 10^{-6} for ε .

A.5 Results and validation

The results are presented in terms of non-dimensional mean streamwise, U_x/U_H , and vertical, U_z/U_H , velocity components, where U_H is the mean streamwise velocity at $z = H$. Figures A_5 compare the CFD results in terms of U_x/U_H and U_z/U_H with the experimental data along five vertical lines (1_v , 2_v , 3_v , 4_v , and 5_v) belonging to the central vertical plane passing through the main axis of the urban canyon of interest and five horizontal lines (1_H , 2_H , 3_H , 4_H , and 5_H) placed at $z = 0.5H$. Overall, a reasonable agreement between the CFD simulations and WT data is found for both U_x/U_H and U_z/U_H . In particular, numerical and experimental U_x/U_H are very similar along lines 1_v (apart from the bottom) and 3_v , while slight deviations are present along lines 2_v and 4_v , especially in the central areas. A much more evident deviation is found for U_z/U_H along line 2_H , while the agreement is satisfactory along lines 1_H , 3_H , and 5_H , even if slight differences occur close to the leeward facades (1_H and 5_H).

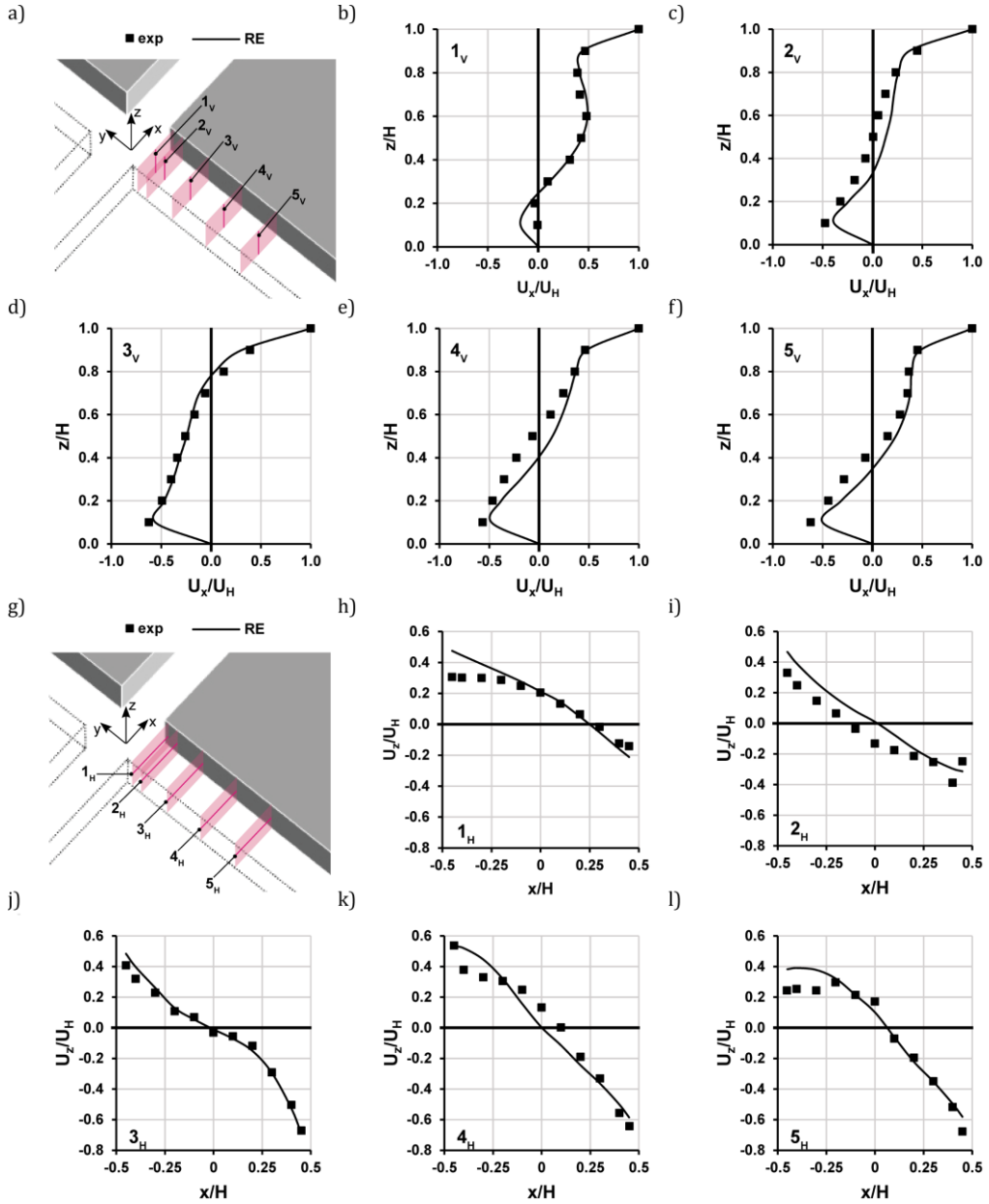


Fig. A_5 - (a, g) Part of the computational model showing the five measurement locations; comparison between the wind tunnel data and the CFD results in terms of dimensionless U_x/U_H and U_z/U_H along (b-f) five vertical lines and (h-l) five horizontal lines respectively in the second canyon perpendicular to the wind direction.

The validation metrics usually employed to quantitatively evaluate the computational settings are [143] the hit rate (q), the factor of 2 of the observations (FAC2), and the factor of 1.3 of the observations (FAC1.3):

$$q = \frac{N}{n} = \frac{1}{n} \sum_{i=1}^n N_i \text{ with } N_i = \begin{cases} 1 & \text{for } \left| \frac{P_i - O_i}{O_i} \right| \leq D \\ 0 & \text{else} \end{cases} \quad A_5$$

$$FAC2 = \frac{N}{n} = \frac{1}{n} \sum_{i=1}^n N_i \text{ with } N_i = \begin{cases} 1 & \text{for } 0.5 \leq \frac{P_i}{O_i} \leq 2.0 \\ 0 & \text{else} \end{cases} \quad A_6$$

$$FAC1.3 = \frac{N}{n} = \frac{1}{n} \sum_{i=1}^n N_i \text{ with } N_i = \begin{cases} 1 & \text{for } 0.77 \leq \frac{P_i}{O_i} \leq 1.3 \\ 0 & \text{else} \end{cases} \quad A_7$$

where P_i is the predicted value (CFD), O_i is the observed value (WT), and n is the number of comparison points. An allowed fractional deviation $D = 0.25$ is chosen for calculating q [151]. The results show that the best performances in terms of both U_x/U_H and U_z/U_H occur at locations y_1 , y_3 , and y_5 (Table A_3). A reasonable agreement occurs at location y_4 , while the worst agreement takes place along lines 2_v and 2_H .

Table A_3 - Validation metrics for U_x/U_H and U_z/U_H along five vertical and horizontal lines in the second canyon perpendicular to the wind direction: hit rate, FAC2 - factor of two observations; FAC1.3 - factor of 1.3 observations.

	U_x/U_H					U_z/U_H					Average values	Ideal values
	1 _v	2 _v	3 _v	4 _v	5 _v	1 _H	2 _H	3 _H	4 _H	5 _H		
q	0.8	0.4	0.8	0.5	0.6	0.4	0.3	0.7	0.5	0.7	0.6	1.0
FAC2	0.8	0.6	0.8	0.7	0.8	0.9	0.6	0.9	0.8	0.9	0.8	1.0
FAC1.3	0.8	0.5	0.8	0.6	0.6	0.5	0.4	0.9	0.6	0.7	0.6	1.0

Since the average value of q is 0.6 and FAC2 is 0.8 (well above 0.5 as prescribed by Schatzmann et al., 2010 [143]), it can be concluded that the agreement between CFD simulations and WT data is satisfactory.

Table A_4 - Validation metrics for U_x/U_H and U_z/U_H along five vertical and horizontal lines in the second canyon perpendicular to the wind direction: hit rate, FAC2 - factor of two observations; FAC1.3 - factor of 1.3 observations.

q	U _x /U _H					U _z /U _H					Average values	Ideal values
	1 _v	2 _v	3 _v	4 _v	5 _v	1 _H	2 _H	3 _H	4 _H	5 _H		
RE	0.80	0.40	0.80	0.50	0.60	0.36	0.27	0.73	0.45	0.73	0.56	1.0
STD	0.80	0.40	1.00	0.50	0.60	0.36	0.27	0.36	0.64	0.64	0.56	1.0
RNG	0.40	0.40	0.50	0.50	0.50	0.18	0.36	0.27	0.64	0.45	0.42	1.0
FAC 2												
RE	0.80	0.60	0.80	0.70	0.80	0.91	0.64	0.91	0.82	0.91	0.79	1.0
STD	0.90	0.70	1.00	0.80	0.80	0.82	0.64	0.91	0.91	0.91	0.84	1.0
RNG	0.90	0.70	1.00	0.70	0.90	0.64	0.64	0.82	0.73	0.91	0.79	1.0
FAC 1.3												
RE	0.80	0.50	0.80	0.60	0.60	0.45	0.36	0.91	0.55	0.73	0.63	1.0
STD	0.80	0.40	1.00	0.60	0.60	0.27	0.27	0.45	0.64	0.64	0.57	1.0
RNG	0.50	0.40	0.50	0.50	0.50	0.27	0.27	0.36	0.64	0.45	0.44	1.0

Moreover, a comparison between the performance of the RE $k-\epsilon$ model and other turbulence models commonly used for urban wind flow simulations [145], i.e., the standard $k-\epsilon$ model (STD) [152] and the Renormalization Group $k-\epsilon$ model (RNG) [153], is conducted. The validation metrics used for assessing the performance are reported in Table A_4, and the comparison is presented in Figures A.6. The results obtained using the STD $k-\epsilon$ model and the RE $k-\epsilon$ model are comparable, while the RNG $k-\epsilon$ model shows an overall performance slightly worse.

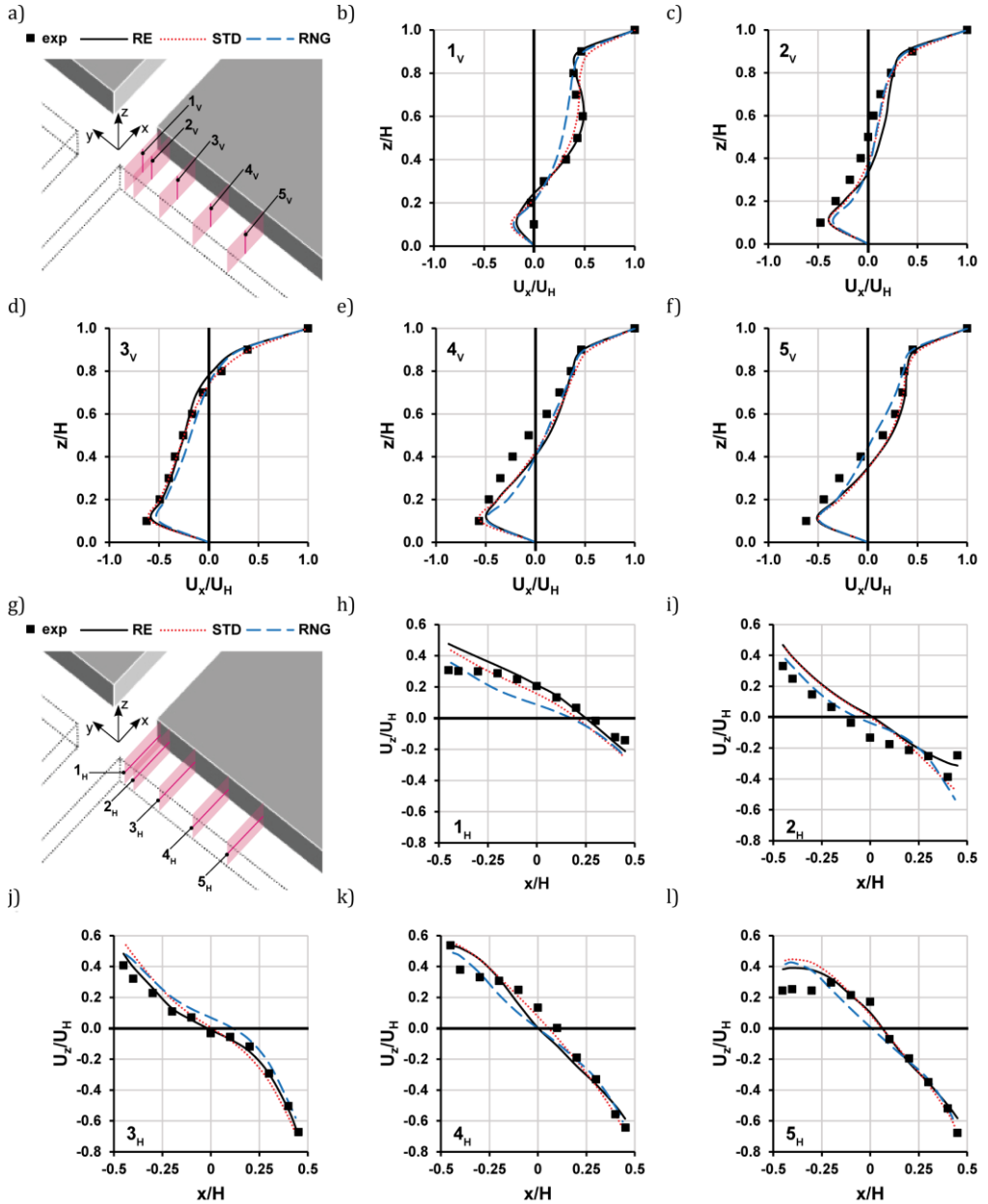


Fig. A_6 - (a, g) Part of the computational model showing the five measurement locations; comparison between the wind tunnel data and the CFD results in terms of dimensionless U_x/U_H and U_z/U_H along (b-f) five vertical lines and (h-l) five horizontal lines respectively in the second canyon perpendicular to the wind direction. The CFD results are obtained with the RE $k-\varepsilon$ model (black line), STD $k-\varepsilon$ model (red dotted line), and RNG $k-\varepsilon$ model (blue dashed line).

Therefore, the choice of the turbulence model closure may be considered validated. The current validation study is used to support the CFD simulations for the case study of the Tuscolano-Don Bosco district.

Finally, the mean velocity vector fields and non-dimensional mean velocity contours (U/U_{ref} , where U_{ref} is the mean velocity at the inlet at $z = 0.5H$ height) along the vertical planes passing through the 1_v, 2_v, 3_v, 4_v, and 5_v lines and along the horizontal plane at $z = 0.5H$ are shown in Fig. A_7b-g, respectively. In the vertical planes, a main clockwise vortex is observed inside the canyon. Such a pattern is typically observed in the skimming flow regime when the wind flow, overlaying the canopy, skims over the top of buildings. However, contrary to the patterns typically observed in two-dimensional UCs [51,154], the main vortex is not centered in the cavity but follows the pattern generally occurring for medium-length UC ($L/H = 5$) with $AR = 1$ [52]. The center of the vortex changes its position (from the bottom of the windward façade to the center, the top, and the center again) as we consider planes located increasingly toward the middle of the canyon. This characteristic reveals the 3D nature of the vortex that is not circular in a plane but helicoidal inside the entire canyon. In fact, counter-rotating vortices can be seen in the horizontal plane (Fig A_7g).

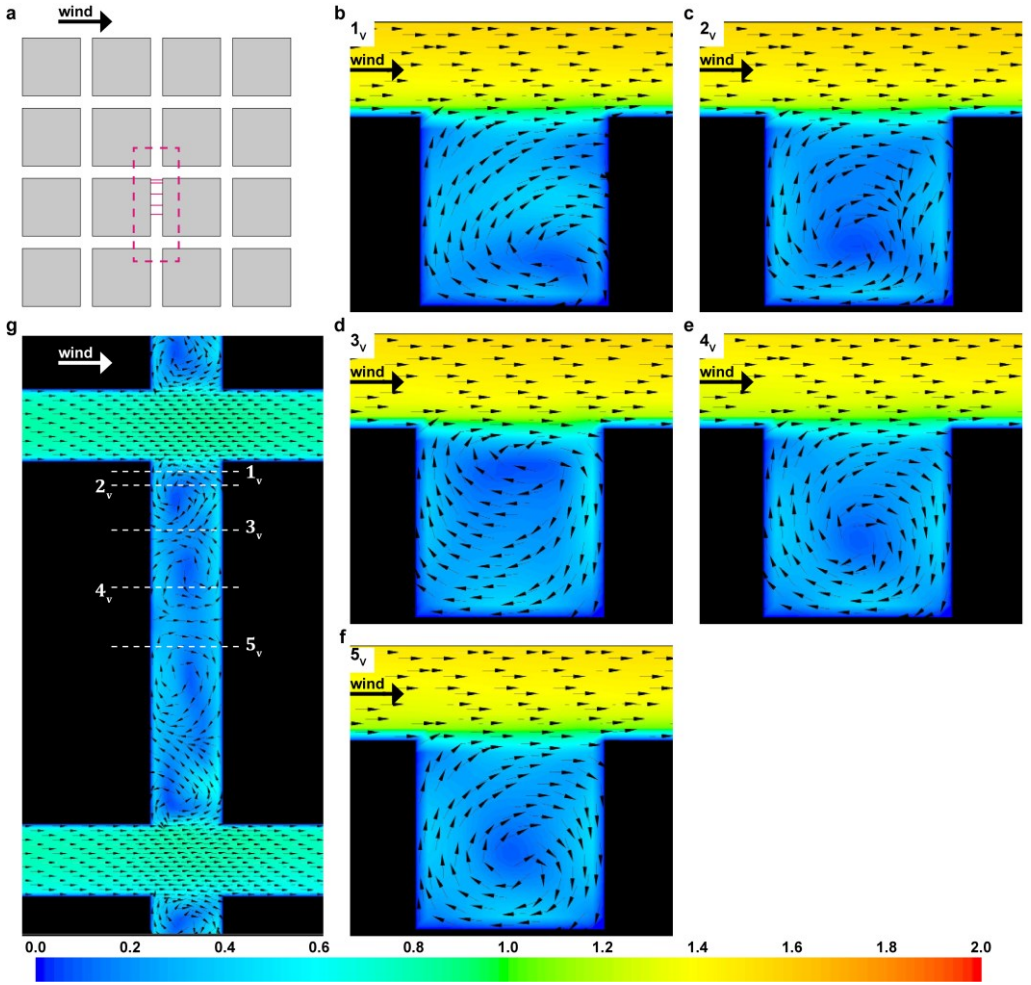


Fig. A_7 - (a) Top view of the model; vector fields and contours of the dimensionless mean velocity (U_{ref} at the inlet at $z = 0.5H$ height) along (b-f) five vertical planes and (g) the horizontal plane at $z = 0.5H$ height. Color bar refers to the dimensionless velocity.

B. Appendix

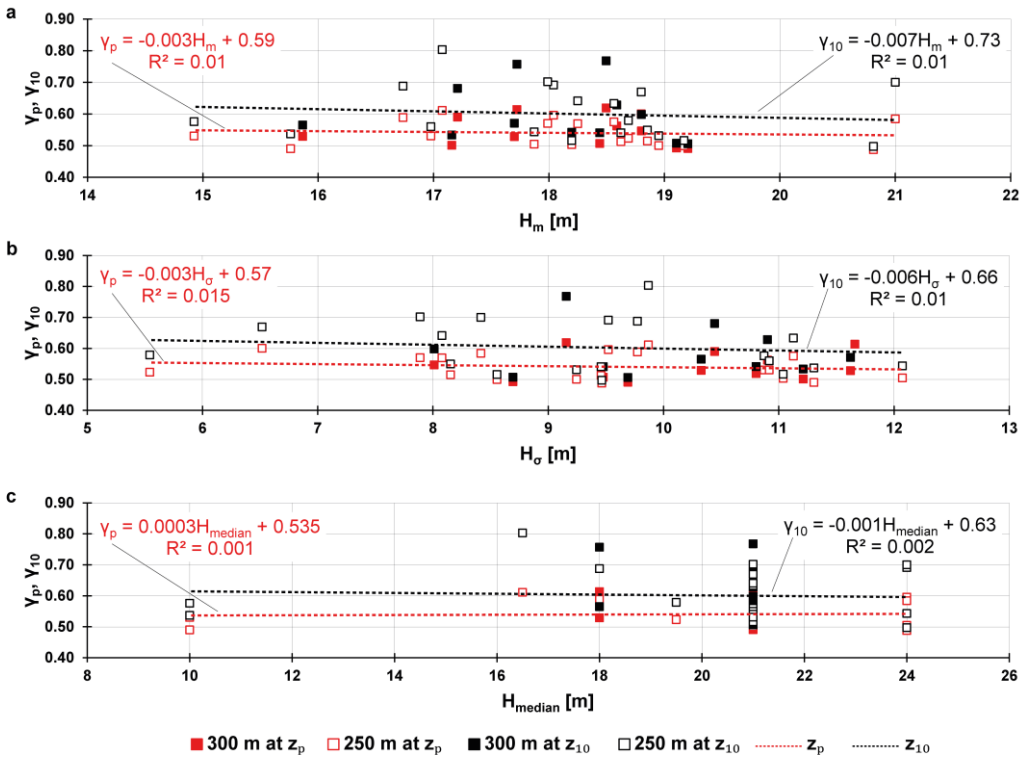


Fig. B_1 - γ_p and γ_{10} as a function of: (a) mean building height, H_m ; (b) root mean square of the building heights, H_σ ; and (c) median of the building heights, H_{med} .

