PARAMETRIC FLOW SIMULATION FOR EARLY DESIGN PHASE: CASE STUDY OF AN URBAN REGENERATION AREA IN IZMIR

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İZMİR

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ABSTRACT

PARAMETRIC FLOW SIMULATION FOR EARLY DESIGN PHASE: CASE STUDY OF AN URBAN REGENERATION AREA IN IZMIR

Climate change and its effects on the planning of cities require new dynamics for designing new expansion zones or neighborhood development projects. In conceptual phases, decision-makers, architects, planners, and engineers must consider extreme weather events and increased wind speeds in cities due to climate change to ensure the safety of pedestrians. Proposed building layouts, geometrical parameters, and features should be investigated in an artificial environment to satisfy wind behavior for acceptable conditions. Computational Fluid Dynamics (CFD) software provides insight into wind effects on the pedestrian level for the proposed layout of buildings and the surrounding area. This insight can boost the design process without conducting experimental wind tunnel tests. This study aims to assess the impact of building geometry (height, width, length) and building spacings in urban development projects for the safety and comfort of users in pedestrian-level wind environments with CFD simulations.

The case area of this study is the first phase of an urban regeneration area in Izmir. The proposed layout is analyzed with prevailing wind speeds and directions to identify the dangerous and comfortable regions around buildings. Sub-configurations of buildings are simulated in CFD software to compare with existing wind tunnel tests for verification and validation.

A design proposal with building features is evaluated with validated CFD parameters to examine the impact on pedestrian-level wind speeds. Mean speeds for corresponding comfort and safety limits of categorized human activities are compared to findings to identify suitable locations for these activities around buildings.

Design parameters of urban layout; distance between buildings, height, and balconies on facades showed significant effects on pedestrian level wind environment. Building height among these parameters proved to be a decisive feature that should be considered in the early design stages.

ÖZET

ERKEN TASARIM AŞAMASINDA PARAMETRİK AKIŞ BENZETİMİ: İZMİR’DE BİR KENTSEL DÖNÜŞÜM ALANININ VAKA ANALİZİ

İklim değişikliği ve bunun şehirlerin planlanması üzerindeki etkileri, yeni genişleme bölgeleri veya mahalle gelişim projeleri tasarlamak için yeni dinamikler gerektirmektedir. Kavramsal aşamalarda, karar vericiler, mimarlar, planlamacılar ve mühendisler, yayaların güvenliğini sağlamak için aşırı hava olaylarını ve şehirlerde iklim değişikliği nedeniyle artan rüzgar hızlarını dikkate almak zorundadır. Önerilen bina yerleşimleri, geometrik parametreler ve özellikleri yapay bir ortamda uygun rüzgar koşullarını sağlamak için araştırılmalıdır. Hesaplamalı Akışkanlar Dinamiği (HAD) yazılımı, önerilen bina yerleşimi ve çevresindeki alan için yaya seviyesindeki rüzgar etkilerine ilişkin bilgi sağlar. Bu yaklaşımla, deneysel rüzgar tüneli testleri yapmadan projelerin tasarım sürecini hızlandırabilir. Bu çalışma, kentsel gelişim projelerinde bina geometrisi (yükseklik, genişlik, derinlik) ve binalar arası mesafelerin kullanıcıların güvenliği ve konforu için yaya seviyesi rüzgar ortamındaki etkisini HAD simülasyonları ile değerlendirmeyi amaçlamaktadır.

Bu çalışmanın örnek alanı, İzmir'de bir kentsel dönüşüm alanının ilk etap aşamasıdır. Önerilen yerleşim, binaların etrafındaki tehlikeli ve konforlu bölgeleri belirlemek için hakim rüzgar hızları ve yönleri ile analiz edilmiştir. Binaların konfigürasyonları, doğrulama ve geçerlilik yapmak için mevcut rüzgar tüneli testleri ile karşılaştırılarak HAD yazılımında simüle edilmiştir.

Bina özelliklerini içeren öneri tasarım doğrulanmış HAD parametreleri ile yaya seviyesi rüzgar hızlarına etkilerini görmek için değerlendirilmiştir. Kategorize edilmiş insan faaliyetlerine karşılık gelen konfor ve güvenlik sınırları dahilindeki ortalama hızlar, binaların çevresinde bu faaliyetler için uygun yerleri belirlemek için bulgularla karşılaştırılmıştır.

Kentsel yerleşimin tasarım parametrelerinden binalar arası mesafe, yükseklik ve balkon konumları yaya seviyesi rüzgar ortamı üzerinde önemli etkiler göstermiştir. Bu parametreler arasındaki bina yüksekliği erken tasarım sürecinde değerlendirilmesi gereken belirleyici unsur olmuştur.

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CHAPTER 1

INTRODUCTION

1.1. Theoretical Perspective

The world's population continuously grows at unprecedented rates, differentiating between continents and cities. Rapid growth recorded in European cities with fossil-based energy sources in an industrial era now shifted to Asian cities, doubling the statistical population expectations (WHO 2010; UN DESA 2015; UN DESA 2016). Increasing populations, services based on fossil energy, and extensive land use policies make these cities primary problematic areas for CO_2 emissions (UN Habitat 2011; IPCC 2016). Population growth and scarce land in cities guided architects to design taller structures with the help of new construction technologies since the beginning of the 1900s (Koolhaas 1994). Steel construction and glazing became the prestigious materials of developed cities but delivered problems in the following century. High-density urbanization, boosted by this population upsurge and material technologies, is also responsible for air pollution, increased temperatures, and other major respiratory illnesses today (Palusci et al. 2021). Meantime these high-density cities are becoming vulnerable targets for severe weather events. Coastal cities frequently hit by powerful winds are now facing more extreme events due to climate change.

Climate change is creating problematic cities that will not be able to provide a healthy environment for people. Overpopulation in densely built environments decreases open areas' ventilation and increases CO_2 emissions. United Nations published the "2030 Agenda" for taking action to solve these problems with goals for governments, including sustainable solutions (UN 2015). A new design approach is required to adopt more passive and sustainable strategies for solving urban environmental issues. Architects and engineers should thoroughly analyze these strategies to find out optimum physical conditions for a healthy built environment (Lawson, 2001; Santamouris 2001)

The wind is a significant parameter affecting the thermal and air quality of the city. Natural ventilation is required to achieve comfortable and healthy urban environments (Blocken 2015). Using wind as a passive cooling and ventilation design parameter in an urban environment is challenging for architects since wind behavior is hard to predict in a dense city. Wind reacts differently while passing through or over a densely built section of a city rather than blowing in rural areas. Building layouts, sizes, and gaps between them should be considered while designing an urban area (DeKay and Brown 2014; Gandamer 1978). The aerodynamic properties of buildings were tested in construction material-based research (Lawson 2001), but for architects and urban designers, it is a newly emerging field to discover (Blocken 2015; Toparlar et al. 2017).

Architects and urban designers started considering energy-efficient design strategies as technology-enabled, more complex calculations related to solar radiation, thermal balance, or lighting. Building energy simulations extended the design concepts of buildings for lowering CO_2 emissions from the built environment (Blocken 2015), but these simulations generally focus on indoor energy solutions. Other passive design strategies like increasing natural ventilation for cooling, pollution dispersion, and pedestrian comfort require more complex solutions and analysis of wind behavior in an urban environment (Toparlar et al. 2017).

Wind analysis is widely used in engineering fields to investigate the aerodynamic properties of buildings (Lawson 2001). These analyses were a primary concern for engineering teams in charge of designing tall buildings to calculate loads on structural systems and facades. Architects delivered design proposals to engineers to test their designs in wind tunnels to acquire data. Wind tunnel testing methodology required specialized knowledge to get sufficiently accurate results focused on mechanical effects on buildings (Irwin, Denoon, and Scott 2013). Full-scale neighborhood-level wind motion and coupled thermal effects on the built environment were maintained with Computational fluid simulations.

Computational fluid simulations help engineers understand the wind's unpredictable movement and its effects on surfaces as pressure differences or heat transfer. Urban designers can also benefit from computational fluid simulations to investigate the wind phenomenon and implement new designs for ventilation of densely built cities (DeKay and Brown 2014).

New urban development areas are designed to accommodate large numbers of the population in a densely built layout. Higher density enables more units to be built in smaller building plots (Ng 2010) but also causes more CO_2 emissions per square area for cooling or ventilation needs. Neighborhoods with taller buildings also disrupt the natural motion of the wind, creating suddenly increased wind speeds around corners at street level or on elevated locations on buildings. Architects and urban designers must work on this problem holistically in the early stages. Computational flow simulations can be used with experimental wind tunnel data to investigate the wind environment surrounding the design proposal, whether a building or a neighborhood, to overcome problems before it is realized.

1.2. Problem Statement

Governments must review their energy policies to create sustainable natural or urban developments (IPCC 2016). Residential buildings and fossil fuel-based electricity production facilities are primary concerns for lowering CO2 emissions in cities (UN Habitat 2011). In European cities, transportation, public services, and new development projects have already adopted CO_2 emission targets. However, in most Asian cities, continuous urbanization and population increase make it harder for policymakers to reach goals (Hsu et al. 2017). The government's search for economic and sustainable ways to implement healthy and energy-efficient strategies for urbanization policies (Krautheim et al. 2014), but it is hard to achieve both qualities when there are societal challenges like pollution mitigation, safety, and public health (Blocken 2015).

Architects and engineers are implementing active and passive energy-efficient design strategies in new development projects; however, it is challenging for designers to balance projects by using innovative technologies and keeping economic constraints in dense urban areas (Krautheim et al. 2014). Designers also must challenge new approaches for passive solutions to produce climate-responsive design because climate-responsive design strategies are now a requirement for designing future settlements to reach CO_2 emission goals (UN 2015).

Climate change challenges the resilience of cities against changing weather conditions. Major natural events like hurricanes, wind-driven floods, heat waves, dust, and pollution dispersion result from global wind effects (Blocken 2015). The wind is an unpredictable phenomenon unlike other climatic events, and it is hard to accurately measure for analysis at a specific location. Meteorologists trace wind with different instruments like satellite images, climate models, and large amounts of data from site measurements. (AMS 2014). This data load is hard to compile and analyze with basic equations, so engineering concepts like aerodynamics, fluid mechanics, and meteorology analysis are required (Lawson 2001).

Wind loads and motions of tall buildings have been tested with experimental approaches in wind tunnels. These experiments are a valid method for understanding the proposed design's behavior before realization in smaller-scale models (Irwin, Denoon, and Scott 2013). However, a significant amount of work must be done before and during wind tunnel tests. It is also not feasible to test every step of the design phase in wind tunnels where there are time and budget constraints.

Computational flow simulations are a useful way to understand wind behavior in urban settings. Compared to wind tunnel tests, engineers can simulate complex equations defining wind direction, velocity, and energy potential with flow simulations on larger areas on full-scale models (AIJ 2004). Nonetheless, architects and urban designers can simulate possible urban wind characteristics in design phases, but the required knowledge of flow characteristics and the number of involving parameters for simulation and processing needs are challenging (Anderson 2014).

Urban design parameters like building layouts, size and shape qualities, or distances between buildings require a larger calculation domain defined in flow simulations. It is an emerging field of architectural and urban design considerations for new settlement projects (Blocken 2015; Toparlar et al. 2017). The design of new development areas carries new potentials for implementing passive energy efficient strategies while overseeing the wind effects around buildings on pedestrians. It is possible to benchmark the final design before it realizes. Building's impact on local climate conditions and changes in local wind flow patterns can be evaluated with flow simulations. These flow simulations can indicate potentially problematic areas for pedestrian activities like walking, sitting, or strolling, but they need to be validated with experimental results.

It is possible to comprehend complex wind behavior and analyze the performance of different building settings with alternative parameters in a study before the project is realized. These performance simulations need to be validated with results, but it is impossible to find validation in the literature that can match every case study in real life. So, another method for validating a case study is required to evaluate the buildings systematically. This method evaluates the sub-configuration of building layouts with single building settings and analyzes geometric features parametrically (B. Blocken, Janssen, and van Hooff 2012).

Simulation results will provide data on wind flow at the pedestrian level for design proposal assessment and help identify critical points for implementing building features like entrances, canopies, and balconies. This data is essential for architects to choose appropriate facade design and help to eliminate possible inconsistencies before the project is realized. Although the results are comparable to design alternatives, there are no universal wind speed limitations for specific human activities in literature (Ratcliff and Peterka 1990). There are existing comfort and safety criteria for pedestrian-level wind speeds for some activities, but their implementations should be evaluated within the context of the design area. The resulting projects also have the potential for further studies to investigate new innovative approaches or to be implemented as guidelines for new developments.

1.3. The Purpose Statement

This study aims to explore the complex behavior of wind and analyze the variables of urban building parameters (height, width, length, and the layout of buildings) related to architectural design and their effects on a case study in an urban regeneration area in Izmir. To understand the wind behavior in the case area, long-term meteorological measurements taken from the national weather service will be analyzed to obtain the prevailing mean wind speed and direction. Design alternative for the new building layout will be examined and limited to the exact boundary. Finally, proposed design alternatives will be simulated with meteorological data, and numerical results of flow simulations will be compared within each design to determine building parameters with a high impact on the area's microclimate. Flow simulations will be conducted with ANSYS Fluent software, an engineering simulation software capable of conducting numerical fluid analysis, and a 3d design program for modeling the case buildings. It is also aimed to compare the results with categorized wind flow types around buildings in literature to provide guidelines for future urban design projects.

1.4. Research Questions

Climate-responsive cities which positively benefit from natural ventilation and support pedestrian wind comfort could be designed by investigating wind behavior around the proposed buildings. Case studies with different building densities, orientations, climate scenarios, and vegetation layouts in the conceptual design stages could be evaluated with computational simulations.

The computational Fluid Dynamics (CFD) simulation method is a fundamental numerical approach for understanding the unpredictable wind effects in an urban environment. Compared to wind tunnel experiments, CFD simulations can be used to analyze building height, width, length, and orientation in proposed layouts in full-scale models of large area layouts. This method yields flow data results for buildings' surroundings areas to assess the microclimate of a neighborhood. Wind tunnel experiments provide accurate data when similarity and boundary conditions are correctly maintained, but these experiments are expensive and time-consuming in the early design stages.

Today, decision-makers and governmental institutions in metropolitan cities are implementing sustainable design strategies and necessary precautions for the comfort and safety of users in tall buildings. Architects and designers can investigate wind flow around buildings in early design stages of projects to gain insight about surroundings and resolve pedestrian level issues while adapting regulatory requirements. Nevertheless, surrounding areas around buildings are generally neglected in densely built areas where services designed on the ground floors of the buildings failed due to neglected wind effects.

Based on these assumptions, the research questions listed below have been examined in this study.

- How do the population growth and increasing wind-associated weather events influenced by climate change affect people in metropolitan cities?
- How do the buildings impose mechanical (physical) wind effects on pedestrian activities in densely populated urban areas?
- What are the advantages and disadvantages of using computer simulations compared to wind tunnel experiments in large areas with building clusters for new redevelopment projects?

- How do building height, width, depth, and orientation layout affect pedestrian activities (walking, standing, sitting, running) in urban spaces?
- What are the most applicable wind speed limits for pedestrian activities developed to categorize the comfort and safety of pedestrians?
- What are the advantages of using CFD simulations to understand wind behavior in an urban layout in the early design stage of new development or regeneration projects?

1.5. The framework of the Thesis

This thesis comprises six chapters, beginning with the ‘Introduction.’ Problems observed in the built environment that governments and organizations consider due to climate change and overpopulation which crosses the common field with problems in urban wind environment, are identified. The purpose of the study, problem statements, and research questions were presented in this context.

The second chapter consists of a literature review about challenging issues concerning today’s cities. Threats and vulnerable points of densely populated areas for health issues and how the wind phenomenon is related within this context are elaborated. The definition of wind environment expanding to different levels of the atmosphere is focused on physical effects on daily human activities like walking, sitting, running, and strolling at pedestrian level. Testing methods and standards for pedestrian activities developed in recent studies were also outlined.

The computational Fluid Dynamics simulation method is described in this chapter, which has been developed to use for flow simulations in different engineering fields. Detailed background information on CFD workflows and required data to achieve validated results are also presented in this chapter.

The fourth chapter addresses the methodological approach for wind assessment in detail. The properties of the case area are described, and a simulation decision model is established using architectural parameters and meteorological data. CFD simulations of simplified building geometries were analyzed for verification and validation to provide a basis for the case area. The focused area which will be primarily investigated in this thesis is presented with compiled data from validated blocks.

In the fifth chapter, the results of simulations are compared accordingly with the impact of architectural elements, including design alternatives. Single and multiple building layouts were studied to discover the impact of architectural parameters in a pedestrian-level wind environment. Surrounding areas around buildings are considered with fitting human activities like walking, sitting, strolling, and proposed with the best possible activities according to categories defined in the literature.

In the final chapter, concluding remarks are summarized, and the impact of architectural features is presented for future studies. Different scenarios for building layouts and geometries are laid out to provide foundation for generalized comfort and safety criterias that can be applied to the built environment in Turkey.

The main structure of this study can be seen in Figure 1.1.