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Urban ventilation in compact cities: wind-sensitive urban morphologies

This chapter is prepared for submission to an ISI journal:

The effectiveness of urban morphology in enhancing urban ventilation: a numerical study for a real compact area in Rome (in preparation)

Among the issues that increasingly threaten human health and well-being in urban areas, air pollution and heat stress represent two aspects to address urgently. They have been associated with weak wind conditions and linked to increased morbidity, mortality, and economic loss. Wind conditions are profoundly modified by urbanization. Hence, urban morphology, defined as the three-dimensional configuration of cities, considering both buildings and open spaces enclosed by them, may be used in a climate-aware approach to urban planning to mitigate the detrimental effects of weak wind conditions by enhancing urban ventilation. Thus, detailed investigations of the effectiveness of different morphologies to enhance urban ventilation in real urban areas are necessary. The present study aims to analyze the ventilation performance and assess the effectiveness in this regard of several urban morphologies characterized by different building typologies of an actual urban area in Rome, Italy. 3D steady-state Reynolds-averaged Navier-Stokes (RANS) simulations have been performed for twelve wind directions (α), and several indicators have been used for the investigation. The results are presented first for the entire area of interest (AoI) and then for a selection of fourteen different morphologies (cases). Results show a high dependency of urban ventilation on wind directions and morphological characteristics and identify morphologies that enhance urban ventilation. On average, pedestrians experience in the AoI a mean wind speed that is 60% of that experienced outside the urban area. The lowest and highest values occur for $\alpha = 210^\circ$ and 270° , respectively, and correspond to mean wind speeds that are 40% and 77% of that measured outside the urban area. Regarding the fourteen morphologies, some determine an increase in mean wind speed up to 35% compared to the average in the entire AoI and, therefore, prove to be able to enhance urban ventilation. Finally, the effectiveness of each of the selected morphologies to enhance urban ventilation has been investigated in detail. To the best of the authors' knowledge, a similar study has not been done before and provides additional knowledge toward climate-oriented planning of existing urban areas renovation.

V_1 Introduction

In the last centuries, urbanization has experienced an increasing trend that is projected to continue in the years to come [1]. Over the decades, urban areas have increased in number, size, and density, enlarging their ecological footprint. Hence, they have more often been associated with environmental degradation, social and economic exclusion, heavy traffic, and pollution [2]. Recently, existing urban areas have been advocated as places to address sustainability and resilience challenges by improving urban adaptation [3,4]. In fact, cities frequently appear insufficiently prepared to tackle increasing threats due to climate change and multifaceted stresses, exposing populations, infrastructures, and activities to extreme weather events. These events are becoming increasingly frequent even in mild or temperate climates, e.g., in Europe and, specifically, the Mediterranean basin [5,6], characteristics of areas with high levels of urbanization. Therefore, urban areas represent vulnerable elements of human life nowadays. Hence, existing urban areas need to be regenerated, increasing their resilience and sustainability to improve human health and well-being. This objective was recognized as primary by all United Nations Member States in 2015 with the adoption of the 2030 Agenda for Sustainable Development [7].

Air pollution and heat stress are issues that increasingly threaten human health and well-being in urban areas and require urgent attention [8]. Air pollution and heat stress have been associated with weak wind conditions [9–13] and have been linked to increased morbidity, mortality, and economic losses [14–23]. They significantly impact the environmental conditions in outdoor and indoor building spaces, limit the use of open spaces, reduce options for building natural ventilation, and increase energy consumption for cooling and air cleaning [24]. As far as solutions can be engaged by urban planning and management, this should be explored through scientific studies [25–27].

As noted by Givoni, wind conditions are meteorological characteristics profoundly modified by urbanization [28]. Wind conditions in urban areas do not depend solely on the synoptic wind, characterized by speed and direction; they are also determined by its interaction with the features of the environment and the obstacles along its path that modify its speed and direction and introduce turbulence. Specifically, an overall reduction in wind speed within and right above the urban canyons (UCs) occurs when an air mass encounters a city. This mechanism contributes to the well-known phenomenon of the Urban Heat Island (UHI), i.e., the increase in air temperature within urban areas compared to that observed in the surrounding rural areas [29–32]. The UHI effect is probably one of the most well-known atmospheric modifications due to urbanization [9].

Weak wind conditions in urban areas result from the interaction between airflows and the three-dimensional geometry of cities, considering both buildings and open spaces enclosed by them, i.e., urban morphology. Urban morphology is, therefore, defined by the shape and dimensions of individual buildings, the building typology, and the mutual arrangements of adjacent buildings. Hence, weak wind conditions, and their detrimental effects on citizens' health and well-being, could be mitigated by adopting urban morphologies that ease air into urban canyons and guarantee adequate airflow levels. In this way, fresh air from the surroundings of an urban area is introduced into the urban tissues, diluting and removing pollutants and heat from their canyons and improving air quality and thermal comfort [10,33]. This capability is regarded as the urban ventilation performance, or urban ventilation potential, of an urban area and is closely related to the morphological characteristics of an urban area. Adequate urban ventilation performances may limit the UHI effect [34] and reduce the citizens' exposure to air pollution and heat stress. Hence, detailed investigations of the interaction between urban morphology and urban ventilation are fundamental to supporting climate-sensitive urban planning and exploiting urban morphology for enhancing urban ventilation. Specifically, it is

paramount to assess the effectiveness of real urban morphologies in enhancing urban ventilation performance.

According to Britter and Hanna, the observation scales of interest when investigating flows and dispersion in urban areas are four, depending on the features of interest: (i) the regional scale ($\sim 100 - 200$ km), (ii) the city scale ($\sim 10 - 20$ km), (iii) the neighborhood scale ($\sim 1 - 2$ km), and (iv) the street scale ($\leq 100 - 200$ m) [35]. The neighborhood and the street scales are the most suitable for investigating features of flows within the urban canopy [35]. A similar conclusion may be drawn from the work by Fernando et al., where six observation scales were identified, i.e., (i) the regional scale ($\sim 100 - 1000$ km), (ii) the city scale (~ 10 km), (iii) the city block scale (~ 1 km), (iv) the building and courtyard scale (~ 100 m), (v) the street canyon scale (~ 10 m), and (vi) tree, pedestrian and vehicle scale (~ 1 m) [31]. Several efforts have been made to investigate the interaction between buildings and airflows at different scales in the past. Most early studies employed idealized building and urban models at small or local scales, i.e., the building, the street, and the neighborhood scales. Nevertheless, the evaluation of ventilation performance depends on many factors, e.g., wind speed and direction, characteristics of single buildings, and urban arrangements. Therefore, although it is valuable to investigate the contribution of specific urban morphological elements and perform parametric studies as mentioned above, simplified and idealized models of buildings and urban areas generally do not reproduce the complexity of the actual built environment. Therefore, at least part of the investigations of the impact of urban morphology on ventilation performance should focus on real case studies.

Previous works conducted using real case studies focused on identifying potential wind corridors for urban cooling and ventilation (e.g., [36,37]). However, these studies were performed by employing grids with relatively low resolution and without systematically describing the local morphological characteristics. Existing urban areas have also been used as case studies for providing simplified models that

correlate urban ventilation performance, expressed in terms of mean wind ratio and morphological parameters (e.g., [38–41]). Nevertheless, these studies aimed not to assess the effectiveness of different specific morphologies in enhancing urban ventilation. Finally, He et al., noting the lack of studies considering the intricate urban morphological characteristics, investigated the potential of urban ventilation for mitigating local warming in a low-dense neighborhood in Sydney [42].

Although investigations of the relationship between urban morphology and urban ventilation have gained popularity within the scientific community in the last two decades, this topic needs further analysis, particularly in real urban areas. No studies have yet been performed evaluating the urban ventilation performance of different morphologies typical of existing compact cities. Therefore, the present paper aims to fill this knowledge gap by analyzing the ventilation effectiveness of urban morphologies characterized by different building typologies belonging to a compact area in Rome, Italy. 3D steady-state Reynolds-averaged Navier-Stokes (RANS) simulations are performed on a high-quality and high-resolution computational grid. The urban ventilation performance is evaluated by a set of indicators consisting of the spatially averaged mean wind velocity ratio (mWVR), the age of air (τ), and their derivatives.

The spatially averaged mean wind velocity ratio has been proven to be a valuable tool in studies focusing on both idealized [43–48] and actual urban areas [38–41]. On the other hand, the age of air represents the time a particle of exhausted air takes to be replaced from a specific location. It may provide valuable insights into the level of entrapment of air particles within the UCs. Nevertheless, the age of air, originally developed for indoor experiments using tracer gas techniques [49][50], is very challenging to be used in complex existing urban areas because it is sensitive to the definition of the initial values [51]. Therefore, new formulations, e.g., the abovementioned air delay, have been derived. In this work, the local age of air, as defined in Section 3, is used to present the results and avoid this issue.

The article is structured as follows. Section V_2 reports a selection of previous works describing archetypes and typical features of airflows around bluff bodies that play a fundamental role in analyzing the wind environment in urban areas. Section V_3 introduces the case study highlighting the main morphological characteristics of the area of interest and the fourteen morphologies selected within it. Section V_4 describes the computational settings, including details on estimating the aerodynamic roughness length and calculating the age of air. Section V_5 presents the results and the discussion that also reflects on knowledge gained from previous studies of idealized buildings and urban models. Finally, Section V_6 reports the summary and conclusions.

V_2 Literature review

This section reports a selection of previous works conducted at small or local scales, i.e., the building, the street, and the neighborhood scales. Figures V_1 and V_2 present some graphical excerpts from the selected studies focusing on archetypes and typical features of airflows around bluff bodies. These elements are fundamental to analyzing the wind environment in urban areas and identifying the mechanisms governing urban ventilation.

One of the archetypes of flows around obstacles is the isolated prismatic building with a façade perpendicular to the approaching wind. This configuration has been investigated extensively in the past (e.g., [52–58]). Although it represents a simplified case, it contains the salient features of flows in urban areas, such as horse-shoe vortices, flow separation, reattachment, and vortex shedding in the wake (Fig. 1a). Penwarden and Wise [63] studied the potential amplification of the pedestrian-level wind speed for the building configuration in Fig. 1b, a study further discussed by Oke [29]. Beranek [59] performed wind tunnel tests on the pedestrian-level wind environment for a wide range of isolated prismatic buildings considering different wind directions (Fig. V_1c).

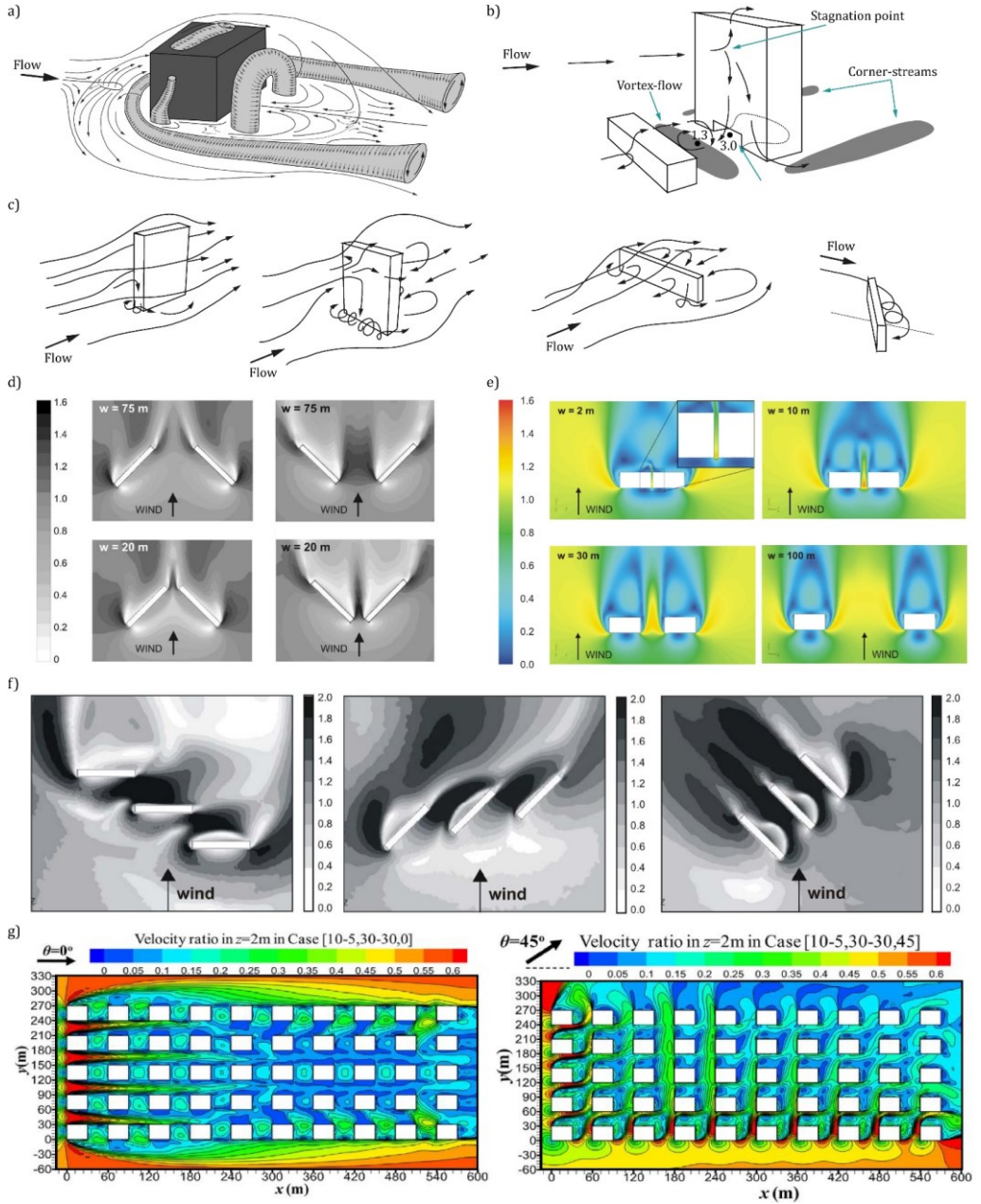


Fig. V_1 - Sketches of (a) the flow pattern around an isolated building (modified from [52]), (b) flow around a tall building with a lower building upwind and a passage at the central bottom part (modified from [29]), and (c) the flow pattern around four buildings (modified from [59]). Contours of (d) the amplification factor in passages between converging and diverging buildings [60], (e) the amplification factor in a passage between aligned buildings [61], (f) the amplification factor in a passage between parallel shifted buildings (modified from [62]), and (g) velocity ratio for different wind directions [47]

Blocken et al. [60] and Blocken et al. [61] analyzed the pedestrian-level amplification factor, i.e., the ratio of the mean wind speed at a specific location to that at the same location without the buildings, in the passage between two buildings (Fig. V_1d-e). They identified three flow types for the passage between aligned buildings (Fig. V_1e), i.e., resistance, interaction, and isolated flows [61]. Blocken and Carmeliet [62] numerically investigate the effects of the pressure short-circuiting in passages between parallel shifted buildings based on wind tunnel tests by Beranek [64] (Fig. 1f). Employing a simplified urban arrangement, Lin et al. investigated the impact of changes in the wind direction on the urban ventilation expressed in terms of the velocity ratio at a height $z = 2$ m [47] (Fig. V_1g). They reported the presence of 3D helical flows in the secondary streets and channel flows along the main street, features also investigated by Soulhac et al. [65] and Zajic et al. [66].

Hang et al. [67] and Buccolieri et al. [68] used simplified urban arrangements to investigate the effects of changes in the wind direction on the urban ventilation expressed in terms of the normalized velocity and age of air and normalized age of air, respectively (Fig. V_2a-b). Furthermore, Buccolieri et al. noted that perpendicular wind directions are often erroneously considered the worst case for urban ventilation and showed that wind with low incident angles might represent the worst and best ventilation conditions based on the orientation of the widest urban canyons [68]. The impact of street morphology on urban ventilation was also investigated by Peng et al. using simplified models of residential streets in Nanjing, China [69]. They provided suggestions about the orientation of the buildings forming the different urban canyons based on the wind direction and evaluated the ventilation performance using the net escape velocity and the air delay, an index derived from the age of air by Antoniou et al. [51]. Finally, Hang et al. [70] focused on street ventilation as assessed by the pollutant transport rate and the net escape velocity. They noted the importance of wind directions and identified the parallel

approaching wind as the best ventilation condition at the pedestrian level in the urban canopy layer [70].

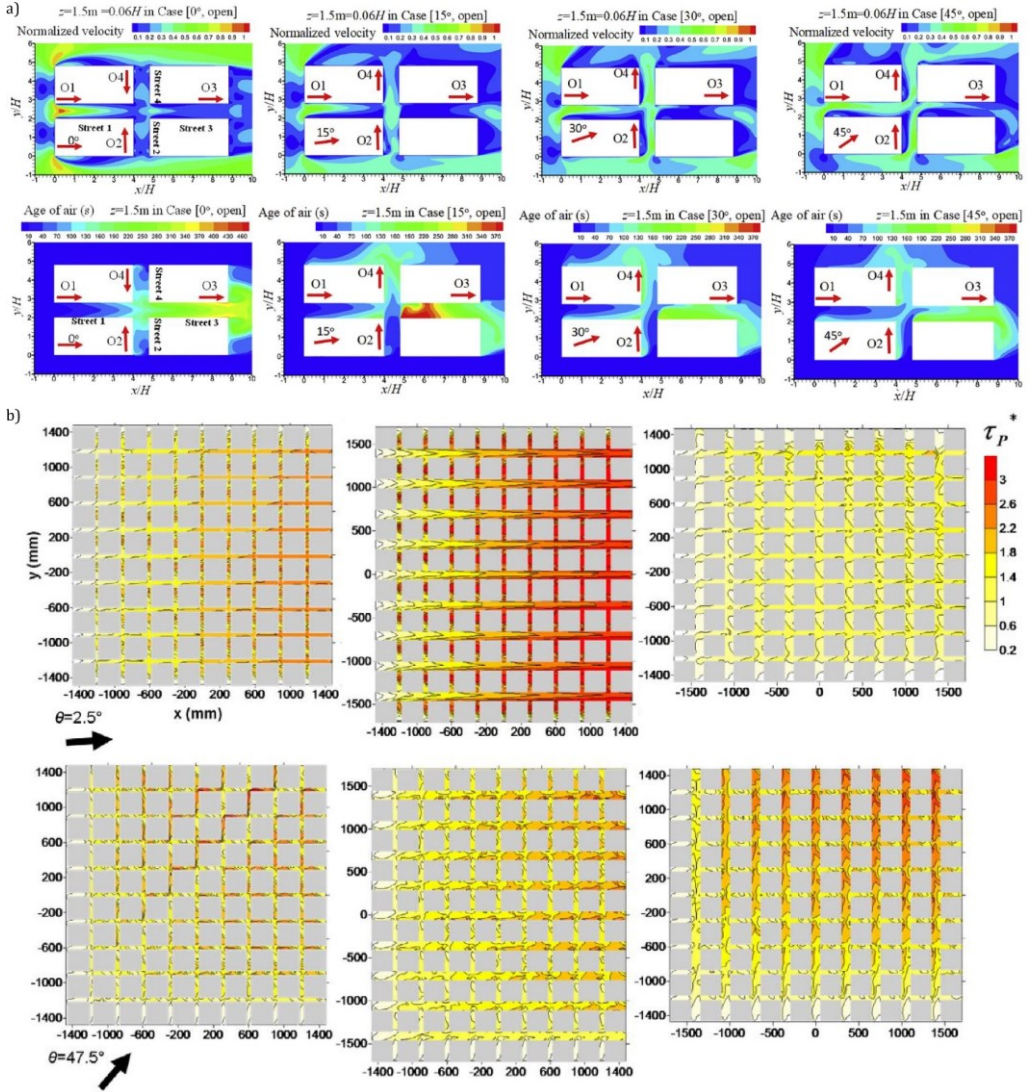


Fig. V_2 - Contours of (a) the normalized velocity and the age of air in the rectangular building arrangements for different wind directions [67], and (b) the normalized mean age of air [68].

V_3 Description of the case study

The compact area selected as the case study for this work is the Tuscolano-Don Bosco district. It belongs to the 7th Municipality (Municipio VII) of Rome (41°51'25.1" N 12°33'43.5" E) and is located in the Southeast part of the city (Fig. V_3). The district is 6 km from the city center, identified with the location of the Colosseum in Fig. 3b, and around 5 km from the Ciampino airport. It is enclosed by parks on the South side ("degli Acquedotti" and "Appia Antica" parks) and the North side ("di Centocelle", a former military airport, and "di Torre Spaccata" parks), by the Quadraro neighborhood on the Northwest, and the commercial-administrative pole of Cinecittà on the Southeast. For information regarding typical meteorological conditions observed in the Roman area, the readers may refer to recent analysis reported by Di Bernardino et al. (2021)[71], Di Bernardino et al. (2022)[72], and Iannarelli et al. (2022)[73].

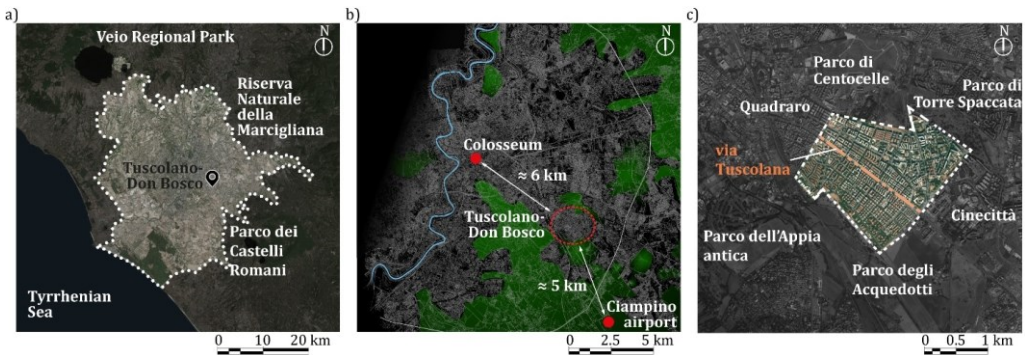


Fig. V_3 - (a) Map of Rome, including the Tuscolano-Don Bosco district location (modified from Geoportale Italiano); **(b)** map with indication of the selected case study; and **(c)** detailed map with indication of the urban area modeled explicitly in the computational domain (white dotted line), (modified from Google Earth 2009).

The results of the numerical simulations are presented first for the entire Area of Interest (hereafter referred to as AoI) and then for fourteen subareas selected within the AoI representative of different urban morphologies and typical building typologies. In this way, it is possible to investigate in detail the urban ventilation

performance in a real urban area and assess the effectiveness of the different morphologies by comparing several cases. Detailed descriptions of the AoI and the fourteen subareas are provided in Subsection V_3.1 and Subsection V_3.2, respectively.

V_3.1 The area of interest

Figure V_4 shows maps obtained using the open-source GIS software QGIS [74]. These maps present an example of the diverse building typologies existing in the area (Fig. V_4a) with perspective views of selected typologies (Fig. V_4b), construction time as deduced from the analysis of aerial photos (Fig. V_4c), and building height (Fig. V_4d) as obtained from the open data provided by the regional authority [75]. In Figure V_4a, the dark-red dashed line identifies the AoI. This area has been obtained by considering at least an additional street block in each direction around the AoI, as suggested by the best-practice guidelines for applying Computational Fluid Dynamics (CFD) to pedestrian wind environment simulations [76,77].

Despite the presence of many different building typologies, the Tuscolano-Don Bosco district is structured according to an orthogonal grid based on the orientation of the main street, i.e., via Tuscolana (Fig V_4a). Via Tuscolana, tilted at approximately 40° from the West-East line, represents the longitudinal axis of the entire district, which is divided into two areas characterized by different morphological features. Overall, the area that lies North of via Tuscolana is characterized by higher buildings, larger public spaces (squares and boulevards), and UCs with long and continuous building fronts or façades. Here, two building typologies are prevalent, i.e., the court and the multi-story slab. The “court” typology is characterized by a continuous front along the perimeter of the entire lot or island, determining a marked separation between public and private spaces. The building height is usually considerable ($H > 24$ m). Conversely, the “multi-story”

typology is characterized by the predominance of one dimension, i.e., the length, over the other dimensions of the buildings. The resulting morphologies may be compact or open based on the position and orientation of the buildings within the island, and the building height varies significantly. In this area, the building height ranges up to 40 m. Podiums hosting commercial activities and occupying the first 4-8 m of the buildings are characteristic of the area and along both sides of via Tuscolana. Conversely, the area lying on the South side of via Tuscolana is characterized by lower buildings, urban canyons with fragmented fronts, and more open morphologies determined by the prevalence of the following building typologies: multi-story slabs, hereinafter referred to as slabs, pavilion-tower, and pavilion-palazzina, referred to as palazzina. The palazzina typology is a characteristic typology of Rome with a limited plan surface and height, similar to the tower typology but with fewer stories, which can be assimilated to a cube or parallelepiped (Figs. 4a-b). Three levels of density, i.e., low, medium, and high, can be distinguished in the area according to the value of the plan area density λ_p , i.e., the ratio between the total area of building footprints and the total land area. The low level identifies morphologies with λ_p up to 0.25. The medium level characterizes morphologies with λ_p from 0.25 to 0.35. The high level has been assigned to morphologies with λ_p above 0.35. The limit of 0.25 has been selected since it is regarded as adequate to guarantee a satisfactory dispersion from street canyons [78] and has been used in other studies, e.g., [79]. The limit of 0.35 has been selected since it is usually considered the limit between the wake-interference flow (WIF) and the skimming flow (SF) regimes [41,80]. This characteristic is fundamental while addressing the urban ventilation performance of different morphologies. In the WIF regime, the aerodynamic interaction of the buildings becomes evident but allows the approaching wind to enter the UCs. Conversely, in the SF regime, λ_p is so large that stable vortices form in the UCs, the approaching wind enters the canyons with difficulties, and the flow skims over the roofs. Hence, large values of

λ_P may produce recirculation of warm and polluted air inside the UCs, compromising urban ventilation. Examples of low-, medium-, and high-dense slab typologies are reported in Figure V_4b.

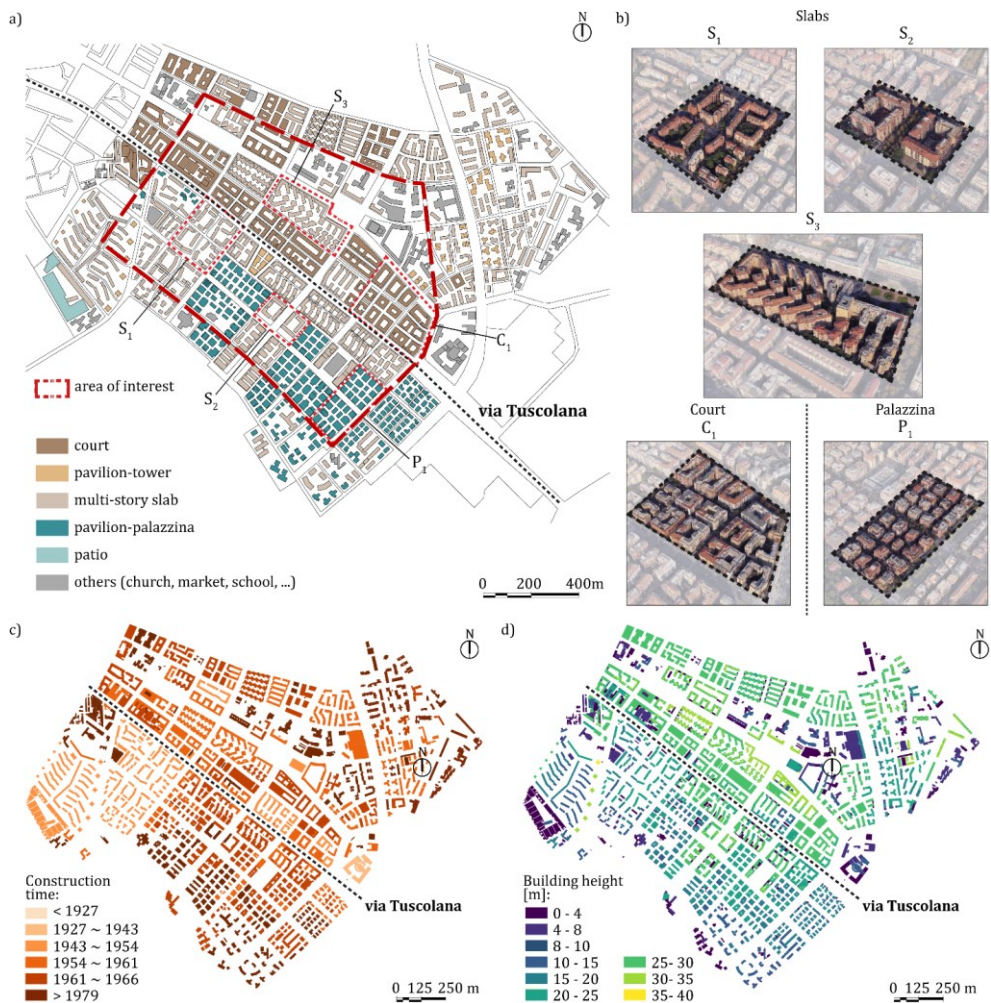


Fig. V_4 - Maps of (a) building typologies with (b) perspective views of selected typologies (modified from Google Maps), (c) construction time, and (d) building height.

V_3.2 The selected fourteen morphologies

Figure V_5a shows the fourteen subareas, hereafter referred to as cases, representing different urban morphologies and typical building typologies in the

AoI. The cases, labeled with letters from A to N, are characterized by three different building typologies:

- Slab: Cases A, B, C, D, E, G, and L;
- Court: Cases G, H, and I;
- Palazzina: Cases J, K, M, and N.

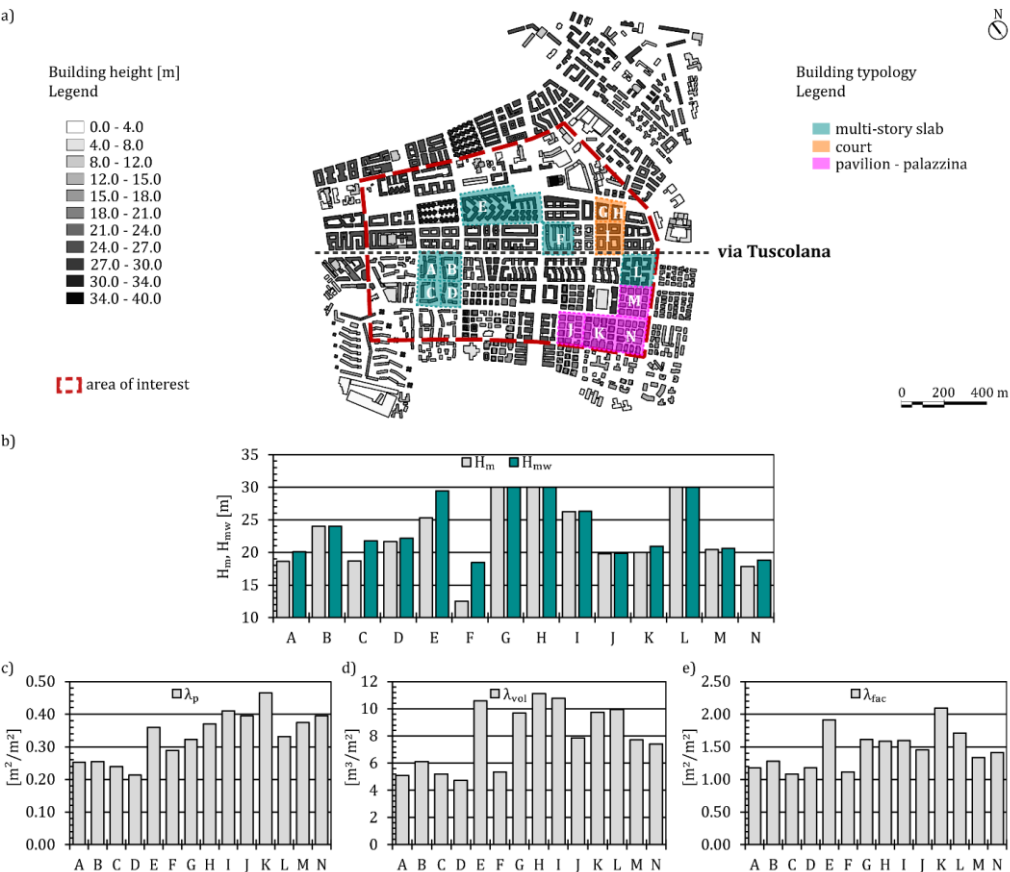


Fig. V_5 - a) Map showing the building height with the identification of the area of interest (dark red long-dashed polygon) and the selected morphologies; column charts of the morphological parameters: **b)** the mean building height, H_m , and the area-weighted mean building height, H_{mw} ; **c)** the plan area density λ_p ; **d)** the volume density, λ_{vol} (i.e., ratio between total building volume and total land surface) and **e)** the façade area density, λ_{fac} (i.e., ratio between total building vertical surfaces and total land area).

Overall, the slab typology creates a central open area, whose characteristics, e.g., size and continuity of the building fronts, depend on the orientation and the features of the buildings forming the morphology. The court typology creates rather small and enclosed courtyards in the central areas and UCs with continuous fronts on the outside. Finally, the palazzina typology may be compared to the staggered or aligned idealized urban arrangements discussed in the introduction.

To further describe the fourteen cases and quantify differences and similarities, five Morphological Parameters (MPs) are used in this study: the plan area density λ_p , the mean building height H_m , the area-weighted mean building height H_{mw} (i.e., the sum of the product between the height and plan area of the considered buildings divided by the total building plan area), the volume density λ_{vol} (i.e., the ratio between total building volume and the total land surface) and façade area density $\lambda_{faç}$ (i.e., the ratio between total building vertical surface area and the total land area). Figures V_5b-e report column charts of these five MPs. Overall, the average values of the abovementioned MPs are $H_m = 22.51$ m, $H_{mw} = 23.75$ m, $\lambda_p = 0.33$, $\lambda_{vol} = 7.95$ m, and $\lambda_{faç} = 1.47$. Regarding λ_p , the low-density slabs present values between 0.21 and 0.25 (cases A, B, C, and D), the medium-density slabs have values equal to 0.29 and 0.33 (cases F and L, respectively), and the high-density slab has a value equal to 0.36 (case E). The courts represent more compact urban morphologies: case G has $\lambda_p = 0.32$ (medium dense), and cases H and I have $\lambda_p = 0.37$ and 0.41 (highly dense), respectively. Regarding the palazzina, their λ_p is high and equal to 0.39 for case J, 0.46 for case K, 0.37 for case M, and 0.39 for case N. Regarding H_m , the minimum value corresponds to case F and is equal to 12.50 m. For H_{mw} , the minimum value corresponds again to case F, but the value is higher and equal to 18.47 m. The comparison between H_m and H_{mw} highlights the significant presence of the podium, especially on the North and along via Tuscolana (cases A, E, and F). Examining λ_{vol} , the slabs exhibit the lowest values except for case E, which is the high-dense slab. The other typologies have values around 8.00 m and above. Regarding $\lambda_{faç}$, the slab

is again the typology with the lowest values apart from case E. The high-density slab and palazzina (cases E and K, respectively) provide the highest values of λ_{jq} equal to 1.91 and 2.09, respectively.

V_4 CFD simulations

The computational parameters and settings used for performing the 3D RANS simulations have been described and discussed in detail in a previous publication [41]. Therefore, the present paper reports only the information regarded as a fundamental basis for understanding and discussing the results. The readers may refer to Palusci et al. [41] for further detailed information about computational domain and grid, boundary and inflow conditions, and solver settings. Nevertheless, new contents are included in this section involving the methodology adopted for deriving the aerodynamic roughness length, z_0 , and calculating the age of air, τ . It should be noted that, prior to the analysis presented in this paper, the CFD simulations were based on actions for quality assurance, including solution verification and validation.

A model validation study was performed by applying the “sub-configuration validation procedure” [12,81–83]. For validation, the wind tunnel (WT) data provided by Soulhac et al. [65] was used since the simplified urban geometry from these WT measurements can be considered representative of components of the actual problem under investigation, as required by the sub-configuration procedure. Furthermore, this simplified urban geometry was also used for the grid-convergence study performed by employing the grid-convergence index (GCI) [84]. Detailed information and results of the grid-convergence and validation studies may be found in Palusci et al. [41]. These results have been used to generate the grid and set the computational parameters for performing the simulations in the Tuscolano-Don Bosco district.

V_4.1 Computational domain and grid

The computational domain was built in accordance with the best practice guidelines [12,82,85,86], considering the height of the tallest building (40 m). Hence, the height of the domain is equal to $6H_{\max}$ (240 m), and the size of the horizontal plane is 5000 m $\times$ 5000 m to allow the full development of the wake region irrespective of the wind direction [12] (Fig. V_6a). The abovementioned guidelines were also followed for the grid, which was generated with a high resolution using the surface grid extrusion technique [87]. The resulting grid comprises about 86 million hexahedral cells (Fig. V_6e-g).

V_4.2 Boundary conditions

At the inlet plane, the vertical profiles of mean wind speed, U (m/s), turbulence kinetic energy, k (m²/s²) and turbulence dissipation rate, ε (m²/s³), were imposed using the following equations:

$$U(z) = \frac{u_*}{\kappa} \ln \left(\frac{z+z_0}{z_0} \right) \quad \text{V_1}$$

$$k(z) = \frac{(u_*)^2}{\sqrt{C_\mu}} \quad \text{V_2}$$

$$\varepsilon(z) = \frac{(u_*)^3}{\kappa(z+z_0)} \quad \text{V_3}$$

where $C_\mu = 0.09$ is a constant, u_* is the friction velocity, $\kappa = 0.42$ is the von Karman constant, and z_0 is the height.

A wind speed of 3 m/s at $z = 10$ m was imposed at the inlet, and twelve wind directions, every 30° starting from North (0°), were considered for the simulations. Three values of z_0 were used to model the urban area upwind of the domain: 0.25 m, 0.5 m, and 1.0 m. The methodology for calculating z_0 is described in the following paragraph. A symmetry boundary condition was applied at the top of the

domain, while zero static gauge pressure or symmetry boundary conditions were imposed at the domain sides, depending on the wind direction (Fig. V_6b-c).

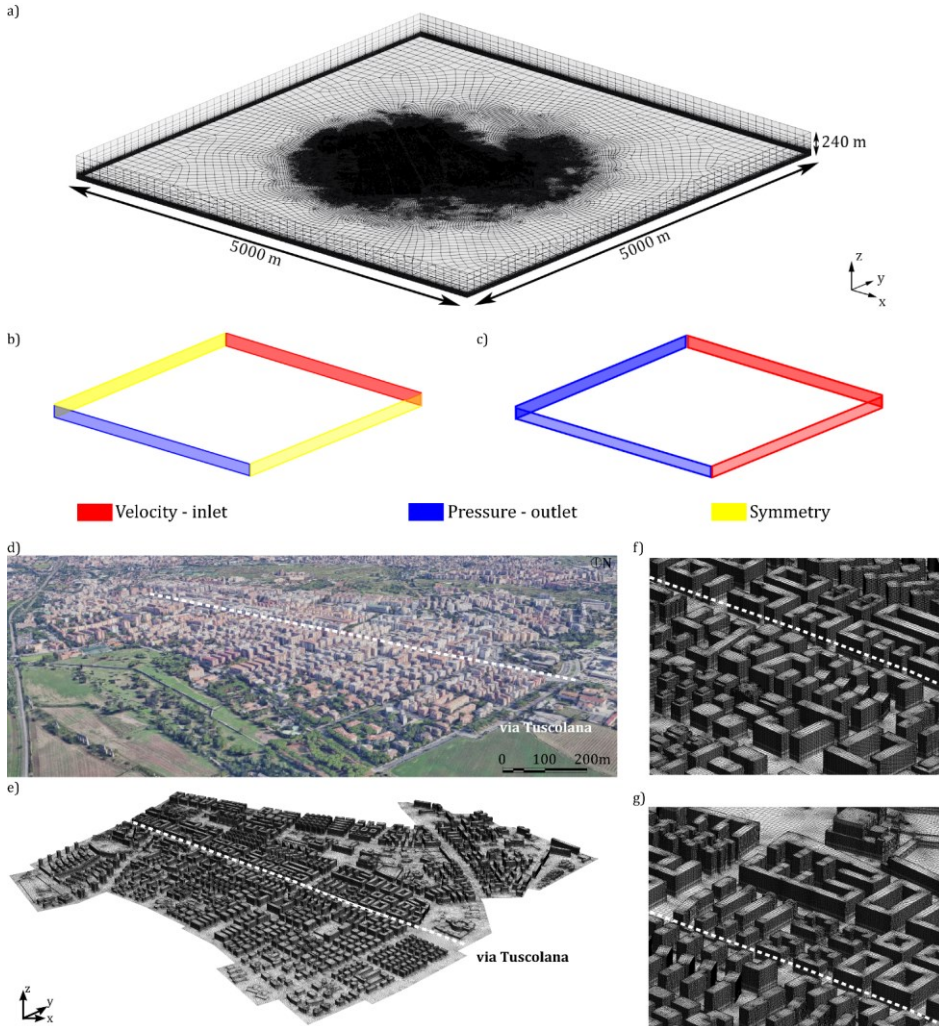


Fig. V_6 - (a) Axonometric view of the computational grid; (b) boundary conditions applied to the vertical planes for simulating wind direction 0° ; (c) boundary conditions applied to the vertical planes for simulating wind direction from 30° to 60° ; (d) perspective view of the area of interest (modified from Google Maps); (e) perspective view of the computational grid; (f) and (g) its enlargement. The total cell count is about 86 million.