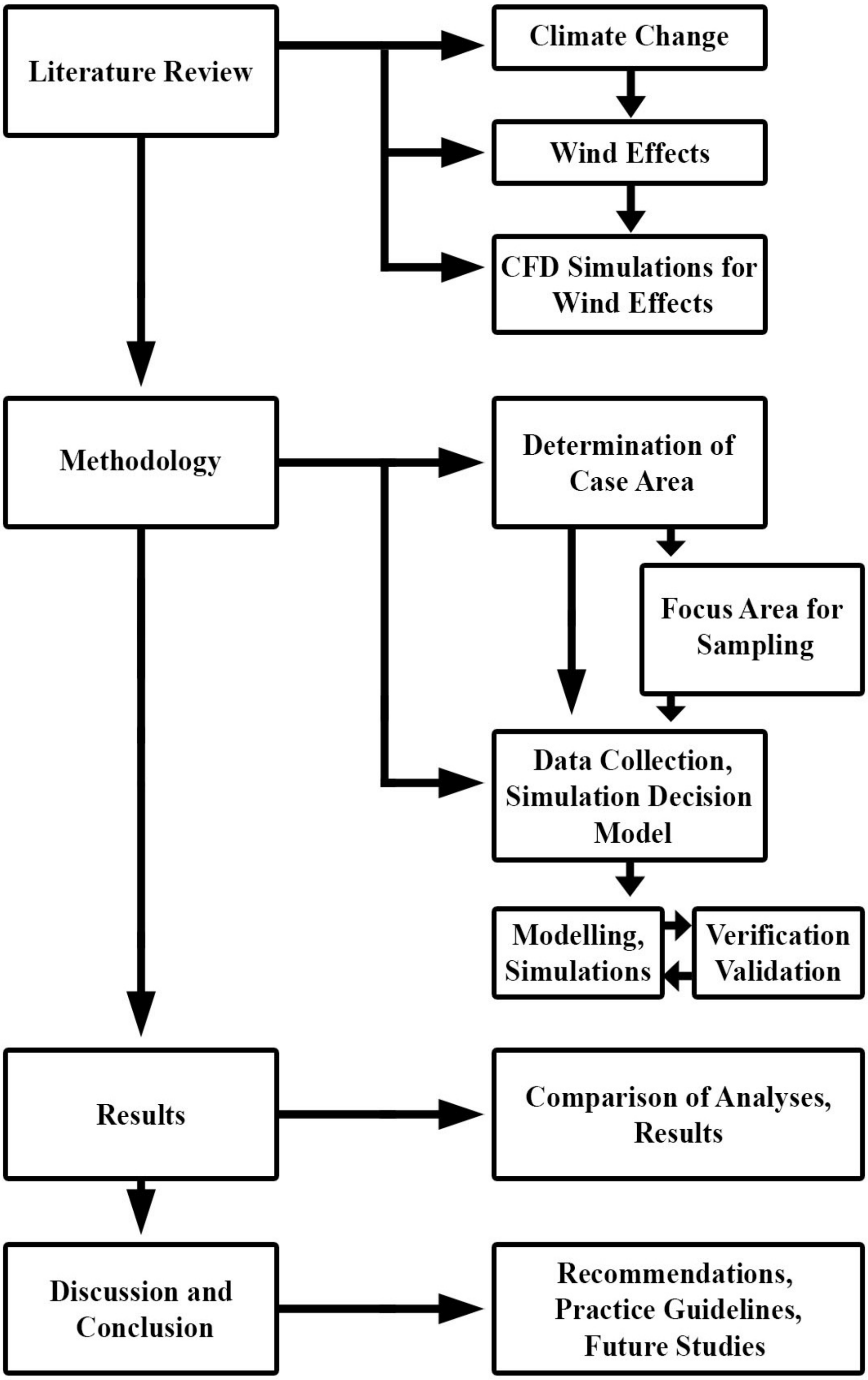


Figure 1.1. The main structure of the thesis

CHAPTER 2

LITERATURE REVIEW

Architectural approach for designing a building that will satisfy the needs of users with adequate functions, adapted in an environment and staying in budget has always been challenging for architects in design stage. Today architects must design more challenging high density urban areas where population is exposed to effects of climate change (Ng 2010). Engineering tools for energy assessments are used by design teams to develop adaptive design solutions for climate change (Anderson 2014). Among the other climate conditions of an area, wind has always been an important factor as a design element (DeKay and Brown 2014), but underestimated more than half century while high rise buildings are constructed. High rise buildings have paramount effect on surrounding areas on pedestrian level and alter the microclimate of a neighborhood depending on density (Tominaga et al. 2004). Investigating this wind environment is also a hard topic for architects and urban designers. It's complex flow terms require technical background for analysis in early design stages and always been a challenge for design teams, but its necessity is increasing parallel with climate change effects on dense urban areas.

2.1. Cities, Population and Climate Change

Cities today supply more than half of the world population. In 1950's only 30 percent of people were living in urban areas, but now it is projected to be 66 percent by 2050 (UN DESA, 2015). This transition is mainly based on economic reasons that attract people towards living in cities. New job opportunities for people are created by increasing demand for industrial, commercial, or public services. DESA report (2015) cited Montgomery et al. with his definition of this process as "a shift in population from one that is dispersed across small rural settlements in which agriculture is dominant economic activity towards one where the population is concentrated in larger, dense urban settlements characterized by industrial and service activities" (2004). This shift in population was happening in moderate levels with the industrial revolution and rapid economic growth, that based on mostly Europe and Northern America cities. (UN DESA, 2015). These cities are referred as “fossil fuel cities” throughout the urbanization of industrial era beginning in the 18th century in England and continued to expand the U.S. in the 19th century and now shifted to Asia by the 20th century (Reusswig, 2014). Today new technologies in transportation, communication, and economic tools led to a shift in central production facilities to locate Asian cities. Production plants are opening with thousands of workers per factory, along with distribution chains to all over the world, began to dominate economic indexes. By 2030, ten cities with populations between 5-10 million inhabitants, projected to become “megacity” with more than 10 million populations. Today, 15 Asian cities already passed that mark (UN DESA, 2016). Also, 20 Asian cities, which are in China, have growth rates 6 percent, which is twice more than average annual rates (UN DESA, 2016).

This accumulation of population in cities changed the organization of settlements using urban planning. Rural settlements, isolated from each other using security and protection, focused on agricultural activities for growth. People traded surplus products for finer and rarer products, and they began to interact more. This interaction attracted rival settlements to acquire goods by force rather than hard work. So that settlement required to build public buildings like walls or fortifications (Toparlar et al. 2017). Toparlar cited Bairoch and Grant et al. to define a settlement as a city; it should be formed as a “permanent urban habitat, composed of buildings built with durable materials, streets and roads arranged to serve the purposes of urban living and public buildings (e.g., city fortifications)” (2015). As settlements transformed into cities, density and population terms become prominent. Cities grow and provide more services thus attract more people to live in communal forms. According to Willis,

- living closer together encourages more community interaction, and reduces isolation for vulnerable social groups, such as young families,
- compact settlements require less transport and reduce car use, with health and environmental benefits,
- higher-density development is environmentally beneficial, resulting in lower carbon emissions,
- in rural areas, more compact villages could help to stem the decline in rural services, such as shops, post offices, and bus services (2008).

Advantages of living in more condensed settings laid out by Willis is still an ongoing debate in urban planning. Scarce land areas should be carefully allocated for further development if the valuable agricultural areas not prepared to sacrifice.

If we consider a densely built city like Hong Kong, the population is taken as 7 million people on 270 square kilometer-built area; it will require 105000 square kilometers agricultural area to feed inhabitants (Vale 2009). So, planning of cities is a key factor for healthy growth. First attempts to deliver healthy city growth consisted of building new towns away from city center with low or middle-density settlements (Vale 2009). But this solution was merely resolving the issues and beyond that causing more problems in-service distributions and lowering the valuable agricultural or recreational lands. Cities tend to access its resources close to the center of the distribution, but this makes difficult to supply equally (UN Habitat 2011).

Increased population and shortsightedly urban planning are now giving its fruits in modern cities today. Transportation, health, and housing problems of rapid growth in cities brought upon societal and as well as urban climate problems. Two main driving reasons for climate change, combustion of fossil fuels for transportation, heating, industrial facilities, and land use changes happening in a condensed area cause deterioration in the carbon cycle. Carbon cycle functions as a protective barrier for incoming solar radiation. Human activities in high-density locations have led to a build-up of greenhouse gases in the atmosphere together with a reduction in the capacity of oceans and vegetation to absorb greenhouse gases (UN Habitat 2011). The role of CO_2 as a greenhouse gas in the carbon cycle is that it helps atmosphere to trap infrared radiation of heat for sustaining natural life on Earth. (Columbia University). But the delicate balance in the atmosphere supported by mechanisms like photosynthesis, respiration, weathering, metamorphism of carbonates1 is threatened by human activities. These human activities resulting the emissions are explained in Habitat (2011) report as,

- Combustion of fossil fuels for heating, cooking, electric generation, running vehicles for transportation or industrial processes.
- Land use changes to supply plot areas for dwellings or production that may lead to deforestation and reductions in the uptake of CO_2 by vegetation.
- Landfill sites are taking up urban wastes that also generate methane.

- Use of Cement as a primary construction material also has a large carbon footprint due to an energy-intensive manufacturing process and high energy cost for transporting.
- Activities, such as agriculture, livestock production, mining, timber collection and lumber production.

These activities are that we do unconsciously are damaging the environment and inevitably increase CO_2 emissions. In a fossil fuel consumer city, residential and commercial sectors are responsible for more than half CO_2 emissions caused anthropogenic effects (Figure 2.1) So, it is imperative that we should understand that the climate change is real and happening. We should be expecting fluctuations in temperatures, changing of wind and precipitation rates or worse scenarios if we are to continue and ignore the clues that environment is already giving us. Policy makers and responsible governments regularly commence and debate on Anthropogenic effects related to climate change.

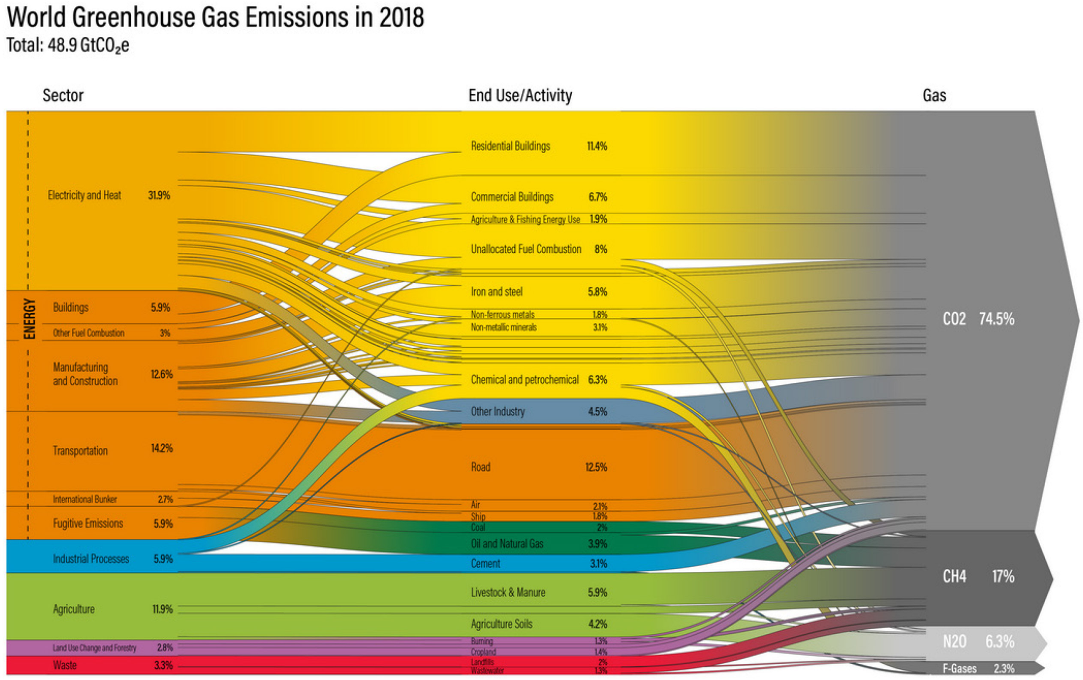


Figure 2.1. GHG Emissions by sector distribution and by source in cities
(Source: Climate Watch Historical GHG Emissions, 2020)

These issues are addressed in Habitat and Intergovernmental Panel on Climate Change (IPCC) (2016) reports:

- Warmer and more frequent hot days and nights over most land areas,
- Fewer cold days and nights in many parts of the world,
- Frequency increases in warm spells/heat waves over most land areas,
- Increased frequency of heavy precipitation events over most areas,
- Increase in areas affected by drought,
- Increases in intense tropical cyclone activity in some parts of the world,
- and increased incidence of extremely high sea levels in some parts of the world.

Urbanization and rapidly growing populations make cities more vulnerable using geographic locations. As well as the capital stocks related to commercial activities, people tend to choose coastal regions rather than inland likewise they choose urban to rural (Reusswig, 2014). This trend of urbanization analyzed in UN reports and by 2030 more than ten cities with million populations are going to be exposed to natural disasters (Figure 2.2)(Figure 2.3). UN reports (2016) take statistics of occurrences that these

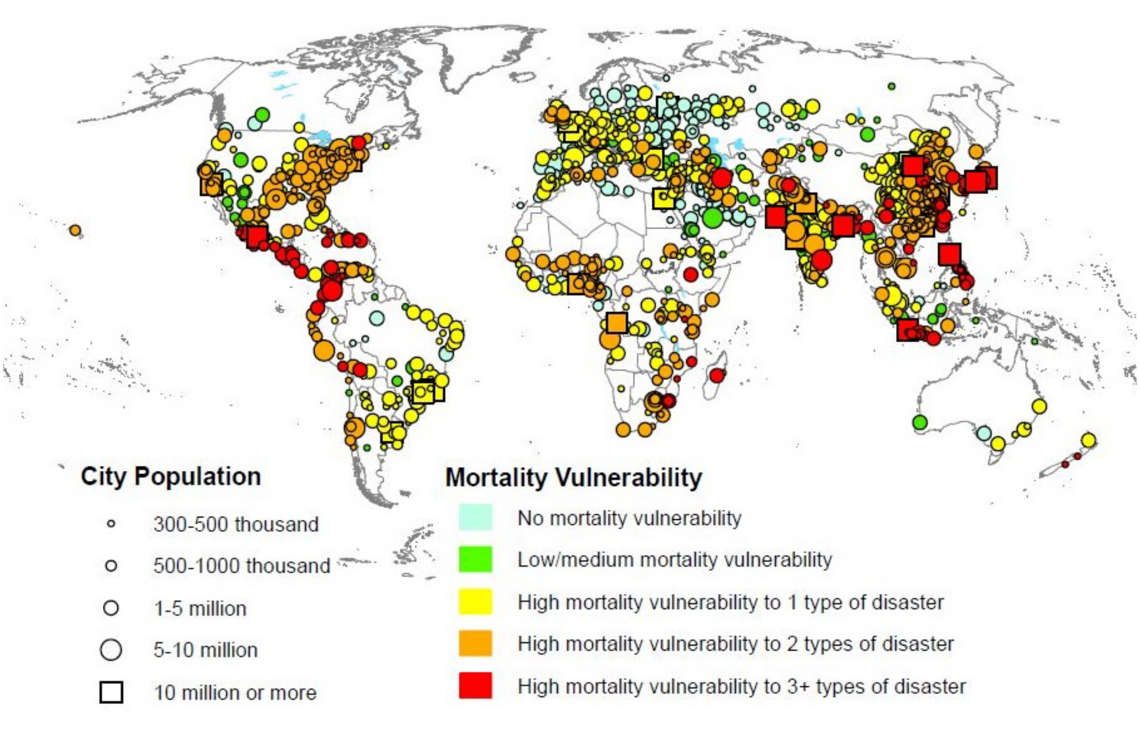


Figure 2.2. City’s risk of exposure to natural disasters
(Source: UN DESA 2016)

climate events happen and estimates probable mortality with economic damage could happen (Figure 2.4) Cities located in Asia, which already exceeds the population expectations, pose higher economic vulnerability for future predictions. They became global partners of US and European companies so that a single regional flood could cause millions of capitals loss on the global scale. But not only external weather events pose a threat to these cities. There are societal challenges in health, transport, and energy issues to be considered while creating future for sustainable development.