The aerodynamic roughness length z_0 was estimated according to the Davenport-Wieringa roughness classification [88] from the land use map [89] (Fig V_7).

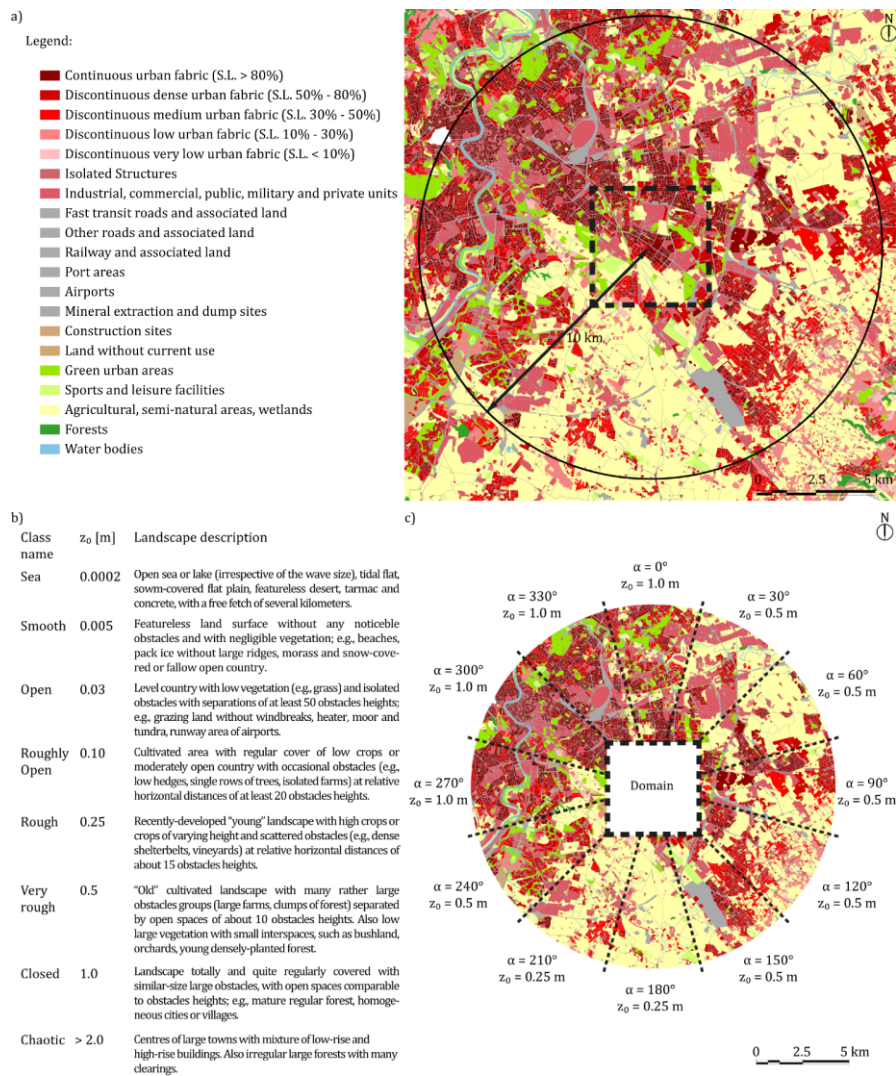


Fig. V_7 - (a) Land-use map from the Urban Atlas with the indication of the dimension of the computational domain (black dashed rectangle) [89]; **(b)** Davenport-Wieringa classification of the aerodynamic roughness length [88]; **(c)** computational domain and evaluation of the aerodynamic roughness length for twelve wind directions considering a radius of 10 km.

For the estimation, an area enclosed by a circle of a 10 km radius around the area under investigation was considered on the land use map of Rome (Fig V_7a). The circle was divided into as many sectors as the considered wind directions; then, the different land uses were identified for each sector. The qualitative descriptions of

the land uses were first combined with the Davenport-Wieringa roughness classification and then translated into the corresponding z_0 class (Fig V_7b). Finally, the area-weighted mean z_0 was calculated for each sector (Fig V_7c). The application of this methodology benefits from using GIS software that allows combining information of different land use types employing algorithms and scripts.

V_4.3 Solver settings

Ansys Fluent 16.2 [90] was employed for performing the 3D steady RANS equations. The following settings have been applied for closure, pressure-velocity coupling, and discretization schemes: the realizable k - ε model [91], the SIMPLE algorithm, and second-order schemes, respectively. Finally, every simulation was run for 12,000 iterations when the scaled residuals showed no further reduction with an increasing number of iterations. The following minimum values were reached: 10^{-5} for continuity and ε , 10^{-4} for k , and 10^{-7} for x -, y - and z -velocity.

V_4.4 Age of air

The homogeneous emission method proposed by Hang et al. [92] was applied to calculate the age of air. This method, originally developed for indoor experiments using tracer gas techniques [49,50], proves to be effective because it avoids the dependence of τ on pollutant source characteristics and location. The method considers an emission released homogeneously within the entire computational domain with an emission rate $\dot{m}$ (kg/m³s). Thus, the mean age of air τ was obtained from the local concentration c (kg/m³) and calculated as:

$$\tau = \frac{c}{\dot{m}} \tag{V_4}$$

The turbulent Schmidt number, $Sc_t = \nu_t/D_t$, where ν_t is the turbulent viscosity, and D_t is the turbulent diffusivity of the pollutant, is assumed equal to 0.7 in the whole

domain. This value was employed in previous studies on both real and simplified urban areas [24,51,67,93,94].

Eq. V_4 can be considered as the link between a concentration value and a time scale [79]. Higher values of τ are associated with cases in which fresh air particles take longer to reach specific locations and replace exhausted air particles. These cases may correspond to weak wind conditions and poor urban ventilation performance. Consequently, accumulation of pollutants and heat may occur in these cases, and citizens may experience poor air quality and thermal discomfort.

V_5 Results and discussion

This section aims to describe the wind environment in a real urban area and quantify the effectiveness of different urban morphologies in enhancing urban ventilation. For this purpose, a set of indicators consisting of the spatially averaged mean wind velocity ratio (mWVR), the local age of air (τ_{loc}), and their derivatives are employed. The indicators are determined as follows:

- γ is the mWVR calculated as $\gamma_{ped} = U_{ped}/U_{ref}$, where U_{ped} is the spatially averaged mean velocity at pedestrian level $z_{ped} = 1.8$ m, and U_{ref} is the mean velocity magnitude set at z_{ped} at the inlet plane. The subscript ped is omitted in what follows since the results presented in this work all refer to the pedestrian level. This indicator can be interpreted as the reduction ($\gamma < 1$) or amplification ($\gamma > 1$) in the mean wind speed experienced by pedestrians and caused by the urban area.
- τ_{loc} is the difference between τ calculated for each wind direction as described in Subsection 4.4 and the minimum value found in the area under investigation, i.e., the AoI or the fourteen cases, for each wind direction. Thus, the contribution due to the location of the area under investigation within the domain is minimized. It should be noted that τ_{loc} is used for

comparing the effects of different wind directions by analyzing the various areas separately. Therefore, it is possible to assume that the position of the case within the AoI is not relevant to the discussion of the results.

- $\Delta\gamma$ and $\Delta\beta$ (the deviations of γ) are calculated as $\Delta\gamma = (\gamma - \gamma_{ref}) / \gamma_{ref}$, where γ is the mWVR of the area under investigation and γ_{ref} is the mWVR observed in a reference condition. Hence, $\Delta\gamma > 0$ entails an increase in wind speed compared to the reference condition, while $\Delta\gamma < 0$ entails a reduction. $\Delta\gamma = 0$ means that the case under investigation does not deviate from the reference condition. Although $\Delta\gamma$ and $\Delta\beta$ have the same definition in theory, it has been decided to name the two indicators differently because γ_{ref} is different in the two definitions. $\Delta\gamma$ is used when γ_{ref} is referred to the wind condition in the entire AoI, while $\Delta\beta$ is used when γ_{ref} is referred to the wind condition of the specific case. The two indicators are used to discuss the results in different subsections. Nevertheless, the list of indicators and their definitions are reported at the beginning of each subsection. This choice seems adequate to avoid possible confusion and misunderstanding.
- $\Delta\tau_{loc}$ (the deviation of τ_{loc}) is calculated as $\Delta\tau_{loc} = (\tau_{loc} - \tau_{loc-ref}) / \tau_{loc-ref}$, where τ_{loc} is the spatially averaged mean local age of air of the area under investigation and $\tau_{loc-ref}$ is the spatially averaged mean local age of air observed in a reference condition. Hence, $\Delta\tau_{loc} < 0$ entails an improvement in the urban ventilation performance with a reduction in the age of air compared to the reference condition, while $\Delta\tau_{loc} > 0$ entails a worsening in the urban ventilation performance with an increase in the age of air. $\Delta\tau_{loc} = 0$ means that the case under investigation does not deviate from the reference condition.

The results are presented and discussed in five subsections based on the objectives. In Subsection V_5.1, the focus is on the description of the phenomenon. In

Subsection V_5.2, the emphasis is on the quantification of the effects of wind directions and general morphological characteristics. In Subsection V_5.3, the effectiveness of different morphologies is quantified and compared. In Subsection V_5.4, the impact of the interactions between the local characteristics of the different morphologies and wind directions is investigated. Finally, in Subsection V_5.5, the results are further discussed by relating the effectiveness evaluated in the previous subsection to the features highlighted in Subsection V_4.1 for specific morphologies. In each Subsection, the definitions of the employed indicators are recalled.

V_5.1 The phenomenology

This subsection focuses on the description of the wind environment in a real urban area. Features that play a fundamental role are highlighted and explained, referring to the studies reported in Section V_2.

Figure V_8 shows the contours of γ for the twelve wind directions (α) considered. First, it is possible to note that $\alpha = 30^\circ$ and 210° are nearly perpendicular to the longitudinal axes of the main UCs of the area, i.e., the long canyons characterized by continuous and tall fronts and parallel to via Tuscolana. In contrast, $\alpha = 120^\circ$ and 300° are almost parallel to them. Regarding the parallel orientations, remarkable speedup areas occur for $\alpha = 300^\circ$ due to channeling effects and formations of horse-shoe vortices with characteristics similar to those mentioned in Section 2 (Fig. V_8m). Conversely, such features are not present for $\alpha = 120^\circ$ because of the tilted UCs on the right side of the analyzed area (Fig. V_8e). Notable speedup areas, arguably due to pressure short-circuiting and tall buildings facing open spaces, are also present for $\alpha = 0^\circ, 30^\circ, 270^\circ$, and 330° (Fig. V_8a,b,l,n). Regarding the other wind directions, regions characterized by localized speedup areas with a limited spatial extent also occur. Specifically, the effects of the presence of tall buildings, i.e., pavilion-tower typology, can be seen in the bottom-left part of Figures V_8l,m.

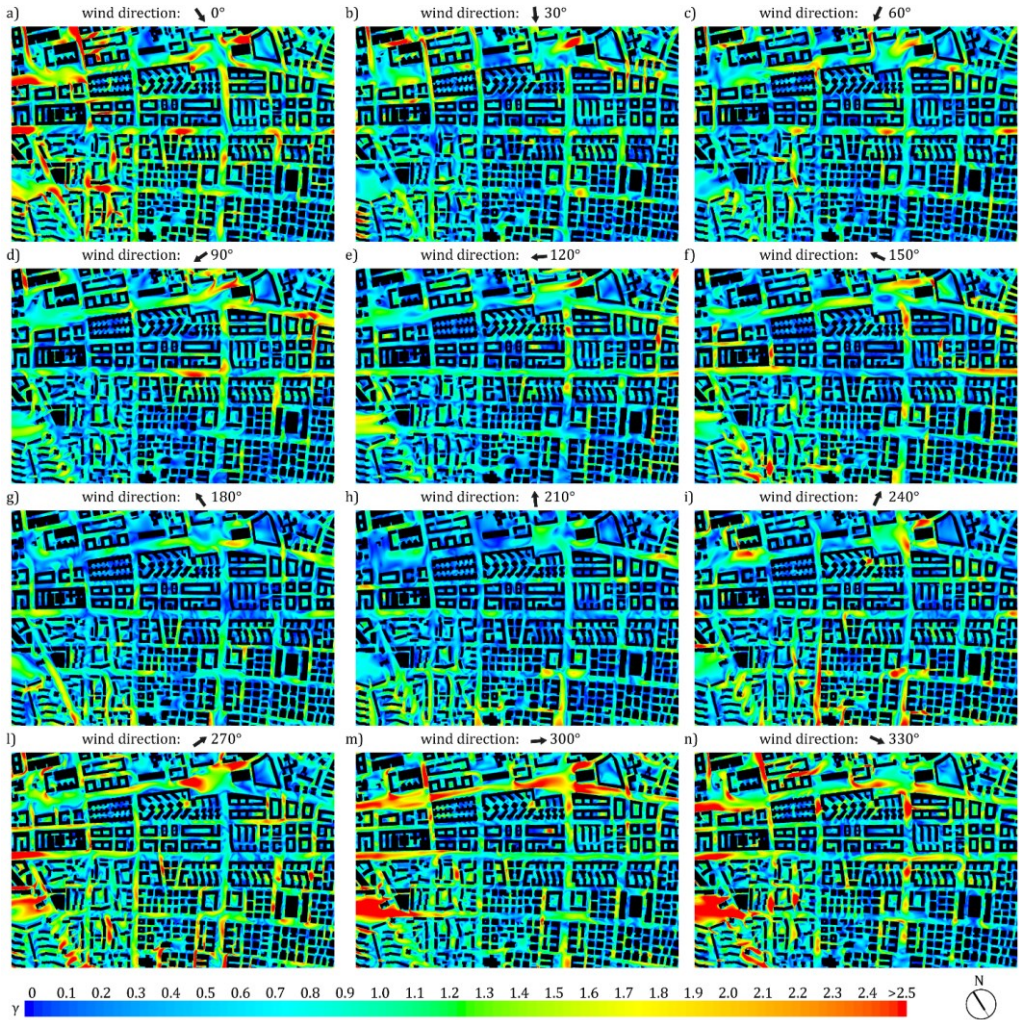


Fig. V_8 - (a-n) Contours of the spatially averaged mean wind velocity ratio, γ , at the pedestrian level for twelve wind directions.

Figure V_9 shows the contours of τ_{loc} for the twelve wind directions considered. It is possible to observe how the diverse morphologies and the characteristics of single buildings, e.g., the orientation compared to the wind direction and the height, affect τ_{loc} . This aspect is particularly evident by analyzing the τ_{loc} distribution within the central area as α varies. For example, the open spaces enclosed by these buildings

experience substantially different values of τ_{loc} depending upon the orientation of the tall slabs.

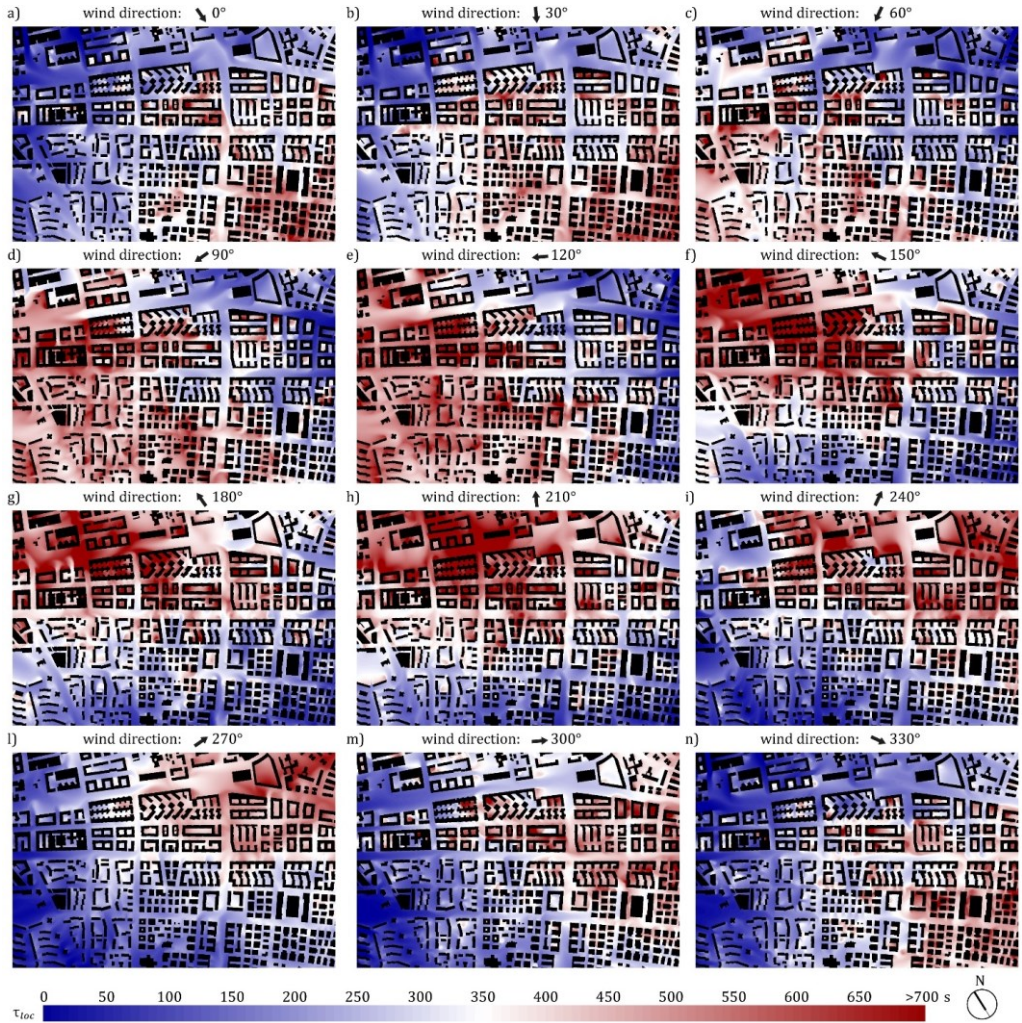


Fig. V 9 - (a-n) Contours of the local age of air [s], τ_{loc} , at the pedestrian level for twelve wind directions.

Five features influencing the resulting urban ventilation phenomenon can be distinguished from the previous analysis:

- the shelter effect due to the long and continuous fronts perpendicular to the wind direction;

- accelerations in the wind speed caused by pressure short-circuiting;
- the channeling effect for wind directions parallel to the main axis of the UCs;
- speedup areas due to horseshoe and wake vortices and high turbulence levels at the pedestrian level caused by the presence of isolated tall buildings;
- helical flows within the secondary UCs that enhance urban ventilation and ease pollutants and heat dilution for wind directions oblique with respect to the axes of the main UCs.

Bearing in mind the morphological characteristics of the area and the differences between the northern and southern regions, it is possible to conclude that there is a clear dependence of the airflow at the pedestrian level on wind direction and urban morphology. Therefore, further analyses are required to quantify the impact of each of these features.

V_5.2 The effects of wind direction and overall morphological aspects

In this subsection, the urban ventilation performance in the AoI is investigated in detail using γ , τ_{loc} , and $\angle\tau_{loc}$ as indicators (Fig. V_10).

Figure V_10a reports a boxplot chart of γ averaged over the entire area of AoI for each wind direction, α , and over the twelve directions. The latter, called avg, has been distinguished in the figure from the others by a red dotted line. For identifying the AoI, please refer to Figures 4a and 5a. The maximum values range from 2.49 to 4.00 for $\alpha = 180^\circ$ and 300° , respectively, with an average value of 3.30. These values are consistent with those reported in the literature corresponding to vortex-flows, through-flows, corner stream areas, and passages between buildings [29,61,62]. Regarding the median of γ , the average value over the twelve directions is 0.52. The lowest median value (0.41) is found for $\alpha = 210^\circ$, while the highest value (0.65) occurs for $\alpha = 270^\circ$. Similar behavior is also observed for the mean values of γ (Fig. V_10c). This characteristic seems interesting to highlight and discuss. Direction

210° is parallel to the discontinuous and low urban canyons in the South and perpendicular to the long, continuous, and tall canyons in the North. Arguably, the shelter effect due to long perpendicular canyons and the scarcity of helical flows in secondary canyons due to almost parallel canyons determines the weakest wind conditions. On the other hand, even though $\alpha = 300^\circ$ entails the highest γ_{max} (Fig. V_10a), as well as the most pronounced and extended speedup areas (Fig. V_8m), γ averaged over the entire AoI does not attain its highest value for this wind direction, but for $\alpha = 0^\circ$ and 270° . This finding is supported by previous studies conducted for idealized urban areas, e.g., [68] (Fig. V_2b).

Figure V_10b shows a bar chart of the mean and maximum values of the spatially averaged local age of air, reporting the mean, τ_{loc} , and the maximum values, $\tau_{loc-max}$, respectively. The average over the twelve wind directions of τ_{loc} is 346 s, while the average of $\tau_{loc-max}$ is 1161 s. Regarding the mean values, τ_{loc} ranges from 297 s for $\alpha = 330^\circ$ to 392 s for $\alpha = 210^\circ$, confirming that the latter corresponds to the weakest wind conditions.

Figure V_10c shows a bar chart of γ and τ_{loc} . Regarding γ , the lowest and highest values are 0.40 for $\alpha = 210^\circ$ and 0.77 for $\alpha = 0^\circ$ and 270° , respectively, while the average over the twelve directions is 0.60. The highest values of γ correspond to wind from the northwestern sectors ($\alpha = 270^\circ, 300^\circ, 330^\circ$, and 0°). This observation may be ascribed to the urban morphology and building typology of the AoI. In fact, the upper-left side of the AoI is characterized by higher buildings, larger public spaces (squares and boulevards), and longer UCs compared to other areas. All these features contribute to the channeling effect since winds approaching from these directions are almost parallel to the longitudinal axis of the main boulevards. This aspect is also evident in Figures V_8a and V_8l-n, as reported in the previous subsection.

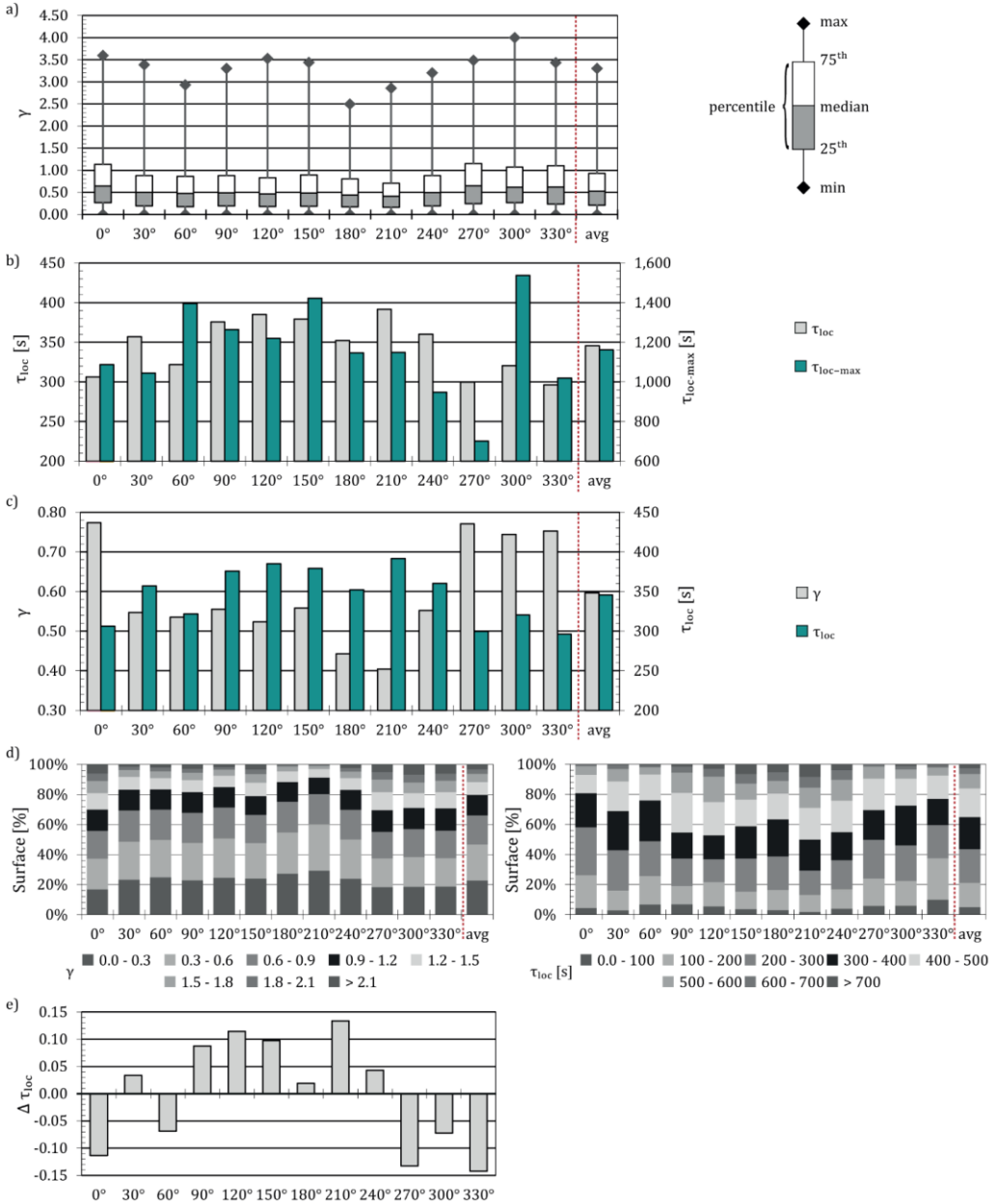


Fig. V_10 - (a) Boxplot chart of the spatially averaged mean wind velocity ratio, γ ; **(b)** bar charts of mean and max local age of air, τ_{loc} and $\tau_{loc-max}$, respectively; **(c)** bar charts of γ and τ_{loc} ; **(d)** stacked bar charts for comparing the amount of surface of AoI where pedestrians can experience the reduction in wind speed showed in the legend with the corresponding local age of air; **(e)** difference between the mean local age of air at the specified direction and that averaged over the twelve wind direction, $\Delta \tau_{loc}$;

Figure V_10d shows the stacked bar charts of the amount of surface of the AoI characterized by specific urban ventilation performances expressed in terms of γ and τ_{loc} . Regarding γ , it is possible to distinguish two main groups: (i) $\alpha = 30^\circ$ - 180° , and 240° , where, on average, in 70% of the AoI, γ is below 0.9; and (ii) $\alpha = 0^\circ$, 270° - 330° , where, on average, in only 56% of the AoI, γ is below 0.9. $\alpha = 210^\circ$ (corresponding to the direction with the weakest wind conditions) is not included since γ is below 0.9 in 80% of the AoI. Regarding τ_{loc} , it is evident that $\alpha = 90^\circ$ - 240° correspond to weak wind conditions, with $\alpha = 210^\circ$ confirmed as the weakest. Finally, these charts prove to be very useful in investigating urban ventilation performance better and highlight its dependence on wind direction. In fact, $\alpha = 30^\circ$ - 90° present very similar values of γ . However, clear differences between the three directions can be noted by analyzing the percentage of the surface with specific values of τ_{loc} .

Figure V_10e reports $\Delta\tau_{loc}$ to examine the effects of wind direction and overall morphological characteristics in more detail. $\Delta\tau_{loc}$ represents the deviation of τ_{loc} calculated in the AoI for every wind direction from the average over the twelve wind directions. For example, $\Delta\tau_{loc-30} = (\tau_{loc-30} - \tau_{loc-ALL}) / \tau_{loc-ALL}$, where τ_{loc-30} is τ_{loc} calculated in the AoI for $\alpha = 30^\circ$, and $\tau_{loc-ALL}$ is τ_{loc} calculated in the AoI averaged over the twelve wind directions. The effect of the wind directions is evident, even if the deviations are not remarkable and range from -0.14 to +0.13 for $\alpha = 330^\circ$ and 210° , respectively. Finally, $\alpha = 300^\circ$ corresponds to a reduction of 0.07 that is equal to the one observed for $\alpha = 60^\circ$ even if γ differs substantially for the two directions: $\gamma = 0.54$ and 0.74 for $\alpha = 60^\circ$ and 300° , respectively.

At the district scale, there is clear evidence of the impact of urban morphology on the urban ventilation performance of the AoI. To further analyze this impact and investigate the effectiveness of different morphologies, fourteen cases have been selected within the AoI, and their ventilation performance is examined in detail in the following subsections.

V_5.3 The effectiveness of the different morphologies

In this subsection, the effectiveness of diverse morphologies in enhancing urban ventilation is evaluated for each of the fourteen selected cases using as indicators γ , γ_{max} , and $\Delta\gamma$ (Figs V_11). The reference condition for calculating $\Delta\gamma$ is the spatially averaged mean wind velocity ratio evaluated for the AoI and averaged over the twelve wind directions. This choice seems suitable for evaluating the beneficial or detrimental contribution, i.e., the effectiveness in enhancing urban ventilation of diverse morphologies. The fourteen cases are subdivided into three groups according to the prevalent building typology by different colors to ease the discussion of the results. To identify the AoI and fourteen cases, please refer to Figure V_5a.

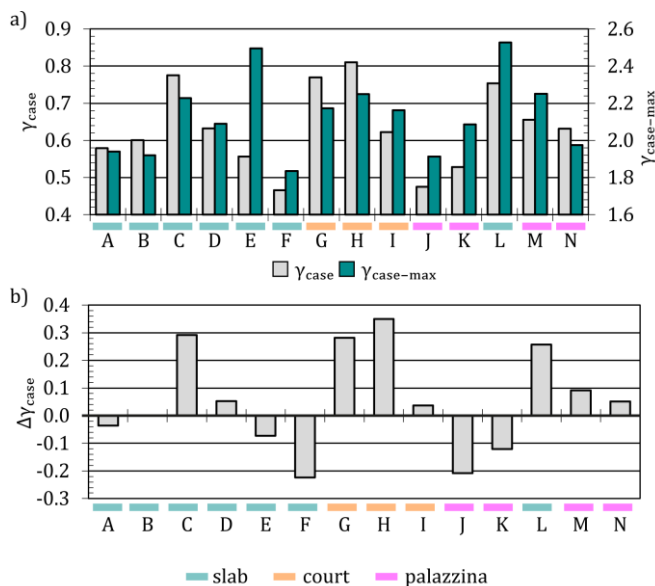


Fig. V_11 - (a) Column chart of the mean and max spatially averaged mean wind velocity ratio, γ_{case} and $\gamma_{case-max}$, respectively; **(b)** difference between the non-dimensional wind speed averaged over the twelve wind directions at the specified case and that calculated as the average over the twelve wind directions for the AoI, $\Delta\gamma_{case}$.

Figure V_11a shows a bar chart of γ_{case} and γ_{max} averaged over the twelve wind directions for each of the fourteen cases. γ_{case} ranges from 0.47 (case F, medium-dense slab) to 0.81 (case H, court). Such a wide range confirms the potential of using urban morphology knowingly for enhancing urban ventilation performance. Based on the magnitude of the reduction, the fourteen cases can be subdivided into three groups:

- Remarkable reductions $\rightarrow \gamma_{case} < 0.55$ (cases F, J, and K).
- Significant reductions $\rightarrow 0.55 \leq \gamma_{case} < 0.75$ (cases A, B, D, E, I, M, and N).
- Slight reductions $\rightarrow \gamma_{case} \geq 0.75$ (cases C, G, H, and L).

Overall, substantial reductions in γ_{case} occur in the selected cases, with evident differences based on the morphologies under investigation. On average, citizens experience, in the selected cases, a wind speed that is 0.63 times that experienced outside the urban area at the pedestrian level. However, it is not possible to find a correspondence between the magnitude of the reduction and the λ_p . As expected, cases J and K (palazzina typology), two of the most densely built cases ($\lambda_p = 0.39$ and 0.46, respectively), show the lowest γ_{case} . Nevertheless, for case F (slab typology), which presents the highest reduction in wind speed ($\gamma_{case} = 0.47$), λ_p equals 0.29. Similar behavior also occurs in the other groups. For instance, slight differences in γ_{case} (0.78 and 0.81, respectively) found in cases C (slab typology) and H (court typology) correspond to significant differences in λ_p (0.24 and 0.37, respectively). Regarding $\gamma_{case-max}$, its minimum (1.83) occurs for case F, while its maximum (2.53) is found for case L. These values are comparable to those found in the literature (Fig. V_1).

Figure V_11b shows a bar chart of $\Delta\gamma_{case}$ listing the deviation of each γ_{case} , i.e., γ_{case} calculated for each case averaged over the twelve wind directions, from γ , i.e., γ calculated in the AoI averaged over the twelve wind directions. Therefore, e.g., $\Delta\gamma_A = (\gamma_A - \gamma) / \gamma$, where γ_A is the spatially averaged mean wind velocity ratio calculated

in case A averaged over the twelve wind directions and γ (0.60) is the spatially averaged mean wind velocity ratio calculated in AoI averaged over the twelve wind directions. This choice seems suitable for assessing the effectiveness of enhancing urban ventilation of different morphologies, as this indicator shows localized improvement or worsening of urban ventilation compared to the entire AoI. Some selected cases stand out for their effectiveness. Specifically, cases C, G, H, and L present an enhancement of urban ventilation between 26% and 35%. Conversely, cases F, J, and K present a worsening between 12% and 22%. Moreover, a wide range of $\Delta\gamma_{case}$ within the same typology can be noted:

- Slabs $\rightarrow \Delta\gamma_{case}$ ranges from -0.22 (case F) to +0.29 (case C). Although cases F and L are both representative of medium-dense slabs, they show very different $\Delta\gamma_{case}$: - 0.22 and +0.26, respectively. A large $\Delta\gamma_{case}$ range is also observed for the low-dense slab category, where $\Delta\gamma_{case} = -0.04, 0.00, +0.29$, and +0.05 for cases A, B, C, and D, respectively.
- Courts $\rightarrow$ large differences are also found for this typology, where $\Delta\gamma_{case} = +0.28, +0.35$, and +0.04, for cases G, H, and I, respectively.
- Palazzina $\rightarrow$ remarkable differences are observed for this typology, where $\Delta\gamma_{case} = -0.21, -0.12, +0.09$, and +0.05 for cases J, K, M, and N, respectively. Although case K shows a high λ_p (0.46), it does not correspond to the lowest $\Delta\gamma_{case}$.

To further investigate the effectiveness of the diverse morphologies highlighting the effect of the wind direction, the quantity $\Delta\gamma_{case-\alpha}$ is shown in Figure V_12. $\Delta\gamma_{case-\alpha}$ is the ratio between $\gamma_{case-\alpha}$ of each case for the specified direction α and γ_{dir} of the AoI for the specified wind direction α . For example, $\Delta\gamma_{A-30} = (\gamma_{A-30} - \gamma_{30}) / \gamma_{30}$, where γ_{A-30} is the spatially averaged mean wind velocity ratio calculated in case A for $\alpha = 30^\circ$, and γ_{30} is the spatially averaged mean wind velocity ratio calculated in AoI for the same wind direction.

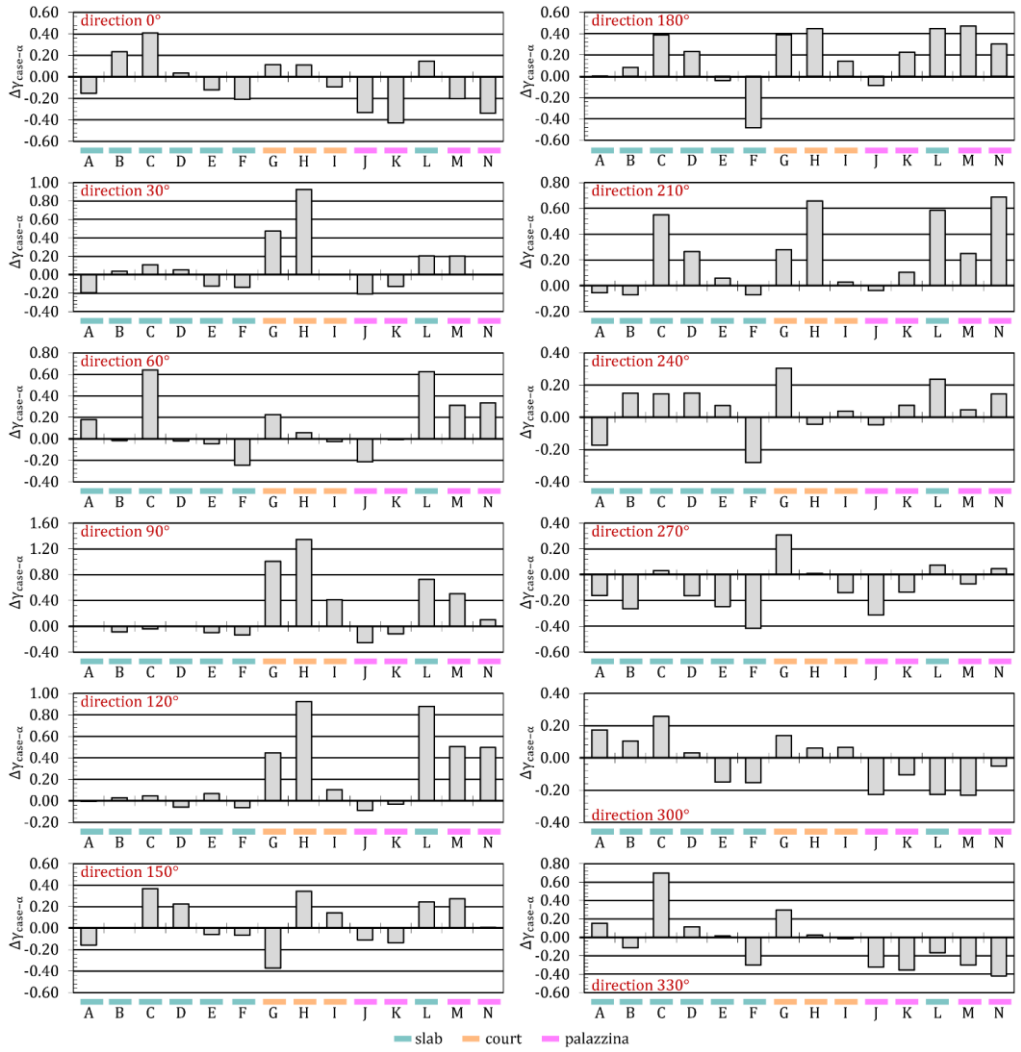


Fig. V_12 - Deviations of the spatially averaged non-dimensional wind speed for the specified case at the specified wind direction from that calculated as the spatially averaged for the AoI at the specified wind direction.

For each wind direction, the most important results can be summarized as follows:

- $\alpha = 0^\circ$. The cases characterized by the palazzina typology imply a remarkable reduction in γ_{case-0} compared to γ_{AoI-0} : $\Delta\gamma_{case-0} = -0.33$ (case J), -0.43 (case K), -0.20 (case M), and -0.34 (case N). Hence, for this direction, γ_{j-0} , γ_{k-0} , γ_{m-0} , and γ_{n-0} are 33%, 43%, 20%, and 34% lower than γ_{AoI-0} (0.77).

Moreover, a slight correspondence between λ_P and $\Delta\gamma_{case-0}$ can be found since larger reductions in γ_{case-0} may be observed for higher λ_P . Incidentally, these morphologies resemble the idealized urban areas formed by cube-like or parallelepiped-like buildings. The angle between the axis of streets and the wind direction is approximately 45° . It is worth noting that morphologies characterized by other typologies do not present univocal behaviors. Regarding the slab typology, while the high-dense slab case E exhibits an expected reduction ($\Delta\gamma_{E-0} = -0.12$), the medium-density slab cases F ($\Delta\gamma_{F-0} = -0.21$) and L ($\Delta\gamma_{L-0} = +0.15$) show opposite behavior. Significant differences in the results are also found for the low-density slab cases: $\Delta\gamma_{case-0} = -0.15$ for case A, $+0.23$ for case B, $+0.41$ for case C, and $+0.03$ for case D. Case C should be carefully considered to avoid pedestrian wind comfort problems. In fact, the reduction in wind speed within AoI for $\alpha = 0^\circ$ is one of the smallest, $\gamma_{AoI} = 0.74$, and a similar increase ($+41\%$) determines an amplification in wind speed, i.e., $\gamma_{c-0} = 1.09$.