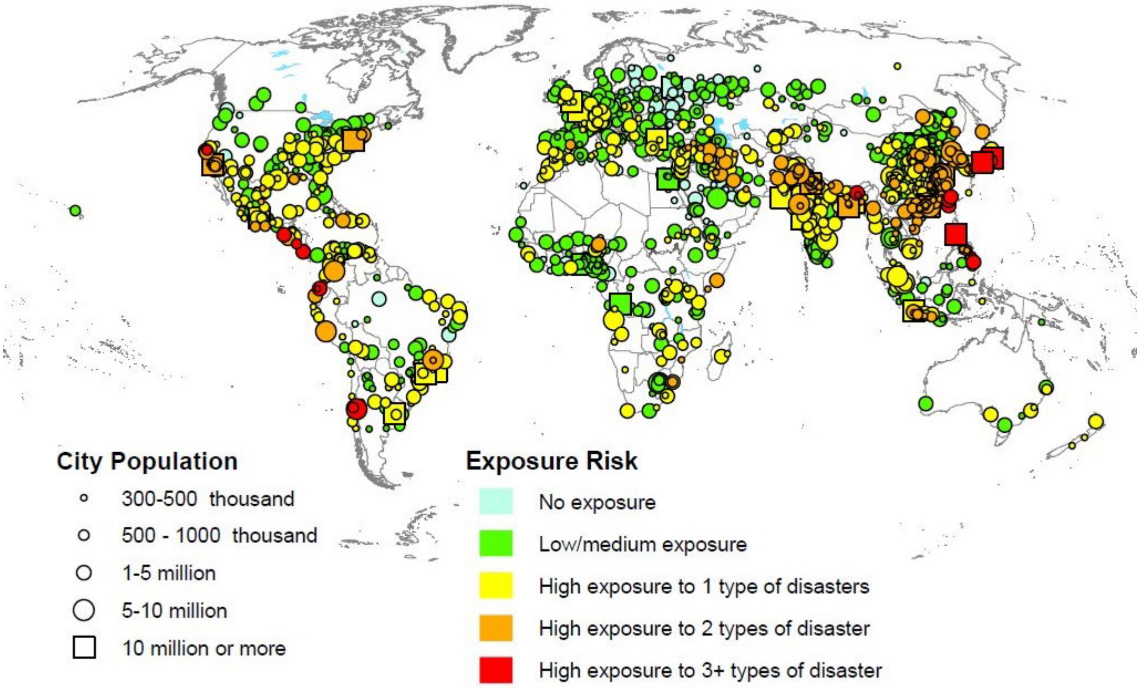


Figure 2.3. City’s vulnerability to disaster-related mortality
(Source: UN DESA 2016)

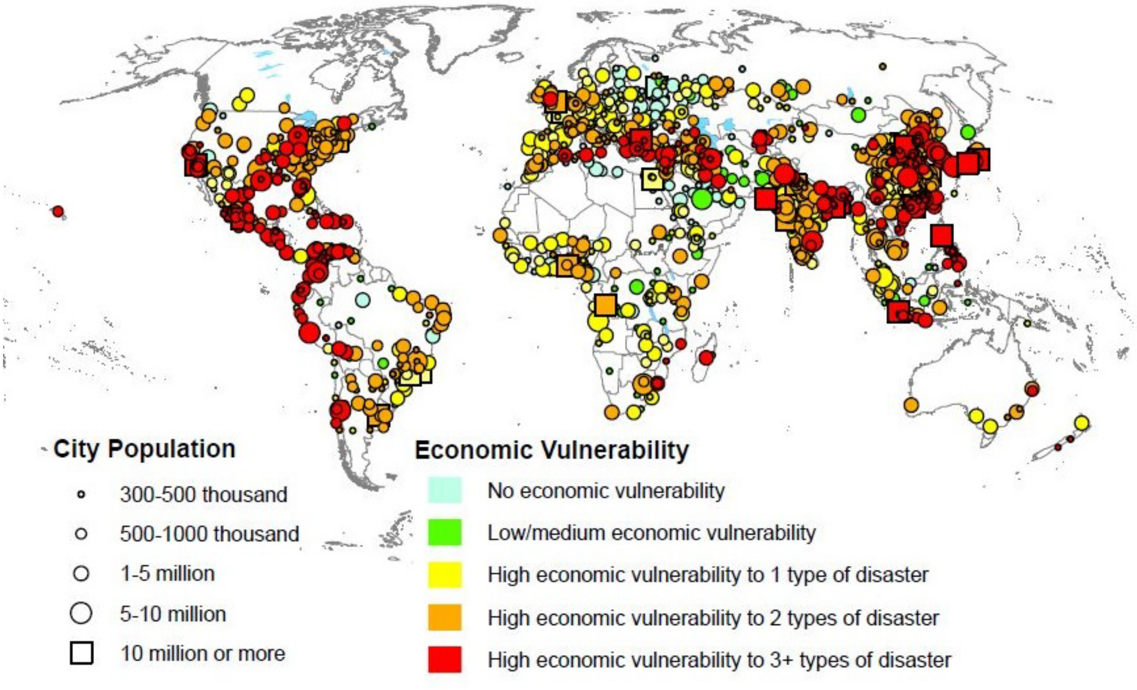


Figure 2.4. City's vulnerability to disaster-related economic losses
(Source: UN DESA 2016)

2.2. Climate Change and Urban Physics

The architecture of built environment is considered as an instrument for sheltering people from climate effects in an orderly manner while living in communal systems. Krautheim et al. defines the architecture as an opponent to physical and psychological threats of climate but also mentions climate "localizes architecture and makes it complex, multi-layered and unpredictable" (2014). It is important to take necessary steps not to isolate people from nature while creating an artificial and resilient built environment. As the anticipation of doubling in population among the suburban areas in cities by 2030, local authorities and policymakers should take actions. Habitat 3 suggest important topics to be focused on cities as, focusing land use, density distribution, resilience to severe weather events, road infrastructure and economic sustainability of cities (2016). Some of these actions require the focus of politics, economics, and communal relationships, but in fact, many of the required actions should be taken by urban planners, architects, engineers, and urban designers. It is documented in Habitat 3 that "low-carbon, resilience-based, and climate effective design of spaces, buildings, and constructions, services, and infrastructure, promote cooperation and coordination across sectors as well as build capacity of local authorities" (2016).

The traditional urban design approach is rather a stand-alone approach for designing cities focusing on spatial production for development (Krautheim et al. 2014). But sustainable development of cities has many focus areas that require the attention of diverse approaches. Politics, health professionals, economists must agree with policies that can shape a better community. Other aspects of infrastructure and urban settlements need to be evaluated for future and possible expansions to a sustainable, secure, and healthier growth. (WHO 2010, UN Habitat 2016). Recent studies show that are two distinct directions for urban design approach.

- Formulation of generic principles for entities like eco-cities, neighborhoods, infrastructure, and smart grids, and
- Case studies on specific topics related to environmental performance, such as material research, energy efficiency, building performance or building integrated systems (Krautheim et al. 2014).

These two approaches are barely scratching the surface of climate responsive design. Architects and urban designers should not have to choose an approach and focus on a single side of the problem. They should implement innovative design strategies in form, program, and spatial hierarchy of buildings to promote sustainable built environment (Krautheim et al. 2014). Architectural design approach without underestimating climate elements require knowledge of all relevant elements and augmenting them in a design process. Using renewable energy sources in active systems and passive design strategies together to achieve protective but, not insulating, environment for users from nature. These subjects are all covered in urban physics that Moonen et al. defined as a "well-established discipline, incorporating relevant branches of physics, environmental chemistry, aerodynamics, meteorology, and statistics."(Moonen et al. 2012) It is a wide research field with many input parameters that can be used to answer problems of urbanization and climate change. Fadl and Karadelis outlined the parameters that affecting outdoor human comfort in an urban climate as wind speed, air temperature, relative humidity solar radiation, air quality, and human factors. (Clothing, age, habits, etc.) These parameters are currently related to the wind in cities (Fadl and Karadelis 2013).

The wind became a considerable parameter to solve problems to ensure a comfortable environment for urban life (Lawson 2001). Early design prototypes of tall buildings were evaluated by engineers so that necessary changes could be made before construction. Air temperature, also affected by wind speeds, felt differently on the people. Lawson (2001) defined this interaction as “Chill Factor” that presence of the wind changes how we sense the actual temperature. Another factor related to wind is the gas emissions affected by the urban environment. Gas emissions from ventilation systems and combustion are important problems on pedestrian and natural ventilation needs. Near and far fields from the exhausts from buildings should be evaluated carefully for health considerations. Engineers and architects work together to pacify and dispose unwanted pollutants before interacting with a building which they are emitted or any surrounding building (Lawson 2001).

Outdoor air quality also affects the indoor air quality. Santamouris (2001) suggested that outdoor pollution is one the sources of the “sick building syndrome” due to inappropriate use of ventilation and source control. These problems are just a few effects that wind can cause at lower speeds. There are also some cases that wind speeds increase too high that they form typhoons or tornados where they have devastating effects on buildings and urban environment. Cermak stated these high-speed wind-related issues and importance in human comfort in cities long time ago; “losses due to wind ($500,000,000 in property damage, 240 deaths and 2600 injuries annually), increased demand and concern for human comfort, serious attempts to control air pollution, and the development and expansion of energy-production capabilities have resulted in applications of engineering to problems for which a body of knowledge has only started to emerge in the United States” (Cermak 1975). Occurrence of these high wind speed extreme events are suspected to be related to climate change. Increased warming of surface effects the wind flow in global scales therefore effecting the frequency and intensity of large storms (Irwin, Denoon, and Scott 2013). recent study shows that an increased intensities and incidences have been witnessed in high category tropical storms (Kossin et al. 2020). These trends investigated in the last four decades of tropical storm events showed correlations with models for temperature estimations due to climate change (Kossin et al. 2020). It could be inconvenient to make assumptions in this stage but there is a rapid improvement on studies investigating both environmental scale and building scale wind effects.

Blocken (2015) defines urban physics as a “rapidly expanding discipline” because of increasing urbanization; urban physics can address the issues and societal challenges threatening cities with fast urbanization transform. These issues are summarized by Blocken (2015), according to their relationships with a graphic (Figure 2.5) that frames the wide area of wind engineering. Wu and Kriksic (2012) also relate wind flow to assess pedestrian comfort which includes a range of microclimate conditions, such as wind comfort and safety, thermal comfort, air ventilation, snow accumulation and rain infiltration (Wu and Kriksic 2012).

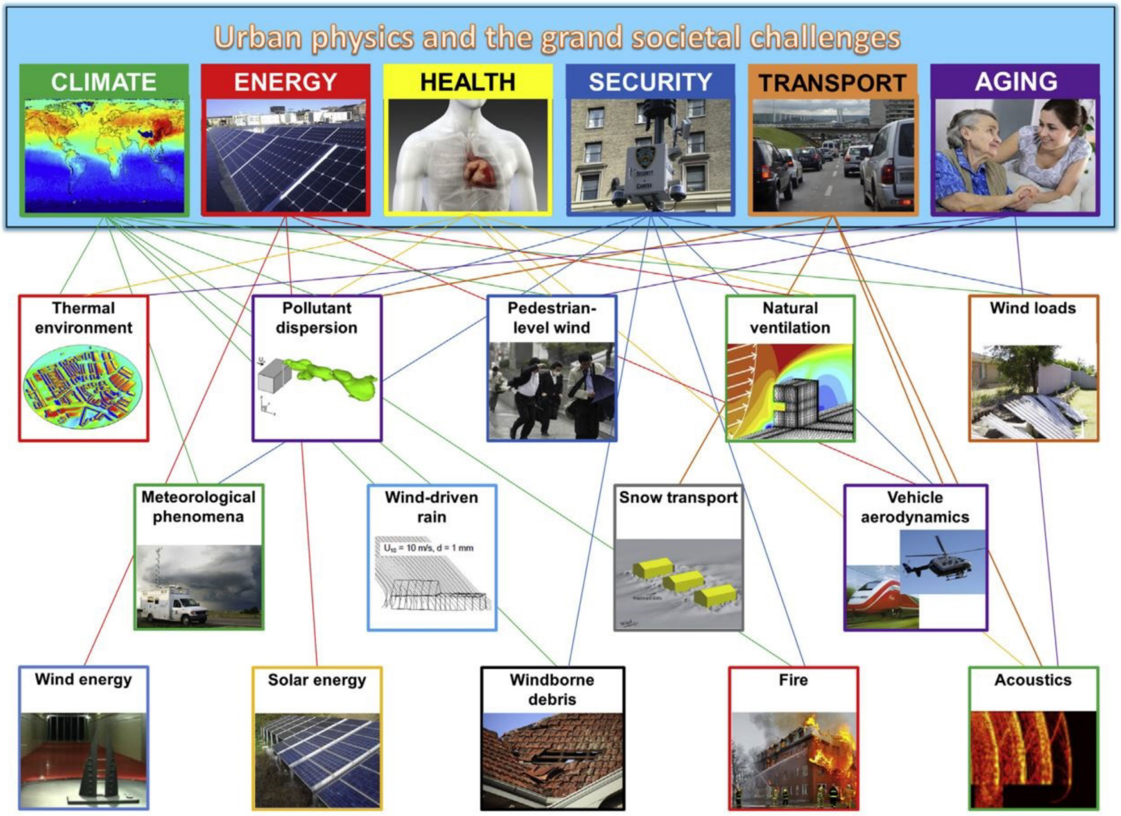


Figure 2.5. Urban physics and its societal challenges

(Source: Blocken, 2015)

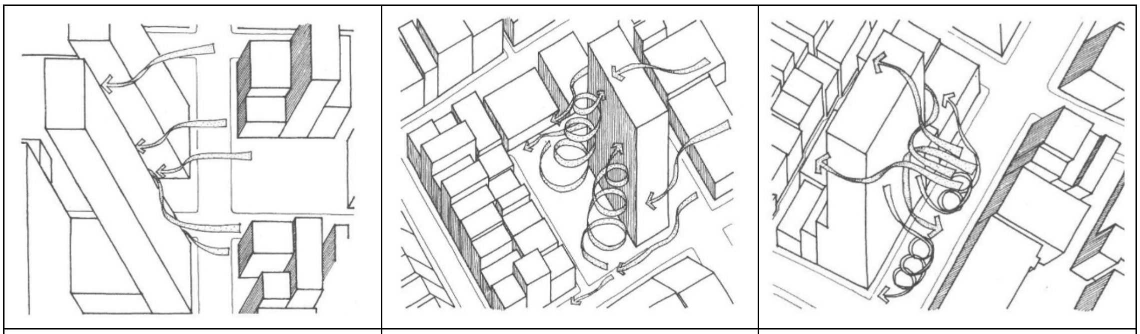
2.3. Urban Physics and Building Design

Common view is developing in the last 20 years' time of sustainable development of cities; it was only a narrow perspective of assessing the building energy performance relying on standalone building configurations and considering neighbors only for solar gains and shading (Vallati et al. 2015). Despite only considering them as physical walls, Vallati et al. considers buildings in urban context, experiencing; “higher ambient temperatures due to urban heat island effects and local heat rejection from other buildings, an altered radiation balance, due to the presence of surrounding buildings, and changed convective heat exchange, due to the different wind flow pattern” (2015).

Further understanding of urban physics requires assessment of larger urban scales and dynamics of wind which are highly related to human comfort. Lawson’s (2001) building aerodynamics suggest the involvement of architect in wind environment (thermal), ventilation, emissions considerations during the design phase. Architects should consider their projects with its surroundings, starting with site data, layout and position of the building in the plot and landscaping. In the past, the wind was often not considered, and arbitrary decisions were made which produced serious wind problems, which could have been avoided without compromising any of the other requirements for the building (Lawson 2001). So that they will have effects on building form, external elements and functional arrangement of spaces which will lead to detailing and material choices (Santamouris 2001).

2.3.1. **Wind Flow Around Buildings**

Wind assessment in an urban environment requires an understanding of air flows around buildings. In the early phases of building design, we need to have aerodynamic considerations while deciding the form of the building. There are three principles listed by Brown and Dekay (2001) to consider while processing the wind in the built environment. These are friction, inertia, and pressure difference principles. Friction is the effect of ground’s “roughness” over velocity of the wind. As the roughness increases due to the density of the urban or surrounding natural environment, wind velocity decreases and gives us a curved profile wind speed. Second principal inertia explains the movement tendency of the wind, which is flowing around objects as a fluid rather than diverting away from them. And the third principle relates to wind direction that wind flows from high-pressure areas to low pressure which is highly related to temperature differences (DeKay and Brown 2014). Because of these principles, various wind effects occur due to the positioning of the buildings and the density of the built environment. Due to higher speeds of wind on the upper parts of the tall buildings, it creates higher pressure on the building surface. Air moves to lower pressure areas in the street levels and create “downwash vortex” effects (Figure 2.6) which result in up to %140 increased speeds and turbulences at pedestrian levels and decreases comfort levels. If wind could pass around building or two buildings with proximity, it gains velocity. This “corner effect” or funneling could increase as the width of the building increases. As the wind passes around the building, its tendency to converge on the surface creates “wake effects” when there is a gap between the other building at leeward (opposite side of wind direction) side of the building (DeKay and Brown 2014). These wind effects are only a small part of data that we could use in the urban environment. As the number of buildings in city increase and take different forms, wind projection and design parameters increase in an orderly fashion.



a b c

Figure 2.6. Wind effects around buildings; a) corner effect, b) wake effect c) downwash vortex (Source: Brown and Dekay2001)

First quantitative studies with wind tunnel verifications about wind behavior in urban context was researched by Gandamer. He identified twelve aerodynamic effects around buildings according to origin of wind, approach, and development of the wind profiles require a larger calculation domain (Gandamer 1978). (Figure 2.7) Buildings in urban context experience higher temperatures, due to increased heat by materials and rejection from other buildings as well as convective heat transfer through paths which are exponentially affected by wind (Vallati et al. 2015). Fadl and Karadelis (2013) cited Emil and Robert (1996) for the definition of extended wind effects around tall buildings and divided into three regions.

Type I: Vortex flow between buildings, near ground level,

Type II: Descending air flows passing around lee-ward building corners, Type III. Air flows passing through openings (passages) at ground level connecting the windward and leeward sides of buildings (Figure 2.8). As the scales of problem region around building increases, wind effects and its behavior differentiate to a point where it is hard to analyze as bulk air movement.