- $\alpha = 30^\circ$. The deviations from γ_{AoI-30} are small ($-0.21 < \Delta\gamma_{case-30} < 0.20$) apart from cases G and H, belonging to the court typology, which stand out, displaying $\gamma_{case-30}$ 47% and 92% higher than γ_{AoI-30} (0.55), respectively. These increases are due to the channeling effect caused by the alignment of the wind direction to the main axis of the long continuous canyons forming the islands. Finally, the palazzina typology determines morphologies presenting different results: $\Delta\gamma_{case-30} = -0.21$ for case J, -0.13 for case K, $+0.20$ for case M and 0.00 for case N.
- $\alpha = 60^\circ$. Three different behaviors can be observed: (i) almost no deviations from γ_{AoI-60} since $\Delta\gamma_{case-60}$ ranges from -0.04 and $+0.06$ for cases B, D, E, H, I, and K; (ii) significant deviations from γ_{AoI-60} for cases A, F, G, J, M, and N since $\gamma_{case-60}$ ranges from -0.25 and $+0.34$; and (iii) remarkable increases in $\gamma_{case-60}$ compared to γ_{AoI-60} for cases C and L belonging to the slab typology

disregarding the density. Although cases C and L belong to different categories, i.e., the low-dense category with $\lambda_p = 0.24$ and the medium-dense case with $\lambda_p = 0.33$, respectively, $\Delta\gamma_{case-60}$ present almost the same value for the two cases, +0.64 and +0.63, respectively. The lack of correspondence between $\Delta\gamma_{case-60}$ and λ_p is confirmed for every building typology selected.

- $\alpha = 90^\circ$. Large increases of $\gamma_{case-90}$ occur for cases G, H, I, L, and M with $\Delta\gamma_{case-90}$ equal to +1.01, +1.35, +0.41, +0.73, and +0.50, respectively, while the other cases show little to no deviations compared to γ_{AoI-90} . The first three cases belong to the court typology. Overall, the increases are due to speedup areas caused by pressure short-circuiting and channeling effects (Figs V_8d and V_14c). $\gamma_{g-90} = 1.1$ and $\gamma_{s-90} = 1.3$, determining an amplification in wind speed compared to that experienced at the pedestrian level outside the urban area. Therefore, cases G and H should be carefully considered to avoid pedestrian wind comfort problems.
- $\alpha = 120^\circ$. Two different behaviors appear: (i) little to no deviations compared to $\gamma_{AoI-120}$ for cases A, B, C, D, E, F, I, J, and K with $\Delta\gamma_{case-120}$ ranging from -0.09 to +0.10; and (ii) remarkable deviations with $\Delta\gamma_{case-120} = +0.45$ for case G, +0.92 for case H, +0.88 for case L, +0.51 for case M and +0.50 for case N. Since this direction is nearly parallel to the long UCs with high and continuous fronts, amplification in wind speed may be related to channeling effects (Fig V_8e).
- $\alpha = 150^\circ$. Two main features are highlighted: (i) the shelter effect caused by the upstream morphologies, particularly evident for case G and significant in cases A, J, and K; and (ii) localized speedup areas for cases C, D, H, I, L, and M (Fig. 8f). The shelter effect determines a reduction in $\gamma_{case-150}$ compared to $\gamma_{AoI-150}$ of -16%, -37%, -11%, and -13% for cases A, G, J, and K, respectively. The localized speedup areas contribute to increases in $\gamma_{case-150}$ compared to $\gamma_{AoI-150}$ above 22% and up to 37%.

- $\alpha = 180^\circ$. Apart from four cases (A, E, F, and J), the selected morphologies present significant increases of $\gamma_{\text{case-180}}$ compared to $\gamma_{\text{AoI-180}}$ with $\Delta\gamma_{\text{case-180}}$ ranging from +0.08 (case B) to +0.47 (case M). Case F stands out, presenting a remarkable reduction in $\gamma_{\text{case-180}}$ compared to $\gamma_{\text{AoI-180}}$, 48%. This characteristic may be due to high buildings placed close to each other just upstream of the selected case that act as a barrier and may compromise the urban ventilation performance. A similar effect has been identified by Yim et al. [43]. Increases are also found in the court category ($\Delta\gamma_{\text{case-180}}$ equal to +0.39 for case G, +0.45 for case H, and +0.14 for case I). The morphologies characterized by the palazzina typology show different deviations for cases K (+0.23), M (+0.47), and N (+0.30) and a reduction in case J (-0.09).
- $\alpha = 210^\circ$. This direction entails the poorest wind conditions within AoI. Nevertheless, a substantial increase in wind speed may be found in some cases, causing desirable improvements in urban ventilation. Hence, $\Delta\gamma_{\text{case-210}} = +0.55$ for case C, +0.27 for case D, +0.28 for case G, +0.66 for case H, +0.58 for case L, +0.25 for case M, and +0.69 for case N. For the other cases, the deviations are rather limited, and $\Delta\gamma_{\text{case-210}}$ ranges from -0.07 for cases B and F to +0.11 for case K.
- $\alpha = 240^\circ$. Case F stands out for the largest reduction in wind speed with $\Delta\gamma_{\text{case-240}} = -0.28$, followed by case A with $\Delta\gamma_{\text{case-240}} = -0.17$. The shelter effects are evident in these cases in Fig. V_8i. Conversely, cases G and L present increases in the wind speed ($\Delta\gamma_{\text{case-240}} = +0.30$ and +0.24, respectively). These increases are due to the speedup areas evident in Fig. V_8i.
- $\alpha = 270^\circ$. Since $\gamma_{\text{AoI-270}} = 0.77$, i.e., a low reduction, it is not surprising if $\Delta\gamma_{\text{case-270}} < 0$ for most cases. Cases F and J show remarkable reductions, being $\Delta\gamma_{\text{case-270}} = -0.42$ and -0.31, respectively. Finally, since $\gamma_{\text{AoI-270}} = 0.77$,

the amplification exhibited by case G ($\Delta\gamma_{g-270} = +0.31$) could compromise pedestrian wind comfort and should be carefully considered.

- $\alpha = 300^\circ$. Since $\gamma_{Aol-300} = 0.74$, i.e., a low reduction, increases in cases A ($\Delta\gamma_{a-300} = +0.17$) and C ($\Delta\gamma_{c-300} = +0.26$) could affect pedestrian wind comfort. Both cases belong to the slab category, and the buildings are alternatively placed perpendicular or parallel to the considered wind direction. Nevertheless, there are evident differences in the resulting morphologies that will be discussed in the following subsections. Finally, a considerable reduction can be found for cases J, L, and M, where $\Delta\gamma_{case-300} = -0.23$.
- $\alpha = 330^\circ$. Since $\gamma_{Aol-330}$ is equal to 0.75, also in this case, it is not surprising if many morphologies present values of $\Delta\gamma_{case-330} < 0$. Conversely, given the increase observed in case C ($\Delta\gamma_{c-300} = +0.70$), this morphology should be carefully considered because it may compromise pedestrian wind comfort.

From this analysis, it is possible to conclude that the large disparities observed for the different cases may not only be related to λ_p but also to specific characteristics of the morphologies and the relation with the wind direction. This feature is analyzed in the following subsections by investigating the urban ventilation performance of each of the fourteen cases separately.

V_5.4 The effects of wind direction for specific morphologies

Figure V_13 shows $\Delta\beta_{case-\alpha}$ and $\Delta\tau_{loc-case-\alpha}$ for each case to investigate the impact of the interactions between the local characteristics of the different morphologies and wind directions. For each case, $\Delta\beta_{case-\alpha} = (\gamma_{case-\alpha} - \gamma_{case} / \gamma_{case})$, where $\gamma_{case-\alpha}$ is the spatially averaged mean wind velocity ratio calculated in the specific case for the specified wind direction, α , and γ_{case} is the spatially averaged mean wind velocity ratio calculated in the specific case averaged over the twelve wind directions. For example, $\Delta\beta_{a-30} = (\gamma_{a-30} - \gamma_a / \gamma_a)$. In this way, it is possible to assume that deviations in wind speed from the average over the twelve wind directions are due to

interactions between morphological characteristics and wind direction. A similar definition has been applied for $\Delta\tau_{loc-case-\alpha}$, where $\tau_{loc-case-\alpha}$ is the difference between the simulated and the minimum values found within the case under investigation. For each case, $\Delta\tau_{loc-case-\alpha} = (\tau_{loc-case-\alpha} - \tau_{loc-case}) / \tau_{loc-case}$, where $\tau_{loc-case-\alpha}$ is the spatially averaged τ_{loc} calculated in the specific case for the specified wind direction, α , and $\tau_{loc-case}$ is the spatially averaged τ_{loc} calculated in the specific case averaged over the twelve wind directions. For example, $\Delta\tau_{loc-a-30} = (\tau_{loc-a-30} - \tau_{loc-30}) / \tau_{loc-30}$. In this way, the contribution due to the location within the AoI of the case under investigation may be considered negligible, and the urban ventilation performance may be quantified for each case under different wind directions. Hence, it is possible to highlight peculiar behaviors of specific morphologies resulting in reductions or increases of the wind speed and local age of air, determining a worsening or enhancement of urban ventilation:

- for $\Delta\beta_{case-\alpha} < 0$ and $\Delta\tau_{loc-case-\alpha} > 0$, the urban ventilation performance is worsen;
- for $\Delta\beta_{case-\alpha} > 0$ and $\Delta\tau_{loc-case-\alpha} < 0$, the urban ventilation performance is enhanced.

Analyzing Figure V_13, the focus is on the following aspects:

- the magnitude of the deviation of $\Delta\beta_{case-\alpha}$ and $\Delta\tau_{loc-case-\alpha}$;
- the existence of outliers;
- the directions where both quantities are increased or reduced;
- the directions where small deviations of an indicator correspond to large deviations in the other.

The first aspect may imply a high dependence of the urban ventilation performance of the identified case on the wind direction. The second aspect may entail peculiar effects of the interactions between urban morphology and wind flow. Finally, the third and fourth features should be further analyzed to highlight the localized effects that determine these conditions.

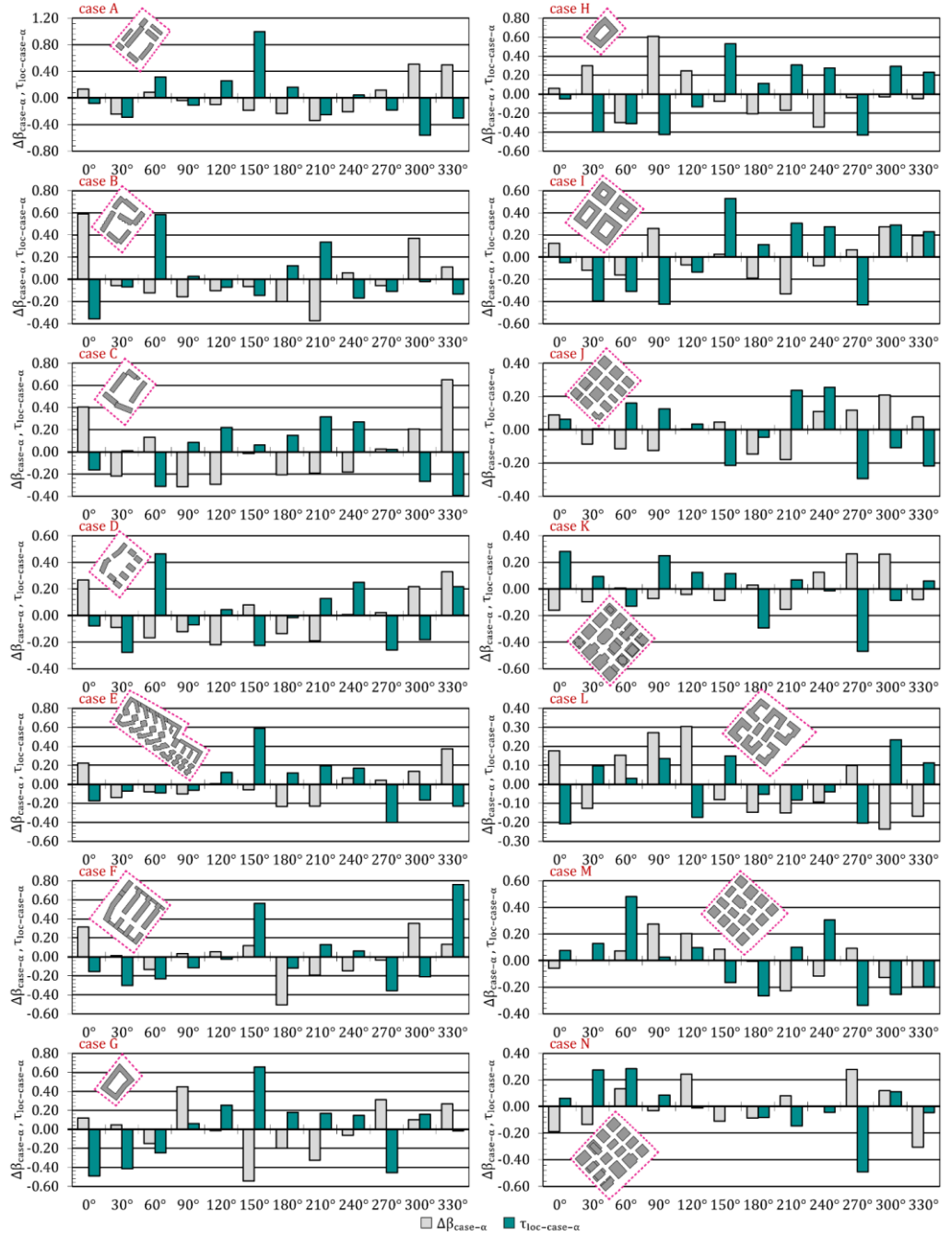


Fig. V_13 - $\Delta\beta_{case-\alpha}$ and $\Delta\tau_{loc-case-\alpha}$ for each case to investigate the impact of the interactions between the local characteristics of the different morphologies and wind directions.

For each case, the most important results can be summarized as follows:

- Case A – $\gamma_a = 0.58$. Significant deviations from the mean ventilation conditions can be found. Although γ_{a-150} does not correspond to the maximum reduction in γ_a (-19%), it implies the maximum increase in τ_{loc-a} (100%). Moreover, for $\alpha = 300^\circ$ and 330° , similar increases in γ_a ($\Delta\beta_{a-150} = +0.51$ and $+0.50$, respectively) correspond to different reductions in τ_{loc-a} ($\Delta\tau_{loc-a-150} = -0.56$ and -0.30 , respectively). It is worth noting that for $\alpha = 30^\circ$ and 210° , decreases in γ_a (-24% and -34%, respectively) correspond to reductions also in τ_{loc-a} (-29% and -25%, respectively). This peculiar behavior is discussed in detail in Subsection 5.5.
- Case B – $\gamma_b = 0.60$. Substantial deviations from the mean ventilation conditions can be found. Specifically, for $\alpha = 0^\circ$, the largest increase in γ_b ($\Delta\beta_{b-0} = +0.59$) is observed, while for $\alpha = 60^\circ$, the largest increase in τ_{loc-b} ($\Delta\tau_{loc-b-60} = +0.58$) occurs. The maximum reduction in γ_b ($\Delta\beta_{b-210} = -0.37$) is found for $\alpha = 210^\circ$.
- Case C – $\gamma_c = 0.78$. Large deviations from the mean ventilation conditions occur. For $\alpha = 330^\circ$, the maximum amplification in γ_c ($\Delta\beta_{c-330} = +0.65$) is observed and corresponds to the maximum reduction in τ_{loc-c} ($\Delta\tau_{loc-c-330} = -0.39$). The wind conditions for $\alpha = 330^\circ$ should be carefully analyzed to avoid pedestrian wind comfort issues since $\gamma_{case-330} = 1.28$.
- Case D – $\gamma_d = 0.63$. Significant deviations from the mean ventilation conditions are found. It is worth noting that for $\alpha = 60^\circ$, the largest increase in τ_{loc-d} ($\Delta\tau_{loc-d-60} = +0.46$) and a reduction of 0.17 in γ_d is experienced, while for $\alpha = 330^\circ$, a remarkable increase in γ_d ($\Delta\beta_{d-330} = +0.33$) corresponds to a significant increase in τ_{loc-d} ($\Delta\tau_{loc-d-330} = +0.22$).
- Case E – $\gamma_e = 0.56$. Slight deviations from the mean ventilation conditions can be found. Nevertheless, $\alpha = 150^\circ$ and 270° stand out for the maximum increase ($\Delta\tau_{loc-e-150} = +0.59$) and decrease ($\Delta\tau_{loc-e-270} = -0.40$) in τ_{loc-e} ,

respectively. Moreover, the maximum increase in γ_e is registered for $\alpha = 330^\circ$ ($\Delta\beta_{e-330} = +0.37$).

- Case F – $\gamma_f = 0.47$. Significant deviations from the mean ventilation conditions occur. Specifically, for $\alpha = 330^\circ$, the largest increase in τ_{loc-f} ($\Delta\tau_{loc-f-330} = +0.76$) is observed and corresponds to an increase in γ_f of +0.13, while for $\alpha = 180^\circ$, the largest reduction in γ_f ($\Delta\beta_{f-180} = -0.51$) corresponds to a reduction in τ_{loc-f} equals to -0.12.
- Case G – $\gamma_g = 0.77$. Large deviations from the mean ventilation conditions can be found. For $\alpha = 90^\circ$, the maximum increase in γ_g ($\Delta\beta_{g-90} = +0.45$) is observed and corresponds to a slight amplification in τ_{loc-g} ($\Delta\tau_{loc-g-90} = +0.06$). The wind conditions in this direction should be carefully analyzed to avoid pedestrian wind comfort issues. Conversely, for $\alpha = 150^\circ$, the maximum reduction in γ_g ($\Delta\beta_{g-150} = -0.54$) is observed and corresponds to the maximum increase in τ_{loc-g} ($\Delta\tau_{loc-g-150} = +0.66$).
- Case H – $\gamma_h = 0.81$. Large deviations from the mean ventilation conditions occur. For $\alpha = 90^\circ$, the maximum amplification in γ_h ($\Delta\beta_{h-90} = +0.61$) is observed and corresponds to a remarkable reduction in τ_{loc-h} ($\Delta\tau_{loc-h-90} = -0.42$). The wind conditions in this direction should be carefully analyzed to avoid pedestrian wind comfort issues. A similar reduction in τ_{loc-h} ($\Delta\tau_{loc-h-270} = -0.43$) corresponds to a slight reduction in γ_h ($\Delta\beta_{h-270} = -0.04$) for $\alpha = 270^\circ$. The maximum reduction in γ_h is observed for $\alpha = 240^\circ$ ($\Delta\beta_{h-240} = -0.35$).
- Case I – $\gamma_i = 0.62$. Significant deviations from the mean ventilation conditions can be found. Specifically, $\alpha = 150^\circ$ corresponds to the maximum increase in τ_{loc-i} ($\Delta\tau_{loc-i-150} = +0.53$) and a slight amplification in γ_i ($\Delta\beta_{i-150} = +0.03$). It is worth noting that for $\alpha = 30^\circ$, 90° , and 270° comparable reductions in τ_{loc-i} ($\Delta\tau_{loc-i-\alpha} = -0.40$, -0.42 , and -0.43 , respectively) are associated with different values of $\Delta\beta_{i-\alpha}$ (-0.12 , $+0.26$, and $+0.07$, respectively).