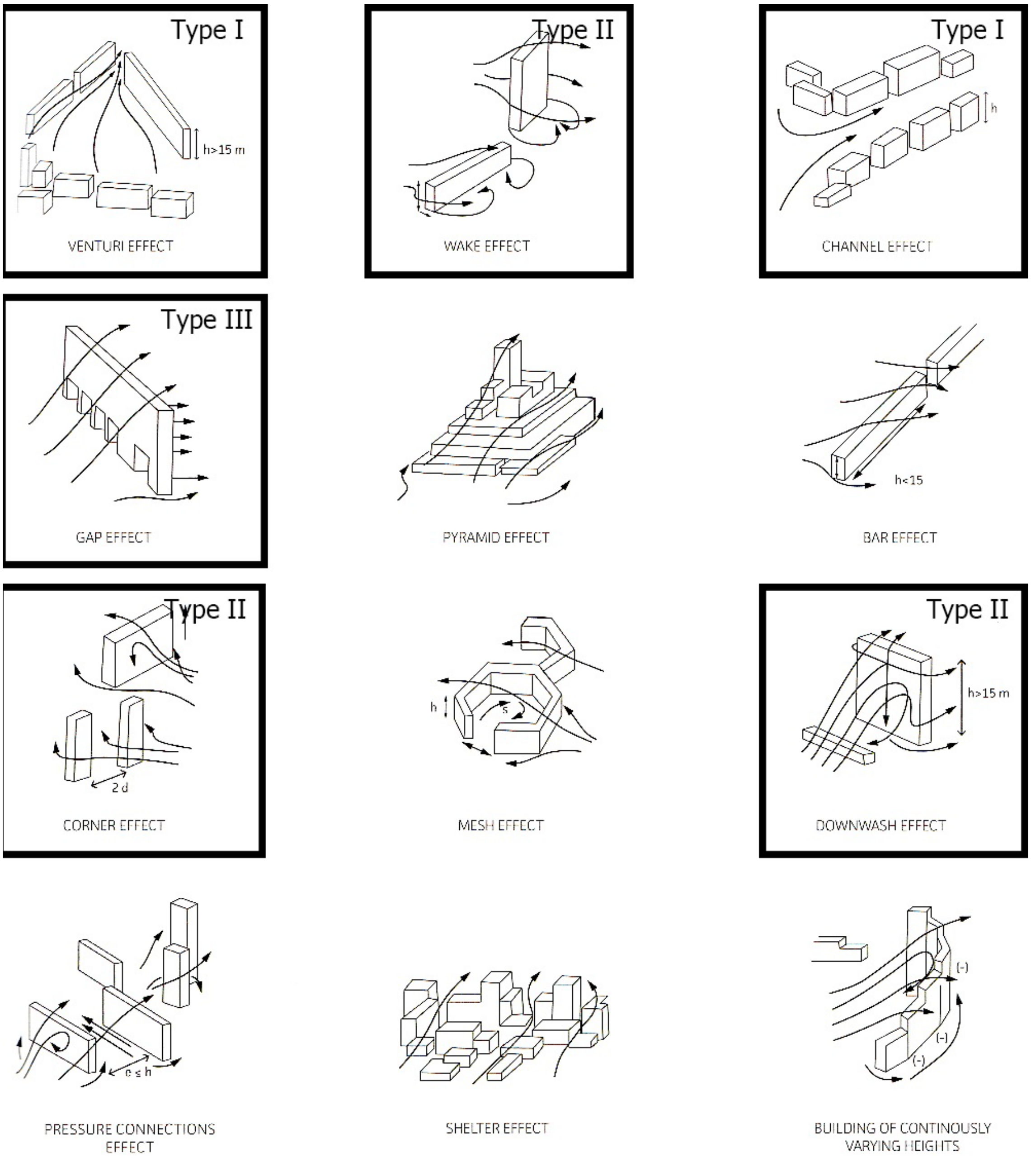


Figure 2.7. Aerodynamic effects around buildings

(Source: Krautheim et al. 2014)

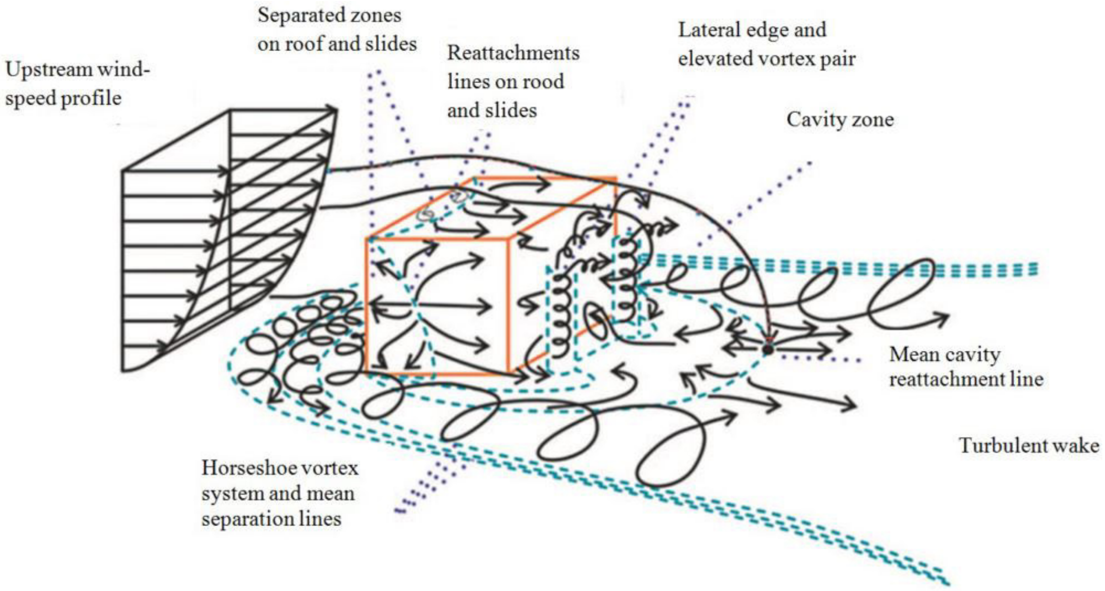


Figure 2.8. Regions of high surface speeds around the tall building
(Source: Fadl and Karadelis 2013)

Calculating or simulating the complex movement of wind requires Computational Fluid Dynamics (CFD) analysis for more accurate microclimatic conditions (Toparlar et al. 2017).There are many differences between CFD analysis and bulk air movement analysis. CFD analysis requires iterative calculations that are highly depended on parameter (wind profile, boundary conditions, turbulence models, model grid, etc.) input for analysis. Bulk air movements are calculated within an energy modeling software and usually focus on annual or defined time frames (Anderson 2014). Application of CFD for hourly or daily calculations would require expensive processing work as opposed to building energy simulations but could resolve detailed issues which can be resulted in as coarse data output in energy simulations (Bert Blocken 2015). Building energy solutions focus on the zonal network of domains, they lack the momentum interactions between zones, so the outcome heat dissipations are poorly laid out (Bartak et al. 2002). CFD calculations are generally accompanied with reduced or full-scale physical experiments, and field measurements, where building energy solutions require CFD calculations before beginning physical experimentation (Bartak et al. 2002). Another problem of building energy simulations is, indoor air is taken as mixed homogenous flow, rendering the results inconclusive for detailed considerations (Wang and Wong 2009).

2.4. Wind Effects and Testing Methodologies

Accurate climate data is required for better understanding of the urban area to improve thermal comfort for the people living in the existing layout and for future planning. For most situations, there could be only point measurements available from national weather services which can be limiting due to the winds' instantaneous velocity or direction changes. Wind measurements taken by anemometers are presented in mean values and require further calculations of turbulence intensity for evaluating as criterias in the design options. So that numerical simulations or wind tunnel experiments should be accompanied with climate models of an existing domain (Allegrini, Dorer, and Carmeliet 2015).

Wind tunnel experiments in built environment context first used on single building blocks on flat terrains to investigate flow patterns (Paterson and Apelt 1989). Using CFD analysis for the urban built environment is an emerging field that could be found in detailed and extensive research topics on different locations with different city layouts. Case studies for different scales of built environments could be done to find best matching results with physical experiments or climate measurements (Bert Blocken 2015).

2.4.1. **Wind Formation**

The differential heating of the atmosphere from sun generates the wind. The atmosphere contains gases that are continuously moving accordingly with geographic forms and planetary forces. In the molecular level, air with a combination of different gases circulates with temperature differences. As the temperature increases, molecules depart from each other and form a low surface pressure area (Krautheim et al. 2014). Colder molecules get close to each other and inversely form high-pressure areas. This circulation movement explained in Figure 2.9.

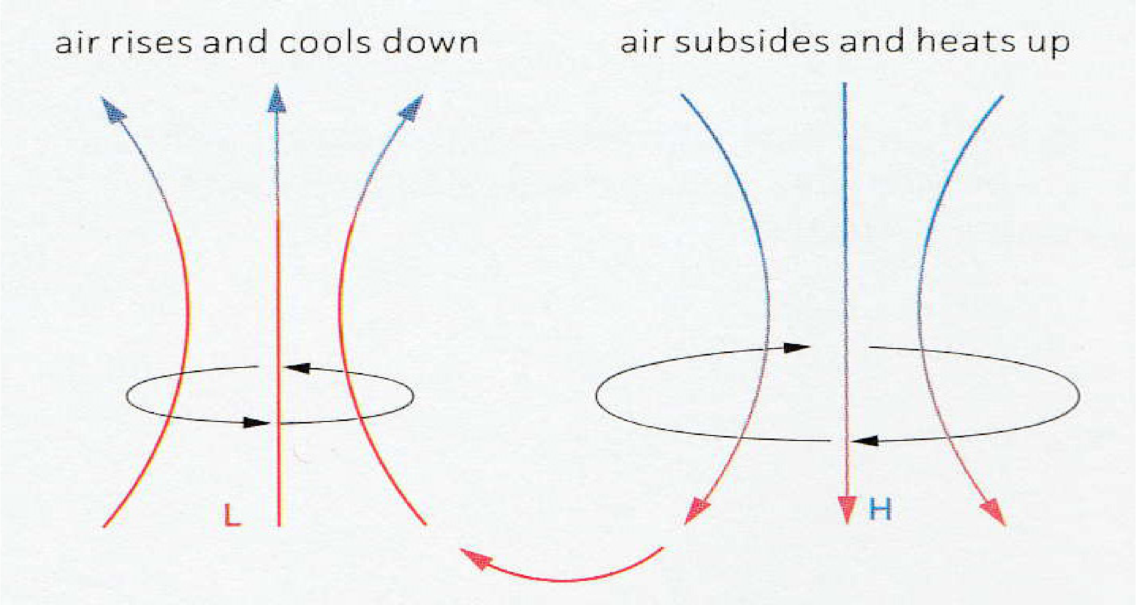


Figure 2.9. Pressure difference movements in the northern hemisphere
(Source: Krautheim et al. 2014)

This pressure difference is kept in balance by the atmosphere as the total mass of the air does not fluctuate. Pressure difference gives us an idea about the direction of the wind, but the earth angular movement (Coriolis effect) and different surface frictions (due to geographic formations) make it harder to predict. There are also more distinctive circulations known as “global circulations” (Figure 2.10) continuously transfer heat from equator regions to polar regions (Krautheim et al. 2014) These circulations were mostly observed by sailing boats and used to identify trade routes or discovery of new continents.

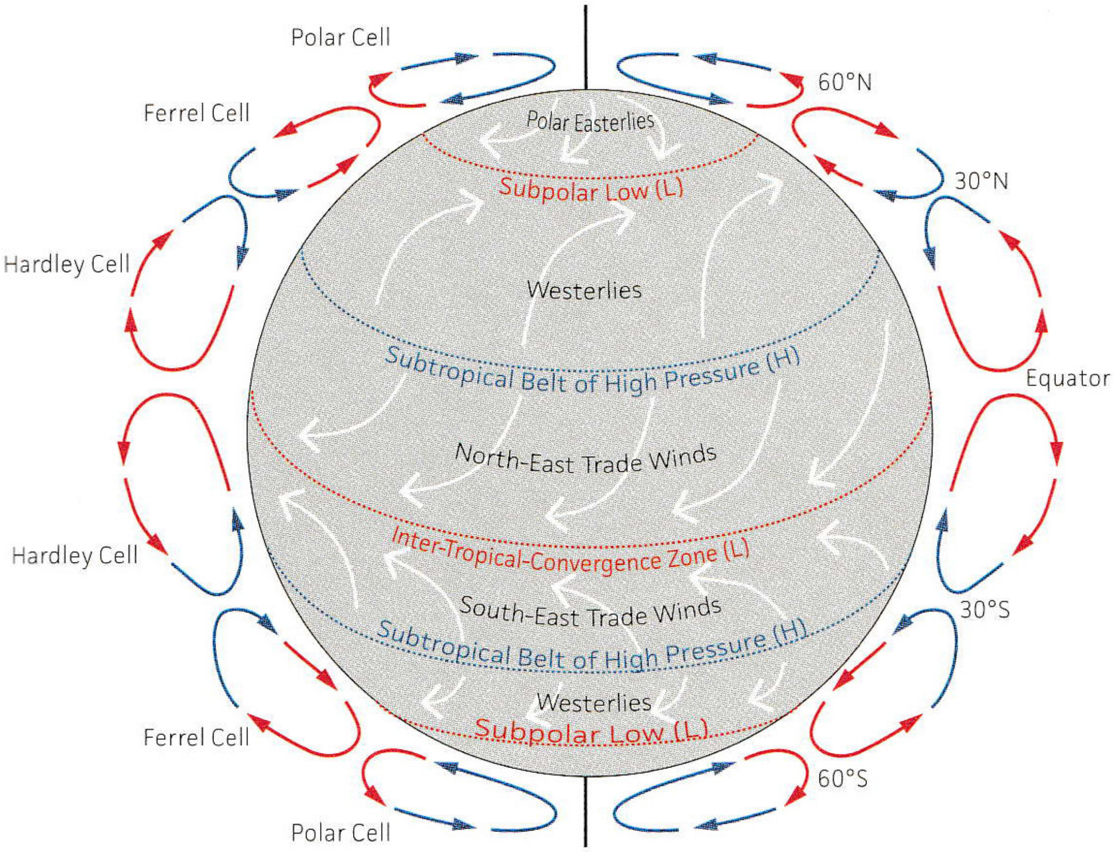


Figure 2.10. Global circulation patterns
(Source: Krautheim et al. 2014)

As the sun's rays approach the earth, most of the solar energy of a wavelength which can be absorbed by the atmosphere is absorbed by the air in the mesosphere (between 80 and 50 kilometers from the surface of the earth, and where the assumption that air is a continuum is first tenable). After that the sun's rays have no energy which can be absorbed by the air, and the air temperature decreases towards the ground (between 50 and 25 km from the surface of the earth): this region is called the Stratosphere. Below this altitude (25 to 10 km.) the temperature remains constant, this is called the Tropopause. The sun's rays then continue downwards until they encounter either cloud or the earth's surface when the remaining energy is absorbed and re-radiated at frequencies which can be absorbed by the air. Consequently, beneath the tropopause, the temperature of the air is highest at the ground, decreasing with height. This behaviour explains why, although the sun is the source of our heat, the temperature close to the ground is highest at the ground, decreasing with height to the tropopause (Lawson 2001).

2.4.2. **Atmospheric Scales of Wind**

Computational simulations can be employed to study urban microclimate at different spatial scales, ranging from the meteorological mesoscale over the meteorological microscale to the building scale and the indoor environment (Toparlar et al. 2017). Santamouris (2013) categorized wind variations above the ground level into two vertical categories in mesoscale; "obstructed" or "urban canopy" sublayer which extends from ground level to rooftops of the urban environment and "free surface sublayer," extending above rooftops.

Cermak (1975) also defined the climatic regions with two vertical categories; most common atmospheric events like thunderstorms or tropical cyclones occurring in the altitudes above 1-2 km ground, and "atmospheric boundary layer" where surface related roughness and friction is recognized rather than centrifugal forces or Coriolis effect (spinning of the earth). American Meteorological Society's (AMS) glossary also defines these regions as macroscale (Figure 2.11), vertical distances beyond hundred kilometers from the surface; mesoscale where the topographical effects are considered for generation of events and microscale, the focus area of urban physics in general, events that are highly affected by human-built environment (Bert Blocken 2015).

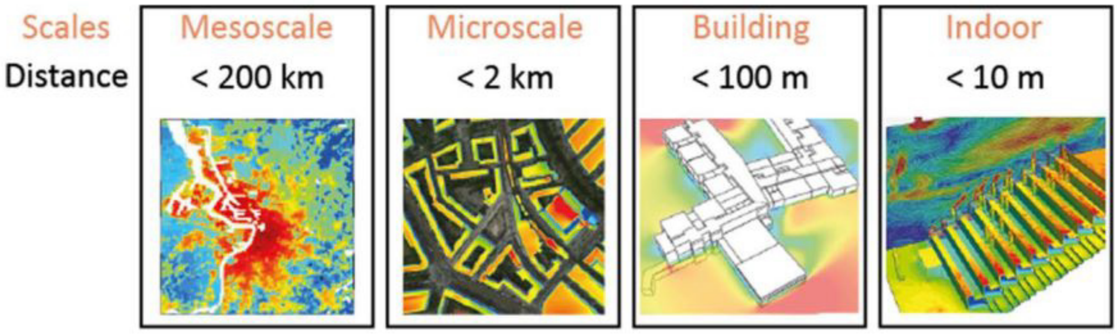


Figure 2.11. Atmospheric scales in climate modeling
(Source: Toparlar et al. 2017)

Spatial climate regions, categorized in two or three different scales, are interconnected on a global scale. Because of ocean currents, centrifugal forces or continental masses, prevailing winds develop, and they affect the seasonal weather events. These seasonal events affect the microclimate conditions in rural or urban environments where human health and comfort is the primary concern. It would be impossible to extend the CFD simulation of an urban setting to trace back to the beginning of developed wind phenomena. There are different scales of case studies in literature extending to limits of mesoscale (Liu et al. 2017, B. Blocken, Janssen, and van Hooff 2012) but, in general, it is feasible to specify the domain size and limit the CFD simulation to compare and match it with physical experimental results and site measurements.

2.5. Pedestrian Level Wind Environment

Wind environment and its representation level depends on the domain chosen for research object. High altitude mesoscale research could define kilometers wide boundary with ten-to-fifty-meter precision, but it would not be a good representation for pedestrian level wind environment. Building level boundary tests with centimeter level accuracy required for correctly addressing the issues around pedestrians around tall buildings (B. Blocken and Gualtieri 2012). Pedestrian level wind assessment was not in scope of wind tunnel experiments with buildings until the 1970's with construction of World Trade Center Towers in New York (Irwin, Denoon, and Scott 2013). First tall buildings in Manhattan Island were built in the beginning of 1900's, with one of the most iconic one, The Flatiron building (Alexiou 2013). Building was extensively higher than the surrounding buildings and its location was critical for the triangular shaped floor plans. This critical geometric design played important role for the recognition of the building as "Burnham's Folly" where architects Burnham and Dinkelberg designed the building like a wedge shape at the intersection of 5th Avenue and 23rd Street (Alexiou 2013). Its irregular shape and height with location specific wind environment caused constant discomfort to pedestrians. Building created a disturbing environment on the block, and unfortunately changed the visitor behaviors in street level (Alexiou 2013).

Wind environment around high rise buildings were not investigated until they are built in existing densely populated areas. Problems surfaced in these areas are originated from the complaints of users where they have been extensively disturbed around the corners of the tall buildings (Gandamer 1978). Wind speed is instantaneously measured occurrence where it changes accordingly to surrounding area. The wind gust that people have blown by were unexpected and could not be estimated simply. Wind behavior in urban environment is fundamentally different from rural areas and vastly open surroundings ((Penwarden 1973). It is not possible to describe instantaneous wind speed with a universal applicable definition of its power. Beaufort scale that was used in naval applications describing the relationship between wind speed and power of the wave forms is first to be used in wind categories effecting people (Gandamer 1978; Lawson and Penwarden 1975; Isyumov and Davenport 1975). National Bureu of Standards included an alternative conversion of Beufort Scale (Table 2.1).

Table 2.1 Beufort Scale of National Bureu of Standards
(Source: Gandamer 1978)

Wind Forcer	Wind Speed (m/s) z = 2 m	Wind Characteristics
2	1.5-3	The face feels the sensation of the wind, Leaves rustle
3	3-4.5	Leaves and small twigs in continual movement Wind unfurls flags constantly Hair is disarranged and loose clothes blow in the wind
4	4.5-7	Dust and papers are lifted Branches are shaken and hair is very much blown about
5	7-9	Small trees and their leaves are blown about, and walk is affected slightly
6	9-11	Force of wind felt on body, danger of stumbling when entering a windy zone
7	11-14	Trees are in constant movement and there is great difficulty in walking against the wind
8	14-17	Tree branches break, in general, pedestrian movement is very difficult and dangerous
9	17-20	Risk of violent throwing to the ground because of squalls

Wind speeds and corresponding occurrences that can be seen in urban environment categorized from research program of Centre Scientifique et Technique du Batiment (CSTB) (Gandamer 1978). Pedestrian discomfort due to wind was addressed by the pure observations in city where high rise buildings are located. Definition of discomfort or an alternative definition for categorizing wind speeds were not made until further studies and experiments were completed. Another beufort scale equivalent wind effects chart proposed by Penwarden (1973) was used for baseline to distinguish different levels of wind velocities and its effects on people (Table 2.1). These categories were interpreted from observations and studies of Melbourne and Joubert (1971). Frequency of the wind speeds in the scale was corresponding to long time periods between 10 minutes to hour but turbulence or intensity values of wind speeds were not defined. There are also important considerations including meteorological conditions, physical quality differences and activity type of users like sitting in an open space, strolling, or running which were not defined in this scale (Gandemer 1978).

Table 2.2 Land Beaufort Scale showing wind effects on people
(Source: Penwarden 1973)

Beaufort Number	Description	Wind speed (m/s) z=1.75 m	Effect
0	Calm	0.0 – 0.1	
1	Light air	0.2 – 1.0	No noticeable wind
2	Light breeze	1.1 – 2.3	Wind felt on face
3	Gentle breeze	2.4 – 3.8	Hair disturbed, clothing flaps, newspaper difficult to read
4	Moderate breeze	3.9 – 5.5	Raises dust and loose paper, hair disarranged
5	Fresh breeze	5.6 – 7.5	Force of wind felt on body, danger of stumbling when entering a windy zone
6	Strong breeze	7.6 – 9.7	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, sideways wind force about equal to forward walking force, wind noise on ears unpleasant
7	Near gale	9.8 – 12.0	Inconvenience felt when walking
8	Gale	12.1 – 14.5	Generally, impedes progress, great difficulty with balance in gusts
9	Strong gale	14.6 – 17.1	People blown over by gusts

Wind flow characteristics are dependent on period of wind speeds measured by anemometers and the surface that has been passed over. Open sea or plains in rural regions have different effect on wind speeds where the fluctuations due to ground layer are less evident than urban areas. In dense urban areas with high rise buildings, wind is significantly affected from building geometries. Murakami et al. (1986) investigated an area around a 40-meter-high rise building where users living in nearby asked to keep diaries about their observations. Anemometers were placed in street on pedestrian level (1.5 meters), and residents were asked to input their feedback according to a questionnaire. Collected data compared to results from anemometers where wind gust speed and mean wind speeds recorded the duration along the street near the high-rise (Murakami et al. 1986). Studies by Murakami et al (1986), showed building height's effect in existing neighborhood. High altitude wind flow could be forced to go down to pedestrian level, increasing speed with joining smaller vortices near ground level, until reaching a corner of the building where it tends to move from high pressure area to low pressure area. Thus, people walking on the sidewalk could be caught into sudden wind gust and lose their balances (Gandemer 1978).

Wind creates a vectoral force on surfaces and its magnitude is directly related to wind speed at a certain time (Penwarden 1973). For a given time wind speed is calculated with Eqn. 2.1 including the fluctuation from average speeds.

$$U_z(t) = \overline{U}_z + U'_z(t)$$ Eqn. 2.1

U_z is the wind speed in certain time *(t)* at *z* location and $\overline{U}_z$ is the average wind speed of measured period that can be seconds to minutes, and some cases hourly scales, summed up with $U'_z(t)$ the fluctuation at given time (Figure 2.12) (Gandemer 1978). Turbulence factor is also definitive for categorizing pedestrian activities (Eqn. 2.2). The amount of deviation for given time from the average speed of wind delivers the turbulence characteristics of the wind for the given time frame (Gandamer 1978).

$$\sigma = \sqrt{\overline{U'}^2}$$ Eqn. 2.2

Turbulence characteristics is a definitive feature for comparing wind environment with reference location before building to data acquired after construction. Comfort criterias can be calculated with characterizing the flow field with turbulence (σ) and average of wind speed ($\overline{U}$) in Eqn. 2.3. In a city wind environment, comfort criteria of a pedestrian activity would tolerate more than an open field or rural setting due to inclusion of turbulence.

$$U_s = \overline{U} + \sigma \qquad \text{Eqn. 2.3}$$

Time constrained wind speed considerations are also critical for understanding the gustiness of wind environments. Sudden changes in wind speeds in three or five second periods could catch people by surprise and disturb their balances. Building facade materials could be stripped and blown away injuring people passing under buildings therefore gustiness should be considered as a safety limit in pedestrian level (Penwarden 1973).

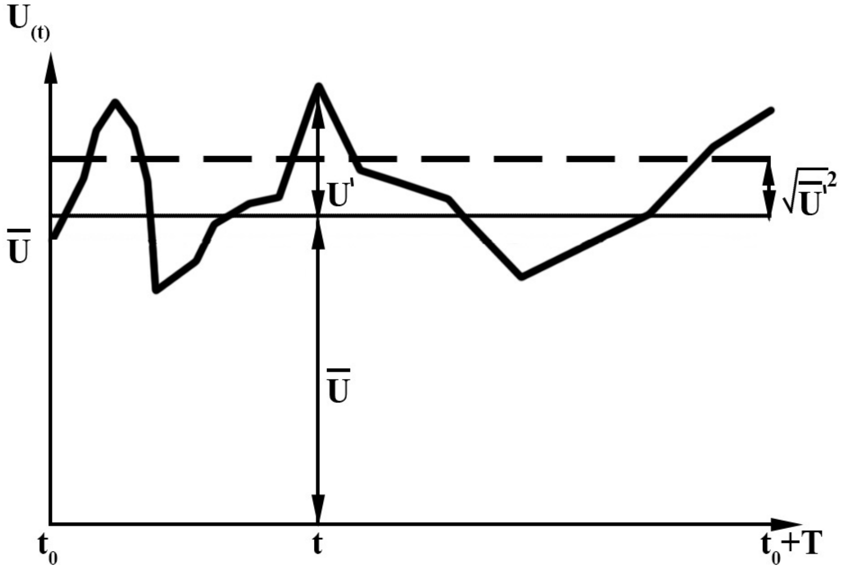


Figure 2.12. Graphical representation of fluctuating wind speed (*U*) for given time (*t*) with mean speeds ($\overline{U}$) (Source: Gandemer 1978)

In previous observation-based categories safety criteria is not well defined with critical wind speeds. Also comfort criteria is not well adjusted for different pedestrian activities behavior of wind was defined in National Bureau of Standards in two concepts, physical comfort, and thermal comfort. Thermal comfort is “physiological heat exchange between the human body and the ambient medium are disturbed” (Gandemer 1978). Thermal comfort depends on the weather conditions, physiology of users and clothing preferences. Physical comfort is relied on wind force exerted on the body of users which is directly related to wind speed. Measuring wind force on pedestrians for quantifiable results to be used in comfort criterias required wind tunnel testing methodology.

It was not possible to do experiments since the user's opinion was biased and wind tunnels were not developed to complete this type of experiments until 1970's (Gandamer 1978). Comprehensive experiments with wind tunnel tests and field tests were conducted by Murakami et al. between 1975-1978 over two thousand pedestrian test subjects. Wind tunnel tests were conducted by taking measurements of walking path deviations (Figure 2.13) accompanied with verbal and visual observations (Murakami, Uehara, and Deguchi 1980). Test results were formatted to distinctive categories of averaged wind speeds gusting with three seconds' time. Criterias based on these tests are simplified forms of wind effects were pioneering for researchers to do more detailed studies.

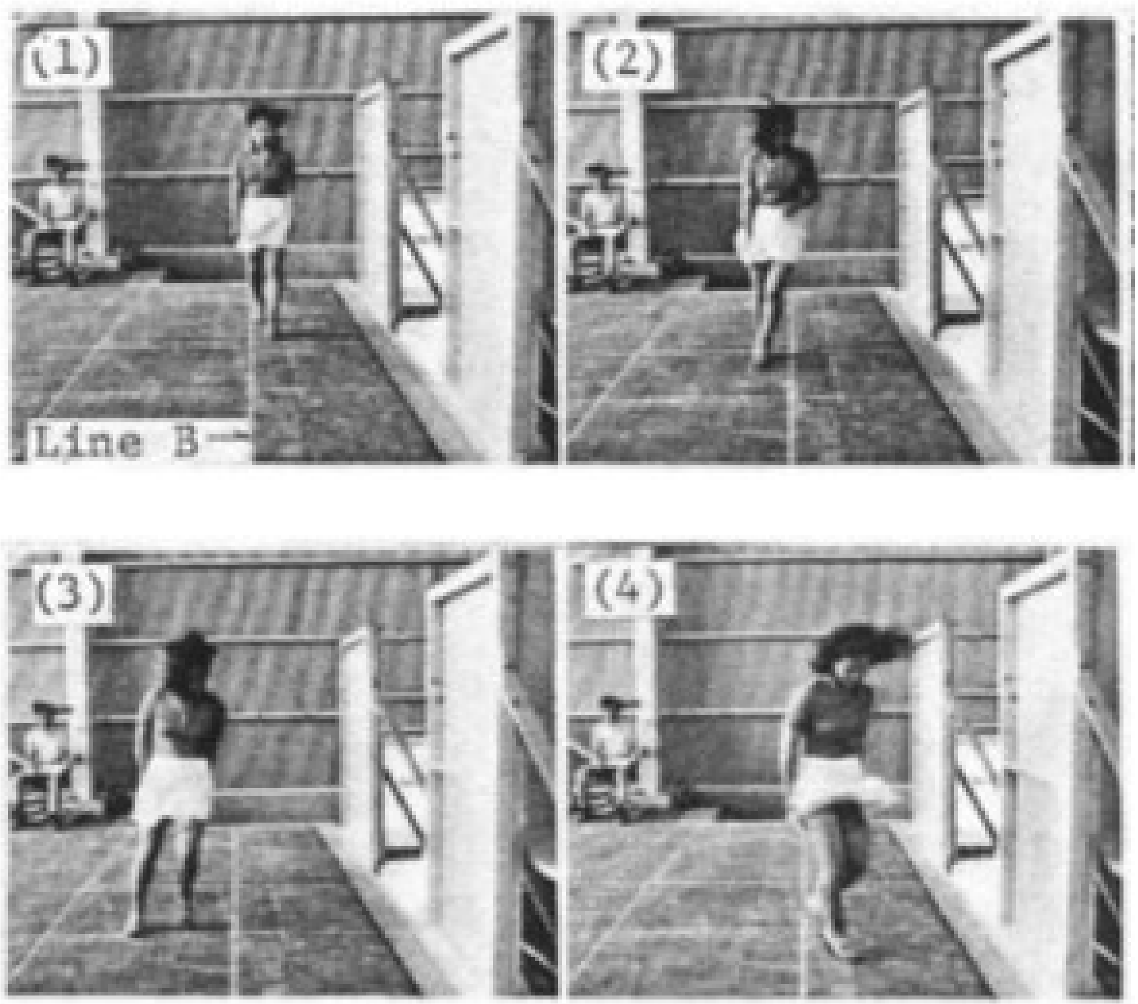


Figure 2.13. Wind tunnel tests of volunteers for pedestrian level wind effects (Source: Murakami, Uehara, and Deguchi 1980)

Verbal feedback from volunteers were not easily quantifiable and biased with gender, age, and body type. Body type was quantified by surface area subject to windward direction and used for calculating the drag force on people (Penwarden, Grigg, and Rayment 1978). Test volunteers with different body types examined while they are standing on or walking over a pressure sensitive plate These tests provided quantified results for specifying the comfort and safety criterias with wind speeds and their frequency of exceedance.

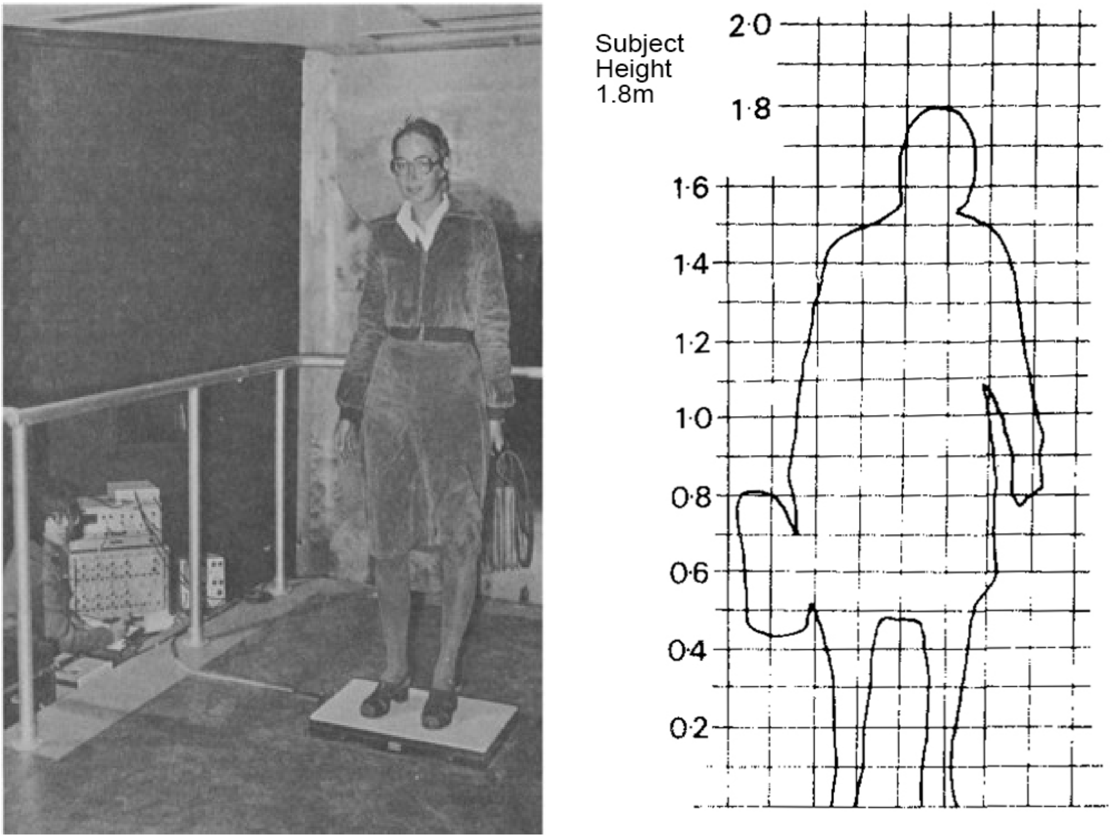


Figure 2.14. Wind force calculations with volunteers on pressure plate and their body measurements. (Source Penwarden et al. 1978)

Pedestrian level comfort criterias were updated with data from wind tunnel studies by Isyumov (1978), Hunt et al (1976), Lawson (1978) and Murakami et al (1980). These criterias emphasized fewer wind categories that are decisive for different activities rather than Beufort scale. Murakami et al. studied wind environment in Japan, as the other researchers investigated in Europe and Northern America where there are significant differences of prevailing winds, macroclimate, and atmospheric effects. These criterias developed for location specific wind speeds and they could not be generalized for universally applicable standards (Gandemer 1978). However, data from wind tunnel tests and observation could be interpreted to create modified comfort and safety criterias specific to regional wind occurrences, governmental policies, or density of urban settlements. Murakami et al. (1980) created four category acceptance criterias for defining wind related incidences specifically happening to people with gender and age-based differences (Table 2.3). Governments and institutions in cities also established standards based on existing wind studies. Dutch NEN (Normalisatie en Normen) 8100 standards introduced in 2005 with setting criterias for pedestrian activities and commonly accepted in literature (Willemsen and Wisse 2002). This standard is based on two wind speeds, 5 m/s and 15 m/s and uses “exceedance probability” to categorize pedestrian activities of walking, strolling and traversing (Table 2.4) (Janssen et. al. 2013). Dutch criterion has been used to comparisons of case specific comfort studies. Exceedance probability is frequently used in other regulations of cities like San Francisco or Montreal and force designers to complete wind tunnel tests or simulations.