- Case J – $\gamma_j = 0.48$. Slight deviations from the mean ventilation conditions can be found. Nevertheless, $\alpha = 270^\circ$ stands out for the maximum reduction in τ_{loc-j} ($\Delta\tau_{loc-j-270} = -0.29$). The maximum increase in γ_j ($\Delta\beta_{j-330} = +0.21$) is observed for $\alpha = 300^\circ$.
- Case K – $\gamma_k = 0.53$. Slight deviations from the mean ventilation conditions occur. Nevertheless, $\alpha = 270^\circ$ stands out for the maximum reduction τ_{loc-k} ($\Delta\tau_{loc-k-270} = -0.47$ and corresponds to an increase in γ_k of $+0.26$. It is worth noting that a similar amplification in γ_k corresponds to a reduction of 0.09 in τ_{loc-k} for $\alpha = 300^\circ$.
- Case L – $\gamma_l = 0.75$. Large deviations from the mean ventilation conditions can be found. Specifically, $\alpha = 120^\circ$ corresponds to the maximum increase in γ_l ($\Delta\beta_{l-120} = 0.30$) and a significant reduction in τ_{loc-l} ($\Delta\tau_{loc-l-120} = -0.17$), while for $\alpha = 300^\circ$, the maximum reduction in γ_l ($\Delta\beta_{l-300} = -0.24$) and the maximum increase in τ_{loc-l} ($\Delta\tau_{loc-l-300} = +0.23$) is observed. Finally, it is worth mentioning that for $\alpha = 90^\circ$, a remarkable increase in γ_l ($\Delta\beta_{l-90} = +0.27$) corresponds to a significant amplification in τ_{loc-l} ($\Delta\tau_{loc-l-90} = +0.14$).
- Case M – $\gamma_m = 0.66$. Significant deviations from the mean ventilation conditions can be found. Specifically, for $\alpha = 60^\circ$, the maximum increase in τ_{loc-m} ($\Delta\tau_{loc-m-60} = +0.48$) corresponds to a slight increase in γ_m ($\Delta\beta_{m-60} = +0.07$); while for $\alpha = 270^\circ$, a comparable increase in γ_m ($\Delta\beta_{m-270} = +0.09$) corresponds to the maximum reduction in τ_{loc-m} ($\Delta\tau_{loc-m-270} = -0.34$). The maximum increase in γ_m ($\Delta\beta_{m-90} = +0.27$) is found for $\alpha = 90^\circ$ and corresponds to a slight increase in τ_{loc-m} ($\Delta\tau_{loc-m-90} = +0.03$).
- Case N – $\gamma_n = 0.63$. Significant deviations from the mean ventilation conditions occur. For $\alpha = 270^\circ$, the maximum reduction in τ_{loc-n} ($\Delta\tau_{loc-n-270} = -0.49$) corresponds to the maximum increase in γ_n ($\Delta\beta_{n-90} = +0.28$). Finally, it is worth noting that for $\alpha = 30^\circ$ and 60° , the highest values of $\Delta\tau_{loc-n-\alpha}$

(+0.28 and +0.29, respectively) correspond to different values of $\Delta\beta_{n-\alpha}$ (-0.13 and +0.13, respectively).

V_5.5 Further discussion

The results presented in the previous subsection are further discussed here by relating the effectiveness of specific morphologies to the features highlighted in Subsection V_5.1. The results presented in Figure V_13 are discussed in detail for a limited number of cases, highlighting the possible links to morphological characteristics. Figure V_14 reports the contours of γ for twelve wind directions for cases A, B, C, and D, belonging to the multi-story slab typology, and Figure 15 show the contours for cases J, K, M, and N, belonging to the palazzina typology, to ease the discussion and the visualization of the phenomenon.

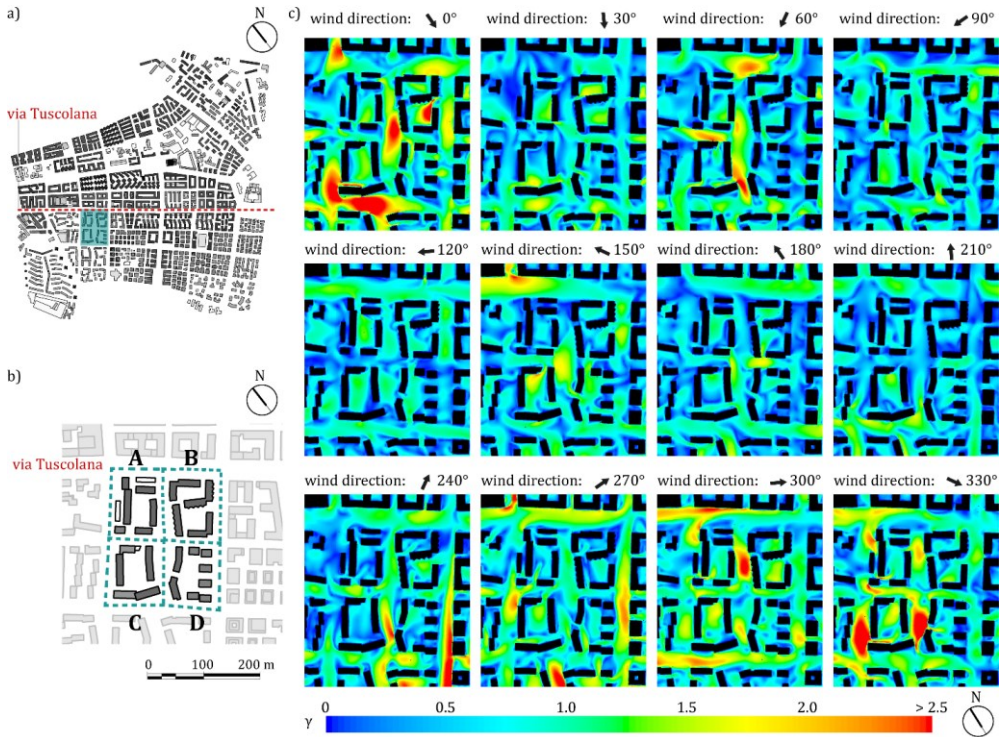


Fig. V_14 - (a) Key map reporting the location of the cases within the area of interest; (b) detail of the cases; and (c) contours of the spatially averaged mean wind velocity ratio, γ , at the pedestrian level.

Case A. For $\alpha = 30^\circ$ and 210° , considerable reductions in γ_a ($\Delta\beta_{a-\alpha} = -0.24$ and -0.34 , respectively) correspond to significant reductions in τ_{loc-a} ($\Delta\tau_{loc-a-\alpha} = -0.29$ and -0.25 , respectively). The meaning of this behavior should be carefully analyzed because it means that despite the significant reductions in wind speed, wind enters the central open space, potentially diluting heat and pollutants. The reason can be found by evaluating the morphology of the case under investigation. The central open area is surrounded by four main buildings of the same height, 24 m, different lengths, and placed orthogonally to each other. The four sides of the open space show different characteristics due to the diverse mutual arrangements existing between buildings. Moreover, the longitudinal axes of the two long buildings are oriented at an angle of about 30° to the South. Hence, $\alpha = 30^\circ$ and 210° result parallel to these two long fronts. Such a building arrangement produces a corridor on the left-hand side of the central space flanked by a long continuous front that may ease the introduction of air, ensuring a reduction in $\tau_{loc-a-30}$ and $\tau_{loc-a-210}$. The peculiar arrangement may also be responsible for the increase in τ_{loc-a} ($\Delta\tau_{loc-a-\alpha} = +0.26$ and $+1.00$, respectively) for $\alpha = 120^\circ$ and 150° . These wind directions are almost perpendicular to the long continuous front. It is also interesting to note that for $\alpha = 60^\circ$, an increase in γ_a equal to 0.09 corresponds to an increase in τ_{loc-a} of 0.32. Even in this case, the morphological characteristics play an important role since the central open area appears shielded by the building placed transversally on the north side. Finally, as expected, the wind directions that exhibit the largest increases in γ_a , i.e., $\alpha = 300^\circ$ with $\Delta\beta_{a-300} = +0.51$ and 330° with $\Delta\beta_{a-330} = +0.50$, present the largest reductions in τ_{loc-a} . Nevertheless, there is a remarkable difference between the two directions: $\Delta\tau_{loc-a-300} = -0.56$ and $\Delta\tau_{loc-a-330} = -0.30$. Even in this case, the building arrangement plays an important role because, even if $\alpha = 300^\circ$ is perpendicular to the long continuous front, it is also parallel to the corridor at the bottom of the central open area. This corridor is flanked by a continuous building and eases the introduction of air in the central area.

Case B. For $\alpha = 30^\circ, 120^\circ, 150^\circ$, and 270° , $\Delta\beta_{b-\alpha}$ and $\Delta\tau_{loc-b-\alpha}$ are both negative, i.e., $\Delta\beta_{b-30} = -0.05$ and $\Delta\tau_{loc-b-30} = -0.07$, $\Delta\beta_{b-120} = -0.10$ and $\Delta\tau_{loc-b-120} = -0.07$, $\Delta\beta_{b-150} = -0.07$ and $\Delta\tau_{loc-b-150} = -0.15$, and $\Delta\beta_{b-270} = -0.06$ and $\Delta\tau_{loc-b-270} = -0.11$. The morphological characteristics of the area should be considered to explain this behavior. The orientation of the buildings is similar to case A, and the building height is the same, i.e., 24 m; however, two main differences may be identified, i.e., the presence of L-shaped buildings and the division of the central open area into two smaller spaces by part of an L-shaped building. Specifically, this building acts as a barrier to wind flows. Moreover, the presence and location of the three L-shaped buildings and the passages between them should be accurately considered because they result alternatively in barriers or corridors for wind flow depending on the wind direction. These morphological characteristics determine that comparable values of $\Delta\beta_{b-\alpha}$ correspond to opposing values of $\Delta\tau_{loc-b-\alpha}$. Thus, for $\alpha = 60^\circ$, a reduction in γ_b of -0.12 results in an increase in τ_{loc-b} of +0.58, and for $\alpha = 90^\circ$, a reduction in γ_b of -0.16 has almost no effects on τ_{loc-b} since the corresponding value is +0.03.

Case C. From a morphological point of view, it should be noted that: (i) similarly to case A, the arrangement of the buildings creates a large, central open area, and there are passages between orthogonal buildings on the bottom part; (ii) the height of the buildings varies; (iii) a large passage between buildings can be found in the upper-right side; and (iv) the front on the South is continuous. These characteristics determine increases in γ_c for α aligned to the passages between buildings: for $\alpha = 0^\circ$, $\Delta\beta_{c-0} = 0.41$, and $\Delta\tau_{loc-c-0} = 0.16$; for $\alpha = 60^\circ$, $\Delta\beta_{c-60} = 0.13$, and $\Delta\tau_{loc-c-60} = 0.31$; for $\alpha = 300^\circ$, $\Delta\beta_{c-300} = 0.21$, and $\Delta\tau_{loc-c-300} = 0.27$; and for $\alpha = 330^\circ$, $\Delta\beta_{c-330} = 0.65$, and $\Delta\tau_{loc-c-330} = 0.39$. Being the amplification for $\alpha = 330^\circ$ particularly significant, the pedestrian wind comfort in this direction should be carefully considered in the passages between buildings. It is also possible to note that for $\alpha = 30^\circ$, a considerable reduction in γ_c ($\Delta\beta_{c-30} = -0.22$) does not result in a worsening of the

urban ventilation performance since $\Delta\tau_{loc-c30} = +0.01$. This behavior may be explained by the presence of the large passage on the upper-right side of the central open area. Finally, comparable reductions in γ_c cause significantly different amplifications in τ_{loc-c} as it is possible to observe comparing $\alpha = 90^\circ$ and 120° , where the reductions are equal to -0.31 and -0.29 and the increases are equal to +0.09 and +0.22, respectively, or comparing $\alpha = 180^\circ$, 210° and 240° where the reductions are equal to 0.21, 0.19 and 0.18, and the increases are equal to 0.15, 0.32 and 0.27, respectively.

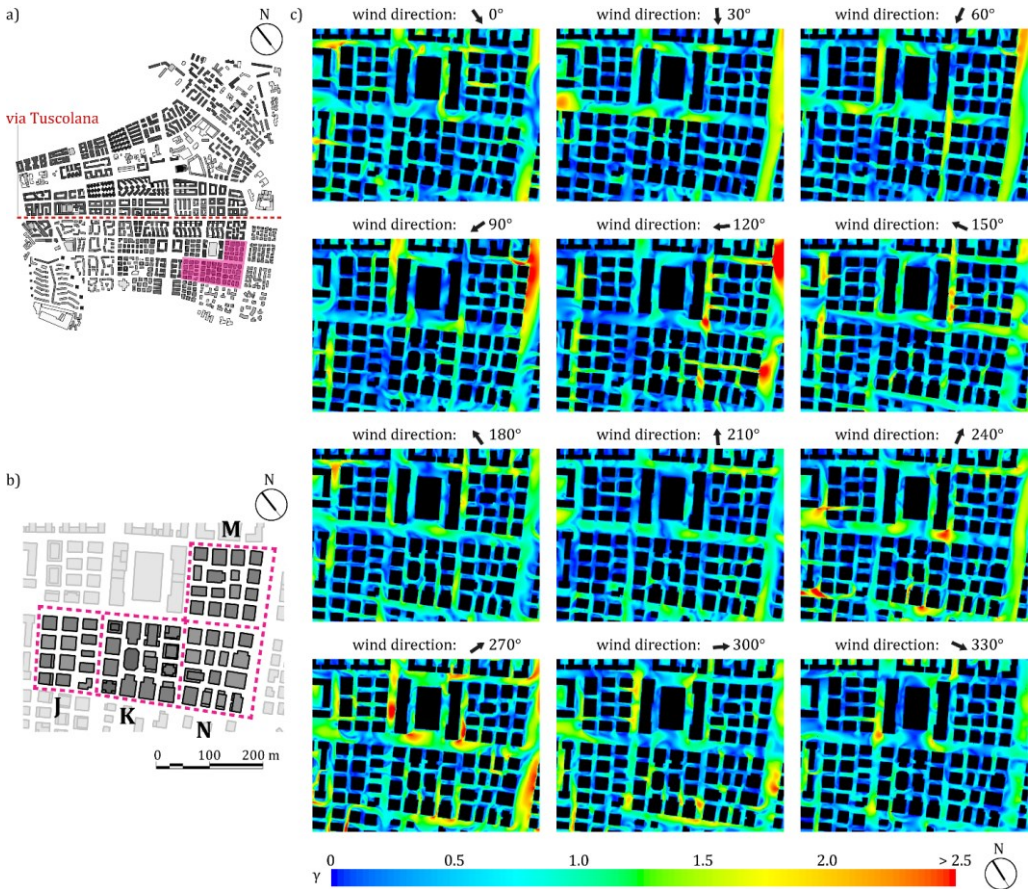


Fig. V_15 - (a) key map for highlighting the location of the cases within the area of interest; (b) detail of the cases; and (c) contours of the spatially averaged mean wind velocity ratio, γ , at the pedestrian level.

Regarding cases J, K, M, and N (Fig. V_15), the wind environment is more homogeneous and presents only sporadic and limited local phenomena. In fact, γ_d and τ_{loc-d} for each case do not differ substantially from the average ventilation conditions apart from $\alpha = 270^\circ$. This direction stands out for the remarkable reduction occurring in τ_{loc-d} corresponding to an increase in γ visible as speedup areas in Figure V_15.

The following main conclusions may be drawn from the analysis of Figures V_13, V_14, and V_15:

- Morphologies characterized by evident asymmetries or the prevalence of one dimension over the others present more pronounced outlier values of ventilation indicators.
- Regardless of the morphology, each case with a continuous and long front facing Southeast exhibits a remarkable increase in $\tau_{loc-case}$ for $\alpha = 150^\circ$, arguably due to the predominance of the shelter effect and the difficulty for the helical flows to enter the secondary canyons and open spaces.
- Apart from cases A, B, and C, a considerable reduction in $\tau_{loc-case}$ for $\alpha = 270^\circ$ occurs regardless of the morphology.
- Based on $\angle\beta_{case-\alpha}$, the cases can be divided into 3 groups corresponding to the building typology:
 - the slab typology presents significant deviations of $\angle\beta_{case-\alpha}$ depending on the wind direction. The mean value of $\angle\beta_{case-\alpha}$ standard deviation, $\sigma_{\angle\beta}$, is 0.12.
 - the court typology presents the largest deviations of $\angle\beta_{case-\alpha}$ depending on the wind directions ($\sigma_{\angle\beta} = 0.19$); the orientation of the urban canyons forming the court plays a substantial role in this behavior determining the changes from parallel to oblique to perpendicular wind directions.

- the palazzina typology presents the least deviations of $\angle\beta_{case-\alpha}$ depending on the wind directions ($\sigma_{\angle\beta} = 0.08$).
- Also based on $\angle\tau_{loc-case-\alpha}$, the three building typologies present different behaviors:
 - the slab typology presents the widest variety of deviations, ranging $\sigma_{\angle\tau_{loc}}$ from 18.35 s (case C) to 57.21 s (case E); the orientation of the main axis of the buildings compared to the wind direction plays a substantial role in this behavior.
 - the court typology presents the largest deviations, and the mean value of $\sigma_{\angle\tau_{loc}}$ is equal to 42.6 s.
 - the palazzina typology presents the least deviations $\angle\tau_{loc-case-\alpha}$ and the mean value of $\sigma_{\angle\tau_{loc}}$ is equal to 28.12 s.

V_6 Summary and conclusions

Among the issues that increasingly threaten human health and well-being in urban areas, air pollution and heat stress represent two aspects to address urgently. They have been associated with weak wind conditions and linked to increased morbidity, mortality, and economic loss. Wind conditions are profoundly modified by urbanization. Hence, urban morphology may be used in a climate-aware climate-sensitive approach to urban planning to mitigate the detrimental effects of weak wind conditions by enhancing urban ventilation. Thus, detailed investigations of the impact of different morphologies on the urban ventilation performance in real urban areas are necessary.

This paper reports a study investigating the effectiveness of different morphologies in enhancing urban ventilation in a real compact area in Rome, Italy. The study has been conducted by performing numerical simulations with Computational Fluid Dynamics (CFD). Urban ventilation is assessed using five indicators: the spatially

averaged mean wind velocity ratio, γ , the mean local age of air, τ_{loc} , the deviation of γ , $\Delta\gamma$, and the deviation of τ_{loc} , $\Delta\tau_{loc}$. Urban ventilation is first described in the entire area of interest, reporting contours of γ and τ_{loc} and highlighting various wind topologies ascribable to the features described in the Introduction and in the Literature review sections for idealized building and urban models.

The urban ventilation performance is then quantified and assessed, and a substantial dependence on wind direction and morphological characteristics is found. On average, a substantial reduction in γ experienced by pedestrians within the area compared to the inlet is observed (40%). Such reduction varies substantially, depending on the wind direction: a minimum value (23%) is observed for $\alpha = 0^\circ$ and 270° ($\gamma = 0.77$), while a maximum value (60%) occurs for $\alpha = 210^\circ$ ($\gamma = 0.40$). On the other hand, τ_{loc} shows small variations, ranging from 297 s for $\alpha = 330^\circ$ to 392 for $\alpha = 210^\circ$. From the observations performed at this scale, it is possible to conclude that:

- $\alpha = 210^\circ$ corresponds to the poorest wind condition.
- For $\alpha = 270^\circ$, 300° , 330° , and 0° , the highest values of γ occur, and this may be due to the morphological characteristics of the area.
- For $\alpha = 60^\circ$, a remarkable reduction in γ (0.54) does not correspond to amplification in τ_{loc} , which, on the contrary, is smaller compared to the mean ventilation conditions, being $\Delta\tau_{loc} = -0.07$.

To further analyze the impact of urban morphology on urban ventilation and investigate the effectiveness of different morphologies, fourteen cases have been selected within the area, and their ventilation performance has been examined in detail. These cases are characterized by three different building typologies, i.e., the slab, the court, and the palazzina typologies. From the observations performed at a smaller scale, the impact of local morphological characteristics is evident, and it is possible to conclude that:

- Cases characterized by morphologies with asymmetries or the prevalence of one dimension over the others present more pronounced deviations of γ_{case} and $\tau_{loc-case}$.
- For $\alpha = 150^\circ$, cases with a continuous and long front facing Southeast exhibit a remarkable increase in $\tau_{loc-case}$ regardless of the morphology, arguably due to the predominance of the shelter effect and the difficulty for the helical flows to enter the secondary canyons and open spaces.
- A considerable reduction in $\tau_{loc-case}$ for $\alpha = 270^\circ$ occurs regardless of the morphology except for cases A, B, and C.
- Based on $\Delta\beta_{case-\alpha}$ and $\Delta\tau_{loc-case-\alpha}$, the cases can be divided into three groups corresponding to the building typology and present different behaviors.

The outcomes of this work may be of interest to professionals, city managers, and policymakers and contribute to advancements in scientific knowledge about the impact and effectiveness of different urban morphologies on urban ventilation performance. The results stress the need to approach urban planning and building design more comprehensively and advocate a climate-aware approach. Urban ventilation proves to be a key factor in curbing heat stress and air pollution. Therefore, analyses of the effects of urban renewal plans on urban ventilation performance in existing and newly built areas are of paramount importance.

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Chapter VI

Discussion

This thesis aims to numerically analyze the dynamic relationships between density, morphology, and wind flow within the general framework of the challenge toward more sustainable and resilient urban areas. The knowledge of these interactions is of primary importance because they affect many aspects of human life, such as outdoor and indoor ventilation performance and energy consumption in urban areas. Assessing urban ventilation could be of significant importance for citizens' health and well-being as adequate performance could improve air quality and thermal comfort in cities, curbing the exposure of citizens to potentially hazardous air pollution levels and thermal stress due to the amplification of heat waves and urban heat island effects. Adequate urban ventilation could be especially beneficial in areas such as the Mediterranean basin, where a continuous increase in the mean air temperature can already be observed. Hence, detailed investigations of the impact of urban morphologies on urban ventilation in real urban areas are fundamental and represent an essential step towards more sustainable and resilient cities.