Table 2.3 Acceptance criteria for pedestrians
(Source: Murakami, Uehara, and Deguchi 1980)

$U_{3\text{-sec}} < 5$ m/s	5~10 m/s	10~15 m/s	$U_{3\text{-sec}} > 15$ m/s
no effect	some effect	serious effect	very serious effect
in case of female, minor effect on hair and skirt	footsteps sometimes irregular, hair and skirt considerably disturbed	walking irregular walking difficult to control upper body bends windward	dangerous for elderly person walking impossible to control body blown sideways or leeward

Table 2.4 Dutch NEN 8100 Standard

Wind Comfort			Activity Descriptions		
Grade	Mean Wind Velocity	Threshold Probability Exceedance	Sitting	Strolling	Traversing
A	5 m/s	2.5%	Good	Good	Good
B		5%	Moderate	Good	Good
C		10%	Poor	Moderate	Good
D		20%	Poor	Poor	Moderate
E		>20%	Poor	Poor	Poor
Wind Danger					
Limited Risk	15 m/s	0.05% - 0.3%			
Dangerous		> 0.3%			

Unlike other wind criterions, Planning Department of Hong Kong ordered increased wind penetration studies when the residents faced SARS (Severe Acute Respiratory Syndrome) caused by overpopulated living conditions in 2003 (Ng 2004) Wind criterias for comfort and safety studies estimated the maximum wind gusts but Hong Kong AVA (Air Ventilation Assessment) required averaged long period wind speeds for natural ventilation in dense urban areas.

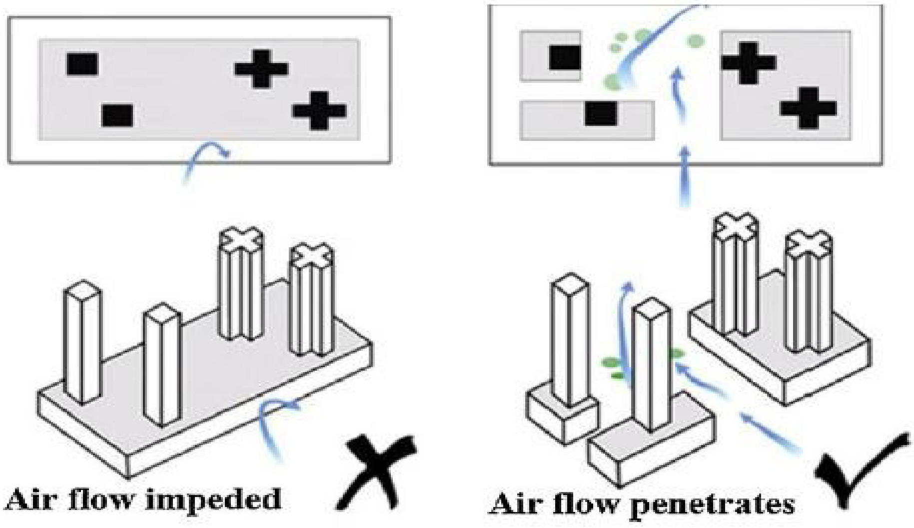


Figure 2.15. Hong Kong AVA guideline
(Source: Ng 2004)

Building design process in Hong Kong is guided with local policies to dispose air pollution and lower the public health risks in dense urban areas (Ng 2004). AVA guidelines regarded as national code rather than generalized criterias which developed from earlier pedestrian comfort studies. City of London has its own guideline which strictly defines the technical requirements of construction projects to take permit from city council (City of London Corp. 2019). Pedestrian activities, sitting, standing, walking is thoroughly defined including cycling activities. Type of assessment whether it should be wind tunnel experiment or CFD simulation is laid out with wind climate properties specific to London central area.

Pedestrian level comfort and safety criterias have been developed with inclusion of new data from study area specific properties. City specific building codes were developed to solve critical problems which has surfaced since the last century, and future problems that will challenge cities result of climate change. However, it is still not found convenient to establish building codes regarding the pedestrian level wind environment for future developments for every city. It is understandable that most cities are not populated enough for building high-rise projects since enough plots for low rise settlements could be built, but for densely built city centers, business districts or housing projects, it is evident that pedestrian level wind comfort analysis should be done. In this context, metropolitan cities in Turkey also, do not have pedestrian level wind assessments. Especially Istanbul and Izmir cities are subject to prevailing winds due to their geographical properties where high wind speeds cause significant damage annually.

CHAPTER 3

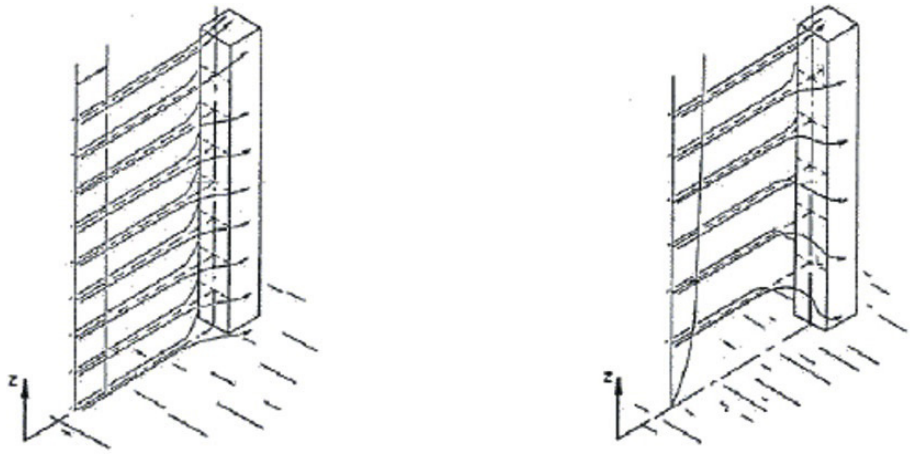
CFD SIMULATIONS FOR WIND EFFECTS

Computational Fluid Dynamics is an essential research and development tool used for analyzing complex fluid flow and associated reactions in specific conditions. Firstly used in aviation and military applications but quickly associated with automotive industry, marine engineering (Versteeg and Malalasekera 2007). It's methodology is a joint approach based on experimental approaches developed through the history of fluid dynamics (Anderson Jr. 1995). Primary field of the CFD calculations were to fulfill the requirements of aerospace engineers in early 1970's. Automotive industry embarked on by localizing the flow field with reduced speeds to investigate design alternatives and lighter materials for fuel efficiency (Shaw 1988) New materials were not limited to automotive or aerospace industries. Potential of using computers for CFD calculations quickly emerged to other fields like naval architecture where physical experiments are required to test prototypes. (Anderson Jr. 1995). Buoyancy and hull design alternatives could be rapidly tested and optimized to reduce research time. Civil engineering and mechanical engineering fields realized the potential also where closed chamber engines, ducts and mixing mediums could be visually investigated (Versteeg and Malalasekera 2007). Structural steel was used for taller buildings in urban areas, and they were too lean to withstand wind gusts like blunt concrete buildings. Tall buildings in cities required to analyze wind loading with CFD simulations and verified with wind tunnel tests (Bert Blocken 2015). Today almost every field which has the primary domain of fluids are using CFD methodologies for research and design development.

CFD is dependent on experimental data which was provided by wind tunnel tests throughout the history started with aircraft aerodynamics (Anderson Jr. 1995). Commercial, military and space applications tested with wind tunnels provided data and aircraft designs were developed rapidly. CFD calculations provided detailed flow field around aircraft wings enabling structural engineers and aerodynamic experts to develop better wing profiles. These results proved that CFD can be used as a tool for research rather than problem solving methodology (Anderson Jr. 1995). Branching to other industries like automotive and naval applications were quick to embrace too. First tunnel tests with tall buildings were focused on wind loading on structural system (Lawson 2001). Further inclusion of surrounding areas and potential of simulating whole environment enabled rapid increase in CFD studies.

3.1. CFD Approach in Built Environment

Blunt bodies like buildings required ground roughness interaction and higher test sections to fully capture boundary layer effects (Lawson 2001). Constant wind profile changes near the ground due to shear forces affected from no slip condition of ground layer (Figure 3.1) Engineers switched to Atmospheric boundary layer wind tunnels with long fetch area in front of building model and taller test sections. Testing methodology developed to capture turbulence effects and shear forces (Stathopoulos 2011) but wind tunnel tests entailed more time spend on planning rather than investigating design alternatives.



a b

Figure 3.1. Constant velocity profile (a) and Boundary Layer velocity profile(b) for tall building CFD simulations (Source: Stathopoulos 2011)

Expensive tests only proved useful for final design of building and did not leave any room for designing architectural elements. Thus, construction industry started to use CFD tools for calculating wind effects on structural elements in early design stages. CFD simulations are highly dependent on the computation power of hardware used for research and development projects (Versteeg and Malalasekera 2007). As the new efficient chips are introduced to engineering community, new range of industrial applications are introduced as CAE (computer aided engineering) tools. Fluid based thermal analysis, chemical reactions and fatigue tests could be coupled with flow simulations. This technique increased the applicable range of industrial branches, increased the complexity of problems solved in case studies (Figure 3.2) and became a vital part of the research and development process (Bert Blocken 2015).

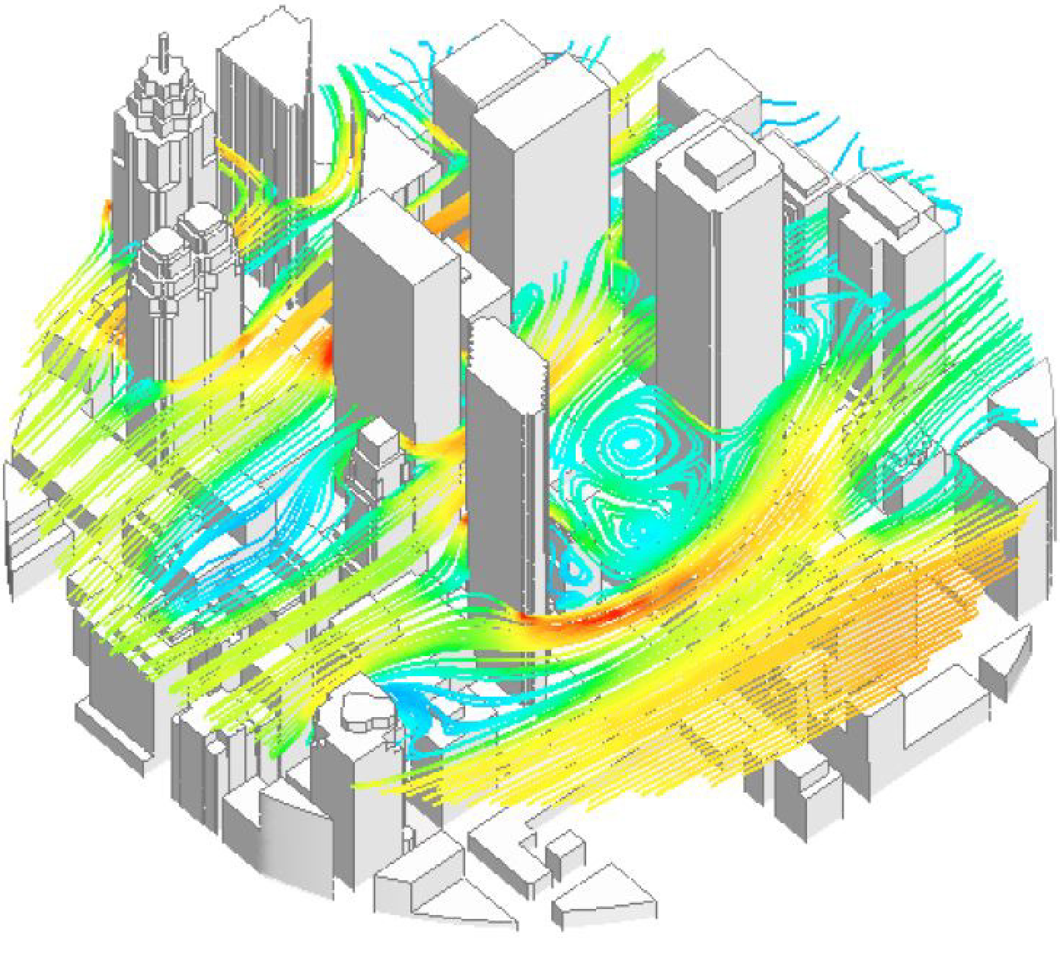


Figure 3.2. CFD analysis of complex external flow in city
(Source: Adamek et al. 2017)

3.2. Fundamentals in CFD Approach

There are three fundamental principles of flow in Computational Fluid Dynamics calculations. First one is the conservation of mass. In a finite volume domain, mass of the fluid is conserved. Next is the Newton's Second Law, defining the motion of the fluid with force applied on the object. Third principle is the conservation of energy. It is equal to summation of work on fluid particle and heat energy. (Versteeg and Malalasekera 2007) Conservation of mass also referred as continuity equation is solved with Eqn. 3.1

$$\frac{\partial(\rho)}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad \text{Eqn. 3.1}$$

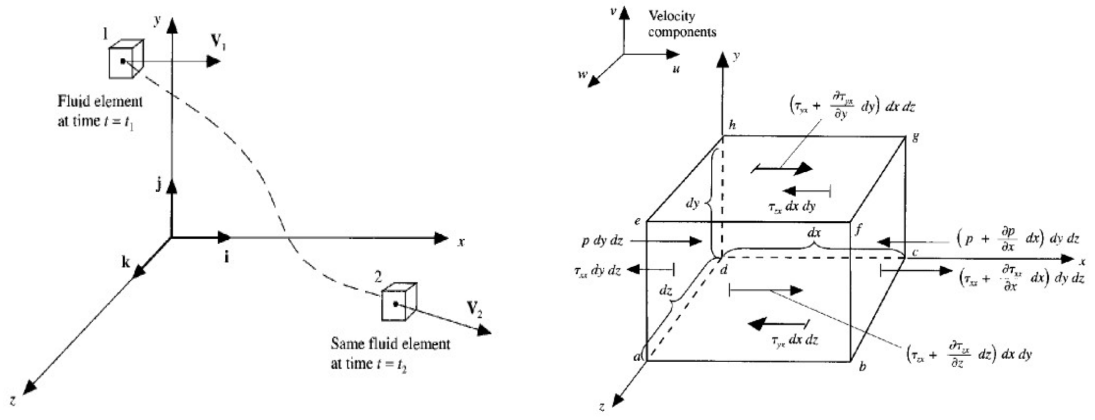
Density of the fluid (ρ) and mass derivation along x, y, z cartesian coordinates are in equilibrium. This simple form of continuity equation is valid for the incompressible flows defined for atmospheric boundary layer simulations (ANSYS 2019). Motion of the fluid is also calculated according to their force direction vectors. Momentum equations are defined in Eqn. 3-2 -3.4

$$\begin{aligned}\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}\\ =-\frac{\partial p}{\partial x}+\left[\mu\frac{\partial^2 u}{\partial x^2}+\mu\frac{\partial^2 u}{\partial y^2}+\mu\frac{\partial^2 u}{\partial z^2}\right]\end{aligned} \qquad \text{Eqn. 3.2}$$

$$\begin{aligned}\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}\\ =-\frac{\partial p}{\partial y}+\left[\mu\frac{\partial^2 v}{\partial x^2}+\mu\frac{\partial^2 v}{\partial y^2}+\mu\frac{\partial^2 v}{\partial z^2}\right]\end{aligned} \qquad \text{Eqn. 3.3}$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial y}+\left[\mu\frac{\partial^2 w}{\partial x^2}+\mu\frac{\partial^2 w}{\partial y^2}+\mu\frac{\partial^2 w}{\partial z^2}\right] \quad \text{Eqn. 3.4}$$

Equations 3.2, 3.3 and 3.4 refer to x, y, z momentum equations respectively. These equations are generally referred as “Navier-Stokes Equations” in literature which are generally used in CFD calculations to describe the flow depending on the coordinate system where the fluid flow is 2 dimensional or 3 dimensional. (Anderson Jr. 1995) These equations were named after French engineer Louis Marie Henri Navier (1785–1836) and the English mathematician Sir George Gabriel Stokes (1819–1903), for their work on viscous terms (Cengel and Cimbala 2013).



a b

Figure 3.3. Infinitesimally small fluid element a) moving in fluid with derivative of velocity, b) x-components of forces acting on element (Source: Anderson Jr. 1995)