Despite its importance, the assessment of urban ventilation and the complex interactions between urban morphology and wind flow is not yet commonly embedded in urban planning and management processes. Moreover, regardless of the continuous effort of researchers, analytical relations that provide information about wind conditions without running computationally expensive simulations are yet not available for practitioners, urban designers, and policymakers. This lack may lie in the nature of the phenomena involved, complex and multi-faceted, and in the consequent difficulty of carrying out these investigations that require both a high specialism and a multidisciplinary approach.

The present research represents an attempt to fill this gap by integrating different disciplines, i.e., urban physics, computational fluid dynamics, building design, and urban planning, to ease the management of the urban environment complexity.

This thesis investigates the dynamic relationships between density, morphology, and wind flow in a real urban area. This choice is inevitable in light of the purpose of the research, i.e., to develop and validate a methodology to investigate urban ventilation in actual urban areas to be embedded into building designs and urban planning processes. The selected urban area is the Tuscolano-Don Bosco district in Rome, Italy. As addressed in chapters III, IV, and V, the district is characterized by 1,500 buildings presenting different building typologies, i.e., the court, multi-story slab, pavilion-tower, and pavilion-palazzina, which produce a variety of urban morphologies. Moreover, the values of the different morphological parameters used to describe the morphological characteristics of the district are comparable to those found in the literature for compact urban areas located in both the Mediterranean basin [1,2] and elsewhere [3,4]. Hence, albeit belonging to a specific city, the Tuscolano-Don Bosco district represents a comprehensive case study from the morphological point of view. Furthermore, the numerical results are expressed in non-dimensional forms in order to be generalized and extended to other cities with similar morphological characteristics.

The focus of the investigations is on the impact of urban morphology since it is considered the driving factor of urban ventilation and an intrinsic characteristic of urban areas that requires planning, investments, and time to be changed. Hence, the shape and size of buildings and open spaces are modeled accurately and represented by a high-resolution computational grid. Over 1,500 buildings belonging to the area of interest are explicitly modeled, and the total amount of cells for the entire computational domain is almost 90 million hexahedral cells. Nevertheless, some geometrical simplifications are needed to (i) reduce the computational cost of numerical simulations for such a large and detailed domain and (ii) avoid features that may be too site-specific. Specifically, the geometrical simplifications entail excluding façade and roof details from the model. It should be noted that earlier studies for isolated building models suggested that balconies,

e.g., [5], and roof types, e.g., [6], might affect the near-façade wind flow patterns. However, the extent of the impact of such features on urban ventilation at larger scales, i.e., the neighborhood, district, and urban scales, has not yet been investigated. Hence, future research could focus on the impact of geometrical façade and roof details on urban ventilation at the neighborhood scale. In this perspective, future studies would benefit if these details about building façades and roofs could be expressed as a function of morphological parameters. In addition, since these details may be relevant in pollutant dispersion and thermal comfort studies, researchers are fostered to include their description and quantification in future morphological analyses.

In Chapter IV, linear correlations between morphological parameters and performance indicators, i.e., the spatially averaged mean wind velocity ratios at two different heights, are developed, obtaining strong (0.62) to remarkable (0.89) coefficients of determination. In addition, the linear correlation between plan area density and spatially-averaged mean wind velocity ratio at the pedestrian level was compared to that found in the literature related to major Japanese cities [3], and similar trends are reported. It is worth mentioning that the correlations developed in this research are obtained using general, not case-specific, parameters and indicators and considering different wind directions. Hence, the linear correlations would be arguably valid also for other cities. Nevertheless, a possible direction for further research is to evaluate the performance of these correlations for urban areas with different morphological characteristics.

As the driving factor of urban ventilation, urban morphology is considered in this thesis as a measure for enhancing or reducing wind speed in urban areas and, consequently, regulating urban ventilation. In Chapter V, different morphologies are analyzed, and their effectiveness in enhancing urban ventilation is assessed. The chapter reports that specific morphologies may improve or worsen urban ventilation by 35% and 22%, respectively, compared to the entire area.

Furthermore, considering specific wind directions, the enhancement can be even more pronounced, up to 135%. Therefore, it is possible to conclude that urban morphology can be used as a measure to regulate urban ventilation. Nevertheless, it should be noted that previous studies have reported that other elements present in urban areas, e.g., vegetation and barriers, may also contribute to improving wind and thermal conditions in the built environment [7]. Some of these measures, e.g., vegetation, could contribute to improving thermal comfort but, at the same time, could affect wind flow in urban areas leading to negative impacts on air quality [7]. Therefore, comprehensive and systematic investigations of such measures and their impact on both wind and thermal environments could represent a direction to explore in future studies.

As addressed in previous chapters, boundary conditions should be set carefully because realistic ones are necessary to obtain meaningful results. In this thesis, CFD simulations are performed by imposing neutral atmospheric conditions. Neutral atmospheric conditions (neutral ABL or neutrally stratified ABL) imply that mechanical turbulence production mainly governs the flow field. On the other hand, stable and unstable atmospheric conditions imply that buoyancy plays a role, i.e., the flow is also driven by density variation along the vertical. Despite being a simplification, neutral atmospheric conditions occur during windy days or cloudy and moderately windy days. These conditions may be observed in different seasons and hours of the day. A study conducted by Pelliccioni et al. [8] for the city of Rome, Italy, reports the frequency of occurrence of the seven stability classes, defined by Holtslag [9]. This study shows that neutral atmospheric conditions may occur in different seasons and hours of the day, reporting the frequency of occurrence (Fig.VI_1). Nevertheless, despite realistic, neutral conditions are one of the possible stability classes characterizing the atmosphere. Hence, a possible direction for future research is to investigate the impact of different urban morphologies on urban ventilation under different atmospheric conditions.

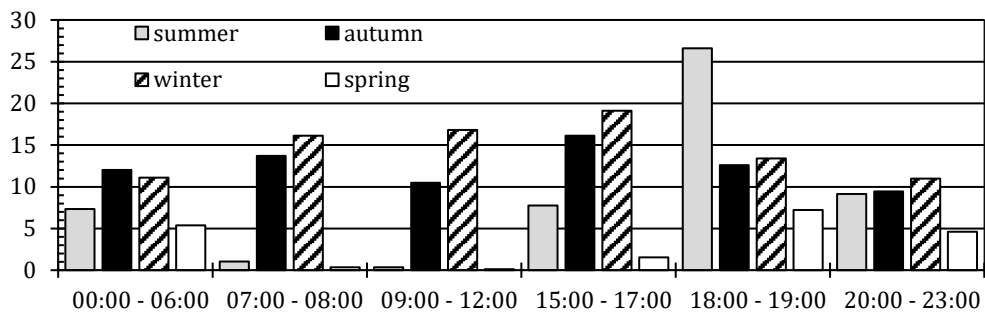


Fig. VI_1 - Frequency of occurrence of neutral atmospheric conditions for different seasons as a function of the time. The dataset used refers to the study described in [8].

Finally, given the number of cells and the computational cost of the simulations, this thesis is based on isothermal CFD simulations, i.e., simulations performed without considering thermal effects. It should be noted that previous studies have shown that thermal effects could affect urban wind flow in urban areas [10,11]. However, systematic investigations of the impact of different urban morphologies on urban ventilation considering thermal effects, i.e., buoyancy, solar radiation, and heat transfer, have not yet been performed in real urban areas. Therefore, this represents a direction worth exploring in future research.

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Chapter VII

Conclusions

In light of the nowadays level of urbanization and climate change, improving the health and well-being of citizens by implementing sustainability and resilience has become a priority in existing urban areas. Among the issues that increasingly threaten human health and well-being, air pollution and heat stress represent two aspects to address urgently. They have been associated with weak wind conditions and linked to increased morbidity, mortality, and economic loss. Wind conditions are profoundly modified by urbanization. Hence, urban morphology may be used in a climate-aware climate-sensitive approach to urban planning to mitigate the detrimental effects of weak wind conditions by enhancing urban ventilation. Thus, detailed investigations of the impact of different morphologies on the urban ventilation performance in real urban areas are necessary. In addition, methodologies for embedding these investigations in the current building design and urban planning processes should be developed to drive the regeneration of existing urban areas that appear insufficiently prepared for the increasing challenges dictated by climate change. These detailed investigations and methodologies are currently unavailable.

The present thesis aims to numerically analyze the dynamic relationships between density, morphology, and wind flow within the general framework of the challenge toward more sustainable and resilient urban areas. It represents an attempt to answer the following research questions:

- Bearing in mind the necessity of reducing land take and soil degradation and promoting efficient management of resources in urban areas, how can we advocate densification and enhance urban ventilation without hindering the efforts to adapt to and mitigate climate change effects?
- What are the impacts of compact urban tissues on the ventilation performance of an actual urban area?

-
- How can we adequately integrate the urban ventilation assessment into the renovation planning phase by adopting a climate-aware/climate-sensitive approach?

Driven by these research questions, various aspects related to urban ventilation in urban areas are addressed in the different chapters of the thesis.

Chapter II presents a critical review of the literature on air circulation in urban areas, also providing an overview of the numerical and experimental techniques used to investigate wind flow in generic and real urban areas at different scales. Detailed information about the governing equations, including the most commonly used RANS turbulence models, is given in this chapter. Finally, airflow above and within the urban canopy is addressed by reporting common flow topologies investigated in previous studies using archetypal simplified geometrical configurations, such as isolated buildings, street canyons, groups of buildings, and street intersections.

Chapter III contains an extensive literature review of the performance-based approach to planning, the evaluation of the performance of urban areas related to morphology, and urban ventilation assessment. Based on this literature study, a multidisciplinary methodology for assessing urban ventilation in complex, real urban areas is developed and embedded in the workflow for urban renovation plans, aiming to improve air quality and outdoor thermal comfort. The developed methodology is based on three main phases:

- physical structure quantification - morphological parameters valid for its quantification and tools for the data aggregation are provided, and the importance of the scale is discussed.
- wind environment simulation - 3D RANS simulations are suggested as a valid method for analyzing the wind environment and computing the performance indicators.
- performance evaluation - three possibilities are indicated, i.e., the comparison of performances in different scenarios, compliance with regulations, and comfort criteria.

The developed methodology is guided by clear strategies and oriented to achievable goals and objectives measured by performance indicators. Hence, it represents a shift in the traditional planning models based on zoning and land use prescriptions that have been proven inadequate to tackle the complexity of the urban environment. Moreover, it eases the construction of scenarios and the evaluation of strategies by comparing performance levels.

In Chapter IV, the developed methodology is tested for a real complex urban area, i.e., the Tuscolano-Don Bosco district. A set of seven morphological parameters is employed to characterize the case study using the open-source GIS software QGIS. Among the employed morphological parameters, the relations λ_P - λ_{vol} and λ_P - λ_{fac} present robust correlations, i.e., $R^2 = 0.82$ and $R^2 = 0.73$, respectively. Moreover, it is highlighted that these relations may be used to characterize urban areas since they not only report quantities about the building plan area, volume, and façade densities but can also provide insights into the building typologies. 3D RANS simulations with the realizable k- ϵ model are performed for twelve wind directions, equally spaced every 30°. The computational setting is validated using the “sub-configuration validation procedure”. The spatially averaged mean wind velocity ratios at two different heights, i.e., the pedestrian level and half of the average urban canyon height, are adopted for the performance evaluation. Thirty-one cases, complying with three requirements entailing their dimensions and locations, are identified within the case study. Linear correlations between morphological parameters and performance indicators were obtained using linear regression analysis. Overall, the proposed linear correlations prove robust, reporting values of the coefficient of determination up to 89% and showing a clear dependency of the ventilation indicators on the selected morphological parameters. The proposed linear correlation between plan area density and the spatially averaged mean wind velocity ratio at the pedestrian level is also compared to a wind tunnel study from the literature about major Japanese cities, and similar trends are reported. Finally,

in line with earlier studies, values of the plan area density are identified that may be interpreted as threshold values for the flow regime change, i.e., from the wake-interference flow to the skimming flow regimes.

In Chapter V, urban ventilation in the selected compact urban area is investigated in detail, and the effectiveness of different morphologies in enhancing urban ventilation is evaluated. The evaluation is based on five indicators, including the spatially averaged mean wind velocity ratio and the local age of air at the pedestrian level. Urban ventilation is initially described by analyzing the simulated wind flow pattern in the entire area of interest. Various wind topologies ascribable to idealized building and urban models are highlighted and described. Then, the urban ventilation performance in the entire area of interest is assessed, emphasizing a substantial dependence on wind direction and morphological characteristics. On average, a substantial reduction (40%) in the wind velocity experienced by pedestrians within the area compared to the inlet is observed. Such reduction varies substantially, depending on the wind direction: from a minimum value of 23% to a maximum value of 60%. To further analyze the impact of urban morphology on urban ventilation and investigate the effectiveness of different morphologies, fourteen cases are selected within the area, and their ventilation performance is examined in detail. These cases are characterized by three different building typologies, i.e., the slab, the court, and the palazzina typologies. From the observations performed at a smaller scale, the impact of local morphological characteristics is evident, and it is possible to conclude that:

- The contribution of local morphological characteristics may be significant for the urban ventilation performance of the entire area of interest.
- Depending on the wind direction, specific urban morphologies may be used as measures to enhance urban ventilation.

The present research represents a further step to integrate different, highly specialized disciplines, i.e., urban physics, computational fluid dynamics, building design, and urban planning, to ease the management of the urban environment

complexity. The developed methodology may be applied to both research and professional purposes. As a research tool, this methodology may be used for investigating the correlation between urban ventilation and morphology, improving the provided prediction models for estimating ventilation performances without running simulations. In addition, the methodology may be employed for implementing comfort criteria and regulations that are scarce in the case of weak wind conditions. As a professional tool, this methodology may be applied: (i) in case of renovation plans, for assessing the achievement of objectives and prioritizing actions, and (ii) in case of urban management, for identifying areas exposed potentially to poor air conditions, and, therefore, vulnerable to pollution and heat stress, easing traffic management and the adoption of mitigation and adaptation measures.

The outcomes of this thesis may be of interest to practitioners, city managers, and policymakers and contribute to advancements in scientific knowledge about the impact and effectiveness of urban morphology on urban ventilation performance. The results stress the need to consider the building design and urban planning processes more comprehensively and advocate a climate-aware climate-sensitive approach. Within the general framework of the challenge toward more sustainable and resilient urban areas, urban ventilation proves to be a key factor in curbing heat stress and air pollution. Therefore, analyses of the effects of urban renovation plans on urban ventilation performance in existing and newly built areas are of paramount importance.

Curriculum vitae

Olga Palusci was born in 1985 in Rome, Italy.

She graduated “cum laude” in Building Engineering – Architecture at the Faculty of Civil and Industrial Engineering of the Sapienza University of Rome with a project concerning the sustainable regeneration of a blighted area in Rome. During her studies, Olga developed a strong interest in reducing energy consumption and implementing sustainability and resilience in the built environment. In 2012, she started working as a researcher at the Department of Civil, Building, and Environmental Engineering of Sapienza University of Rome, and, at the same university, she obtained a Second Level Master degree in sustainability and energy savings, with a focus on urban microclimate modeling and the regeneration of existing urban areas. At the end of 2012, she started her Ph.D. at Sapienza University of Rome, supervised by Professor Carlo Cecere and Paolo Monti. In November 2014, Olga joined the research group of Professor Bert Blocken and started her double Ph.D. between the Sapienza University of Rome and Eindhoven University of Technology. During her Ph.D., Olga participated in the Urban Physics Winter School, the WINERCOST training school, and the School on Numerical Methods for Parallel CFD data. Since 2012, Olga has been involved in educational activities as a teaching assistant. Throughout her Ph.D., she worked as a teacher, practitioner, and consultant in building physics and sustainability for several engineering firms. In 2017, she worked on a project for the numerical investigation of the performance of an active system to reduce outdoor particulate matter in the built environment and as a curator of the exhibition “Wind in the City” for the faculty of the Built Environment at TU/e.

In addition to her primary research activities, she has conducted research on the reduction of energy consumption, regeneration of urban areas, optimization, and urban microclimate modeling being a member of different research groups:

Building Physics in Eindhoven, SoS Urban Lab in Rome, and Micro-meteorology Lab in Lecce, Italy. She (co-)authored several ISI journal papers and conference contributions and attended several international conferences. Finally, she is a reviewer for more than 15 international scientific journals. Parallel to her research, she is the co-supervisor of 1 Ph.D. student and more than 15 M.Sc. students. Since July 2022, she has been working as a fellow researcher on monitoring and mitigating the urban heat islands in compact European cities.

List of Publications

Journal articles

1. Esposito, A.; Grulois, M.; Pappaccogli, G.; Palusci, O.; Donateo, A.; Salizzoni, P.; Santiago, J.L.; Martilli, A.; Maffei, G.; Buccolieri, R. On the Calculation of Urban Morphological Parameters Using GIS: An Application to Italian Cities. *Atmosphere* 2023, 14, 329.
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1. Di Bernardino, A., Palusci, O., Pini, A., Leuzzi, G., Cacciani, M., Pelliccioni, A., Monti, P. (2021). Air Circulation in Urban Areas. In Urban Microclimate Simulation for Comfort and Energy Studies, Springer, 195–221.

Conference contributions

1. Palusci, O., Monti, P., Cecere, C., Montazeri, H., Blocken, B. (2022). Numerical Investigation of the Impact of Morphological Parameters on Urban Ventilation in Compact Cities a 5th International Conference On Building Energy and Environment, COBEE 2022 – Montreal, Canada 25/07/2022 – 29/07/2022.
2. Agostini, B., Palusci O., Cecere C. (2022). Rigenerazione urbana dell'ex fabbrica di saponi Mira Lanza a Roma: un nuovo scenario di parco resiliente a 2° Stati Generali del Patrimonio Industriale – Roma 09/06/2022 – 11/06/2022.
3. Massarelli L., Cecere C., Paris S., Palusci O. (2022). Rigenerazione dei fabbricati viaggiatori della stazione ferroviaria e riqualificazione dell'ex stabilimento delle Fornaci Briziarelli di San Gemini” a 2° Stati Generali del Patrimonio Industriale – Roma 09/06/2022 – 11/06/2022.
4. Mannucci, S., Peduzzi, A., Palusci, O., Rosso, F., Cecere, C., Ferrero, M. (2021). Strategie adattive per l'ambiente costruito: possibilità di applicazione di approcci e metodi del Decision Making Under Deep Uncertainty a Colloqui.AT.e 2021 – Salerno 08/09/2021 – 11/09/2021.
5. Palusci, O., Cecere C. (2020). La Ventilazione Urbana Nella Città Compatta Mediterranea: Una Metodologia Operativa Multidisciplinare Per Migliorare La Sostenibilità e La Resilienza Delle Aree Urbane a Colloqui.AT.e 2020.

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 8. Palusci, O., Montazeri, H., Blocken, B., Monti, P., Cecere, C. (2017). Thermal vulnerability of compact urban tissues: CFD simulation and validation. Urban Transitions Global Summit 2016: Towards a better urban future in an interconnected age – Shanghai, China 05/09/2016 – 09/09/2016.

Other publications:

1. S. Mannucci, A. Peduzzi, O. Palusci, F. Rosso, C. Cecere, M. Ferrero. Strategie adattive per l'ambiente costruito: possibilità di applicazione di approcci e metodi del Decision Making Under Deep Uncertainty, (2021) Colloqui.AT.e 2021 Design and construction: Tradition and innovation in the practice of architecture. 8-11 settembre 2021, Salerno, EdicomEdizioni, pag. 1475-1489. ISBN: 978-88-96386-62-0
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In the global challenge towards more sustainable and resilient urban areas, strategies that entail the densification of urban tissues and the introduction of economic and production facilities within residential areas are regarded as optimal for the regeneration of existing urban areas to reduce soil consumption and optimize transport and energy supply. Possible consequences of densification are augmented heat and pollution production within urban tissues and weak wind conditions. Weak wind conditions can be responsible for potentially hazardous air pollution levels and increased amplification of heatwaves and human thermal stress. Hence, densification may significantly impact human health and well-being if not adequately investigated. These detrimental effects may be mitigated by urban ventilation. Urban ventilation represents the capacity of a built area for introducing fresh air within its tissue and diluting pollutants and heat within its canyons. The phenomenon is closely related to the level of urbanization and urban morphology.

How can we advocate densification and enhance urban ventilation?

This doctoral dissertation numerically analyzes the dynamic relationships between urban density, morphology, and wind flow. An operational methodology is developed, validated, and applied in an existing compact area. Easy-to-use models that correlate morphological parameters and performance indicators are provided for highlighting areas potentially vulnerable to poor air conditions without running computationally expensive simulations. Additionally, the effectiveness of existing morphologies in enhancing urban ventilation is assessed. This research contributes to establishing a knowledge base of the wind environment in compact cities and developing guidelines for prioritizing regeneration plans in existing urban areas. This work represents a further step to integrate different disciplines, i.e., urban physics, building design, and urban planning, to ease the management of the urban environment complexity. The research outcomes are of interest to stakeholders, practitioners, policymakers, and researchers.

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