Navier-Stokes equations are all in one CFD approach for atmospheric boundary layer specific external in flows (Montazeri et al. 2013) In these studies air is accepted as Newtonian fluid like most common gases and liquids (Cengel and Cimbala 2013). Newtonian fluids are easy to operate under viscosity related mathematical models. For incompressible flow conditions that is mostly used in subsonic wind tunnels Eqn. 3.5 defines the viscous stress related to strain rate with a simple formulation. Shear stress defined by τ is scalar proportional to derivative of velocity (du/dy) with μ constant. Other properties of fluid density (ρ) and kinematic viscosity (ν) are also accepted as constants in incompressible flow. Laplacian operator ∇ is used for cartesian coordinates, three operators of velocity components to modify operation to fewer definitions. Eqn. 3.4 represents the continuity equation in Laplacian operator form.

$$\tau = \mu \frac{du}{dy} \qquad \text{Eqn. 3.5}$$

$$\vec{\nabla}.\vec{V} = 0 \qquad \text{Eqn. 3.6}$$

Navier-Stokes equations describes the turbulent flow properties defined accordingly for type of flow. Continuity and momentum equations are solved for all types of flow, but energy equations must be included if heat transfer features are going to be calculated (Figure 3.4). Fluid mixtures or compressibility also require specific variations to conservation equations (ANSYS 2019). Species transport equations are also needed for

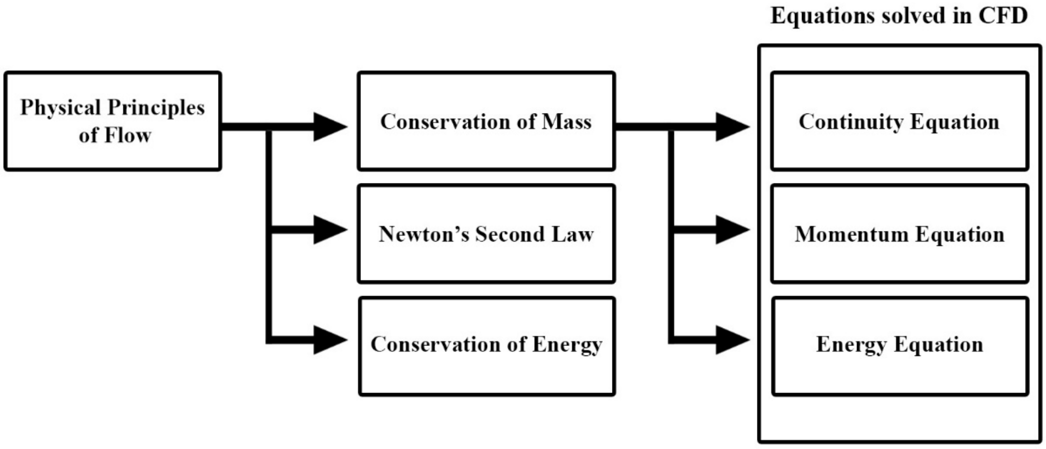


Figure 3.4. Flow chart for Equations solved in CFD calculations

solving turbulent flows. These equations are solved by embedded codes to simulation software and validated with experimental results and accepted in literature but it is not possible to describe hundred percent accurate wind phenomenon with simulations (Hargreaves and Wright 2006). Verification and validation of simulations should be done in order to present results in agreement with experimental results (Roy and Oberkampf 2016). In order to do verification and validation, computational domain and appropriate grid size should be defined. After these steps, proper turbulence model should be picked which best describes the fluid motion in study.

In this study flow field around the buildings at pedestrian level investigated. This flow field solved in 3 dimensional cartesian coordinates. Building surfaces and ground defined with no slip conditions. Fluid properties of air with incompressible turbulent flow were used but heat transfer and radiation equations were not included since this study outlines the investigations of mechanical effects of wind.

3.3. Computational Domain

Size of the computational domain is an important parameter for simulating and testing the physical environment. In the built environment, we require specific measurements to be examined for better understanding the wind accumulations. These measurement points could be located very far from the case area so that boundaries of the test case should be extended. But the problem of extension is that new and nonessential buildings or open spaces had to be included in the domain. This recognition will increase parameters, the complexity of the problem, required processing power, and similarity issues. The computational domain could be considered as a box extending away from the case area in two- or three-dimensions (Figure 3.5).

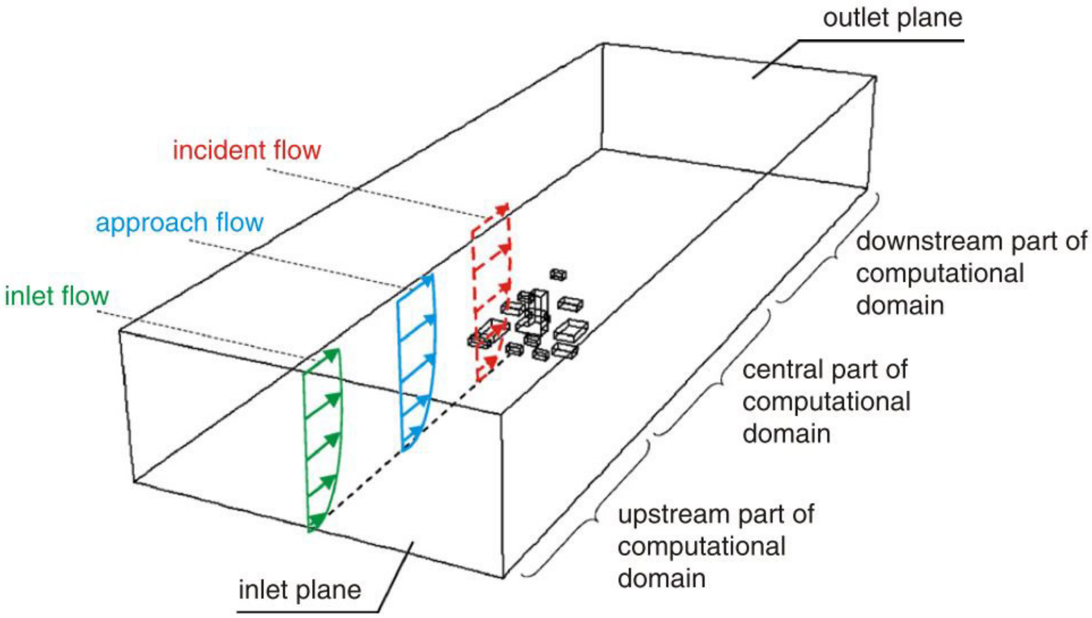


Figure 3.5. Computational domain with building models
(Source: et al. 2007)

Wind flow regime is defined by "Reynolds Number", (Eqn. 3.7) calculated with properties of the fluid. Inertial force of the fluid divided with viscous force gives us information about the characteristic of the flow whether it is turbulent flow or laminar flow. Reynolds number is calculated with density (ρ), speed of fluid (V) in given coordinates and length (characteristic length *D*) divided with dynamic viscosity of the fluid (μ). It is also possible to lower the number of input parameters with changing the properties of the fluid used in with Eqn. 3.6. Substituting the parameters in Eqn. 3.5, kinematic viscosity of the fluid can be used to compute Reynolds number (Eqn. 3.7).

$$Re = \frac{\rho V D}{\mu} \qquad \text{Eqn. 3.7}$$

$$\rho = \frac{\mu}{v} \qquad \text{Eqn. 3.8}$$

$$Re = \frac{V D}{v} \qquad \text{Eqn. 3.9}$$

Upstream and downstream parts of the domain are calculated with roughness index where the actual urban environment is not detailed or sometimes modeled. Two sides and the top part of the boundary layer (domain walls) are important because their distance to model affects the flows passing around the objects in the center. They could cause gradients in the streamlines and interact with turbulent effects around corners resulting in diversions from the physical experiments (Bert Blocken, Stathopoulos, and Carmeliet 2007). Tominaga et al. (2008) defined the distances around model on horizontal and vertical planes to be at least five times more than the height of the tallest object in the model from previous studies. Effective dimensions of the horizontal and vertical section of the model area should also satisfy the "blockage ratio," where sectional area of the model must be below 3 percent of the section of the domain. For the outlet distance from the model, it is important to analyze scaling of gradual wind speed changes and wakes generated behind buildings. Architectural Institute of Japan (2004) recommendations are ten times the height of the tallest object for the distance of outlet plane (Tominaga, Mochida, Murakami, et al. 2008).

Profile differences in the upstream part of the computational domain are required for finding correlations between physical experiments and simulations. The inlet flow can be calculated from the "Logarithmic Law" (Eqn. 3.10) introduced with mean velocity and turbulence intensity in the inlet plane (Ramponi and Blocken 2012).

$$U(z) = \frac{u_{ABL}^{*}}{k} ln\left(\frac{z}{z_0}\right) + A \qquad \text{Eqn. 3.10}$$

Logarithmic law is used for calculating u^*_{ABL} where, k is Von Karman constant (0.40-0.42), z_0 is the roughness constant and $U(z)$ is the known with speed at z height. (A) is the model constant generally equivalent of 0. Approach flow is calculated with parameters in the upstream computational domain where roughness and urban settings are considered changing as the wind travels. The incident profile is provided by same boundary conditions with an empty set to associate experimental and simulation data (Bert Blocken, Carmeliet, and Stathopoulos 2007).

Computational domain dimensions framed by Tominaga et al. (2008) and Architecture Institute of Japan used in the different selection of buildings by Blocken (van Hooff and Blocken 2010, B. Blocken, Janssen, and van Hooff 2012). These different urban layouts revealed new information about the geometry of the boundary layer. Simulations revealed that while working with wider buildings, corner effects are accelerated more, resulting in inconsistencies with boundary layer test. So that his study suggested using the square root of 3 percent ratio, 17 percent building height to vertical and 17 percent building width to horizontal ratios (Bert Blocken 2015).

3.4. Grid Sensitivity

Investigations about domain size and numerical approaches are continuously challenged by researchers. Liu et al. (2017) used a considerable domain size to extend a category between mesoscale and microscale model. This approach was necessary to use weather station data, which is several kilometers away from the case area, to be used in inlet profile. The resulting full-scale model was covering 2 kilometers wide and 20 kilometers long area with an upstream part extending more than 10 kilometers range (S. Liu et al. 2017). This full-scale model requires special attention to surface properties as well as domain dimensions. An important surface parameter that can have an impact on the calculations is, grid resolution of the model, which Franke et al. (2004) defines that "grid should be fine enough to capture important physical phenomena like shear layers and vortical structures with sufficient resolution."

Tominaga et al. (2008) cited his previous studies for grid quality and division; "minimum grid resolution should be set to about 1/10 of the building scale (about 0.5–5.0 meters) within the region including the evaluation points around the target building" (Tominaga et al. 2004). For pedestrian level wind calculations (1.5-2 meters) there should be at least three grids above the ground surface and at least ten cells per sides of the model Grid generation part requires special care when modeling the computational domain. It requires confirmation with predictions that they do not deviate significantly (Tominaga, Mochida, Yoshie, et al. 2008). Franke et al. (2004) defined at least three grids to be generated with 1.5 times increasing number of cells in every dimension, which will result in 3.4 times finer (1.53) grids to be generated. Blocken (2015) also advised the use of hexahedral cells over tetrahedral cells (Figure 3.6) "as hexahedra yield smaller truncation errors and better iterative convergence." This definition can be applied as a rule for using hexahedral cells for rectangular model elements and domain walls to yield accurate results.

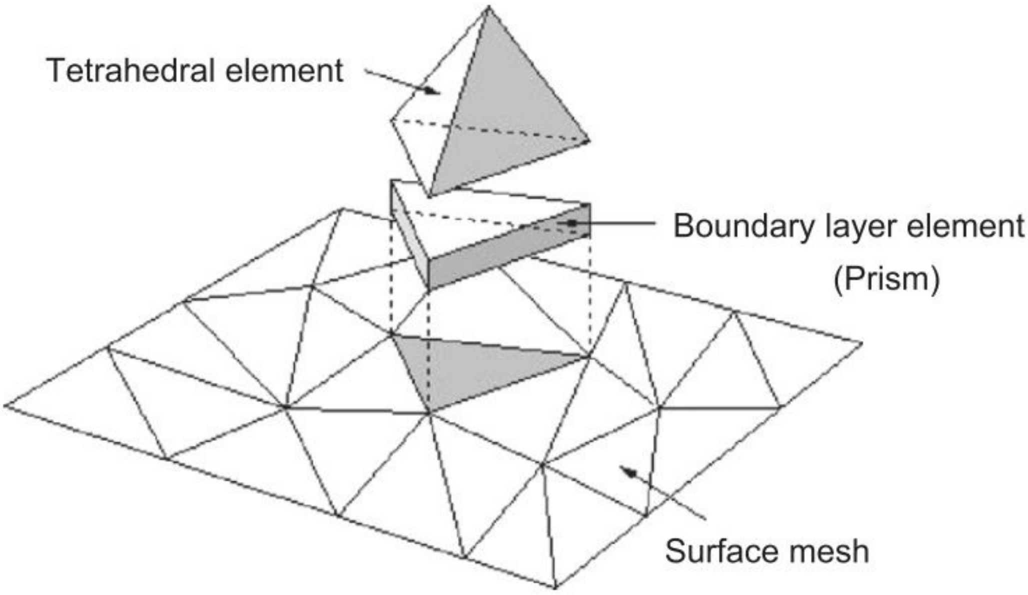


Figure 3.6. Surface meshing with tetrahedral elements
(Source: Tominaga et al. 2008)

Grid generation process takes important computation time and should be done carefully to mitigate deviations from experimental data. There are further studies based on grid-sensitivity analysis with three different levels of cell counts following Franke et al. (2004). Montazeri and Blocken (2013) studied with coarser and finer grids of their base models and found that refining only provided negligible results. But in a different study, where indoor and outdoor flows are simulated on a model with openings provided a 7.5 percent deviation between coarse and fine grids (Ramponi and Blocken 2012).

3.5. Surface Roughness

For practical estimations of computer domain and physical experimental domain approximations, we need to know the local terrain or urban setting affecting the wind development. Instantaneous wind velocity measured by wind probes cannot be attributed directly to flow simulations (Figure 3.7). Wind velocity is dependent on turbulence intensity and averaged time (Irwin, Denoon, and Scott 2013). Turbulence changes accordingly to distance from earth surface, as the height increases, turbulence intensity decreases, and less turbulent flow regime can be formed. Wind velocity also change form according to terrain and environment category. Open sea or flat terrain with no trees have less influence than urban areas with low-rise buildings. Dense urban environments have the most influence therefore increasing the turbulence intensity levels higher(Cochran and Derickson 2005) (Figure 3.8) Mean velocity gradient of wind flow formed as mean wind velocity profile should be calculated. It would be impractical to implement every tree, boulder, hedge, or wall to the computational environment as well as on the scaled-down experimental wind tunnel domain. For these influences, we can use area-averaged surface drag coefficient, roughness parameter (Wieringa 1992) Roughness was first introduced and categorized by Davenport in 1960's and updated with experimental data results with different settings and materials.

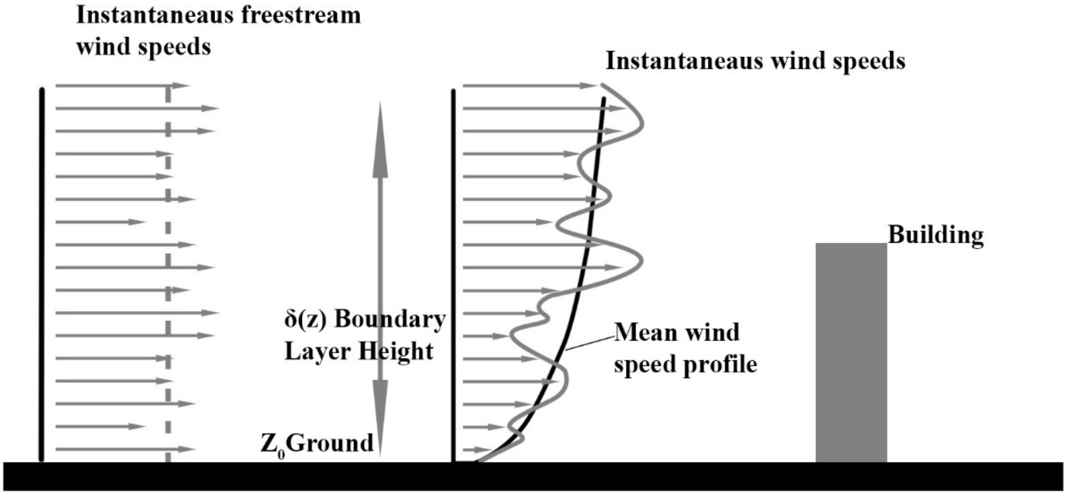


Figure 3.7. Wind speed profile change due to ground roughness

Wieringa (1992) stated "Davenport classification deals realistically with the intermediate and rough terrain but requires a large correction at the smooth side of the roughness spectrum" Updated roughness categories put urban environments in only two classes. Gál and Unger (2009) outlined the problem was not categorical but "determination of roughness length and displacement height" depends on visual estimations, field observations or geometrical input methods. Latest studies in aerodynamic roughness length have provided detailed eight categories and four constants of “n” used in power law for estimating the mean velocity profile in Eqn. 3.11

$$\frac{U(z)}{U(ref)} = \left(\frac{z}{z(ref)}\right)^{n} \qquad \text{Eqn. 3.11}$$

U_{ref} is the reference velocity at z_{ref} and “n” is the constant (0.10-0.33) to fit velocity profile according to ASCE 49-12 Wind Tunnel Testing for buildings and Other Structures (2012). Roughness categories provided in the literature does not have any strict distinction between categories but give enough information for designing wind tunnel tests with obstacles (Cochran and Derickson 2005).

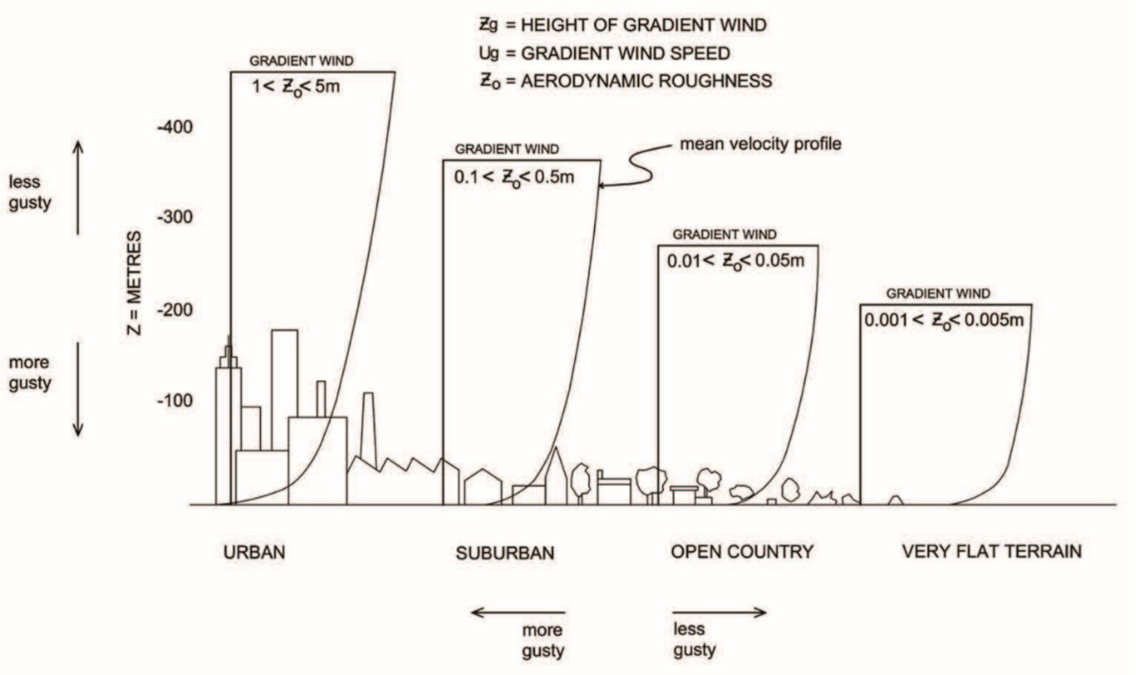


Figure 3.8. Change of mean velocity profile according to aerodynamic roughness (Source: Cochran and Derickson 2005)

3.6. Turbulence Models

CFD calculations are iterative operations with scales of hundreds to millions of cell calculations required to reach one outcome. Three important laws of physics are concerned in CFD: “conservation of mass (continuity); conservation of momentum (Newton's second law); and conservation of energy (first law of thermodynamics). While strictly the term Navier - Stokes (NS) equations only cover Newton's second law, in CFD it is generally used to refer to the entire set of conservation equations (Bert Blocken 2015).

Studies cover extensive uses of different turbulence models on various computer domains. Turbulence models do not have an exact specification to model geometry or scale since they are mostly used together to achieve best similarity graphics to correspond to physical experimental results. Toparlar et al. (2017) recently investigated CFD studies and outlined Reynolds-Averaged Navier-Stokes (RANS) equations are used more than 95 percent.

Blocken (2015) defined RANS equations as “derived by averaging the NS equations (time-averaging if the flow is statistically steady or ensemble averaging for time-dependent flows).” These equations are used for flow specific applications and accompanied with turbulence models to approximate the values of mean velocity, temperature, pressure, and concentration (Bert Blocken 2015).

Toparlar et al. (2017) stated that standard k-ε model turbulent is commonly used for RANS equations. Other models like RNG k-ε, Realizable k-ε and Modified k-ε turbulence models are improved versions of the standard k-ε model, and they are extensively used in recent publications with comparisons. Tominaga et al. (2008) defined the problem of standard k– ε model’s inability to “reproduce the separation and reverse flow at the rooftop of a building due to its overestimation of turbulence energy k at the impinging region of the building wall.” Modified turbulence models provide different results in same case scenarios. In this study, Van Hooff et al. (2017) studied a hybrid outdoor and indoor flow over a simple body with two openings (

Figure 3.9). When subjected to same boundary conditions RNG, SST and RSM models provided almost same locations for the maximum velocity profiles. But Standard (SKE) and Realizable (RLZ) k-ε models showed the maximum velocity at higher than other models as Tominaga et al. (2008) suggested.

Another recognized equation in CFD simulations is Large Eddy Simulations (LES). They are also used for turbulent energy calculations in studies and known with accurately performing similar results with wind tunnel test. But the downside of LES equations is that calculations require too much processing power compared to RANS simulations (Tominaga, Mochida, Yoshie, et al. 2008, van Hooff, Blocken, and Tominaga 2017). Earlier studies support this statement since RANS simulations are predominantly used due to lower processing power needs and calculation time required to solve equations (Toparlar et al. 2017). Although recent studies include LES simulations to compare energy models with wind tunnel measurements by using advanced visual particle tracking components and cloud-based computer arrays.

Van Hooff et al. (2017) investigated LES and RANS equations for accuracy comparisons on a coupled internal and external flow case (Figure 3.9). A previous comparison of RANS simulations revealed that modified version Shear Stress Transport (SST) is more successful than Standard *k-Ɛ* (SKE) model in comparison, where maximum velocities over the building estimated in the wrong location. On the other hand, SST model was not found successful visualizing the internal flow field (Van Hooff et al. 2017). Furthermore, LES simulations result with better accuracy of velocity profiles where SKE and SST models failed. Standard *k-Ɛ* model was commonly used in external flow simulations of buildings since the analysis of urban microclimate studies increased rapidly in the beginning of 2000s (Toparlar et al. 2017). New models have been developed for realistic modeling of microclimate research, but they cannot be universally applicable. Case specific studies, and if possible, experimental wind tunnel test should be included for validation and verification of the turbulence model (Roy et al. 2016). Tominaga et al. (2008) investigations were based on testing different turbulence models, which were produced as modified codes of commonly used models validated with wind tunnel studies. Revised *k-Ɛ* model showed better agreement than standard models in some locations, but still LES models outperform RANS models in outdoor simulations. (Tominaga et al. 2008, Blocken 2018)

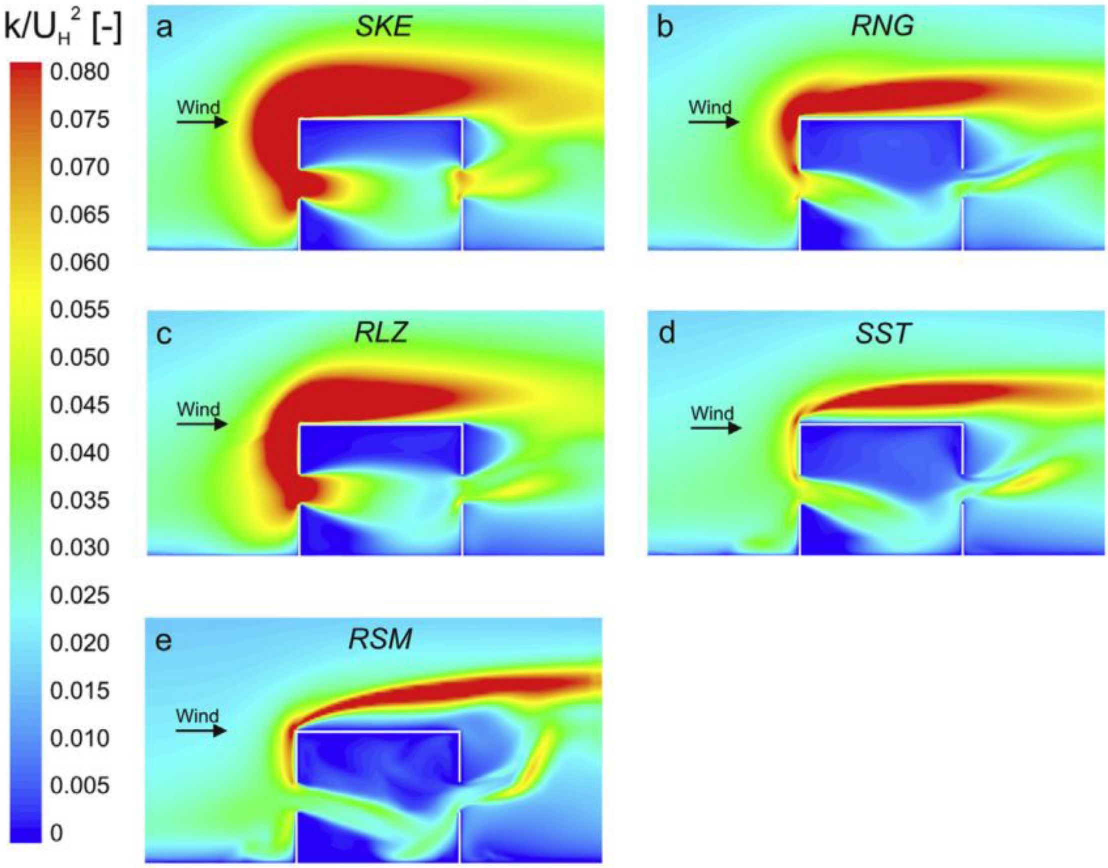
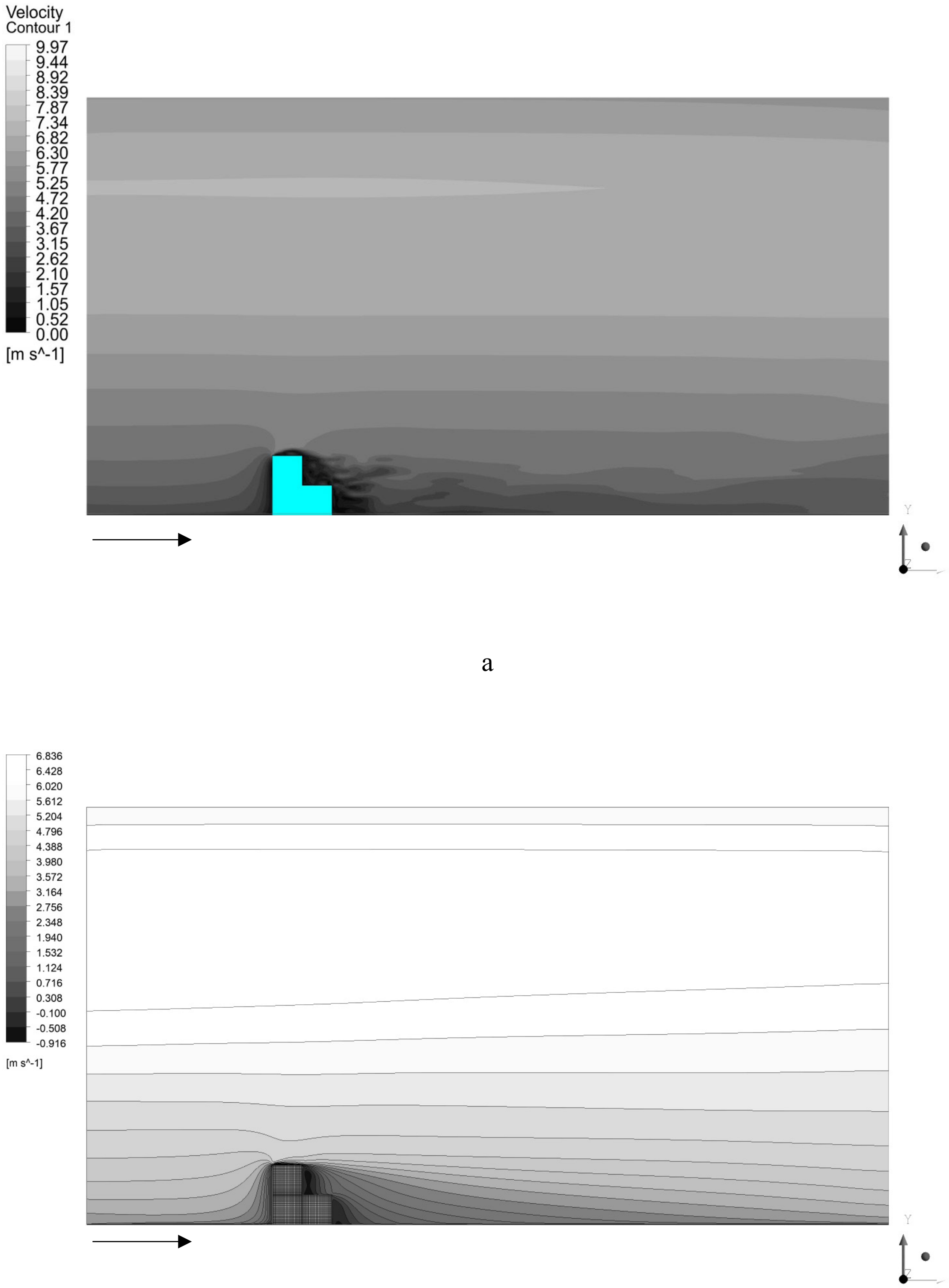


Figure 3.9. Turbulent energy equations compared in a hybrid (indoor and outdoor) flow (Van Hooff et al. 2017)

LES model approach provides accurate and versatile results in cases of indoor and outdoor simulations. LES are getting increasingly popular in validation cases where wind tunnel experiments are presented (Blocken 2018). Still there are some important considerations regarding the use of LES. RANS turbulence was accepted and regarded as principal turbulence model while developed for years with wind tunnel experiments. Pedestrian level wind studies, pollutant dispersion scenarios and large area building layout effects thoroughly investigated with validated RANS models. LES models require well established inputs for boundary parameters for accurately predicting the applicable results, while RANS provides faster solutions than LES.

In this study Standard *k-ℰ* model with modified constants according to validation case selected as primary turbulence model (Tominaga 2004). Alternatively, LES turbulence model of single building (Figure 3.10) investigated for comparing possible advantages and disadvantages of each scenario. Flow direction is left to right.



a

b

Figure 3.10. LES (a) and RANS Standard *k*-$\mathcal{E}$ (b) turbulence models comparison

LES fundamentally different from RANS model. LES could capture the flow structures based on filtering with governing equations. Unresolved smaller eddies are modeled while RANS cannot predict unsteadiness. Eddy formations are distinctive in LES and can be seen in Figure 3.11. Flow separations and reattachments on top of the building as well as behind the building are evident in LES model. RANS model is also similar with separating flows in LES, but reattachment distances are further. This situation could be the result of chosen Standard *k-Ɛ* model that was addressed in previous section.

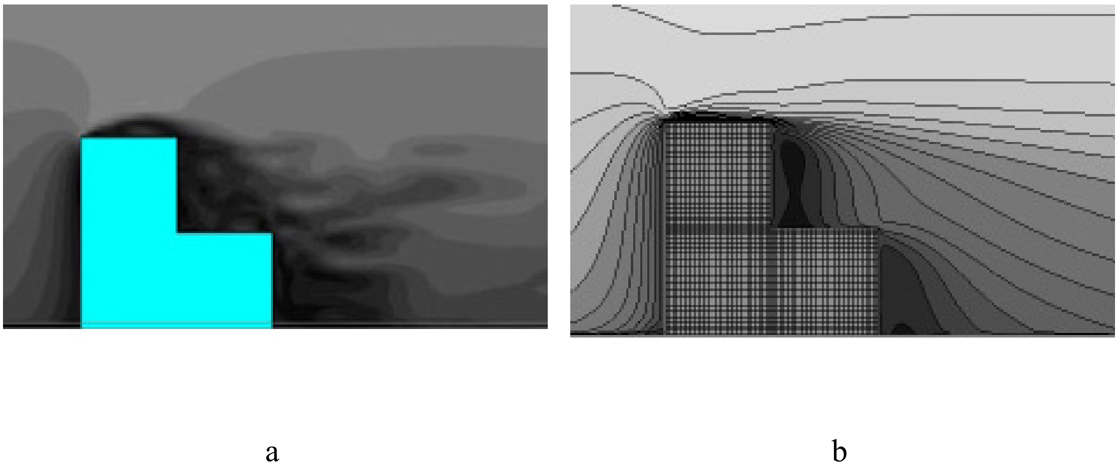


Figure 3.11. Close view of LES (a) and RANS Standard *k-Ɛ* (b) turbulence models

LES studies are also resource demanding simulations that should be considered before starting the research. In this case study, LES model simulations took almost six hours on 16 core workstation pc while RANS on took around forty minutes. Projects on lower budgets or time constrains should use RANS simulations for convenience.

CHAPTER 4

METHODOLOGY

The methodology of this thesis is based on validating simulation results of the case with the wind tunnel studies conducted by Architecture Institute of Japan (Meng and Hibi 1998). They have tested series of different size and shapes of single building and urban layout scenarios to provide baseline for further studies. Single building scenarios with 1-1-2 (depth x width x height) and 1-4-4 proportions provide insight to wind effects in front of the building, corner and over the building and behind the building while subject to wind flow perpendicular to front facade of the building.

4.1. Case Area

Urban The case of the study is large environment extending in neighborhood scale bounds of redevelopment area so that it requires specific approach for simulations to be completed successfully. There are many alternative approaches for this type of large study areas but it is not always possible to achieve good results by using same approaches (B. Blocken, Janssen, and van Hooff 2012). One type of approach requires using on site wind data to validate and compare existing condition with results for simulated design alternatives. This approach requires multiple measurement points in case area for a period which could be impossible every occasion. Another approach uses wind tunnel test results of generic building forms to validate design options. This approach is useful in most cases since it provides faster results and accurate approximation of scaled models in controlled environment development area chosen for case study is located at southern axis of Izmir, stretching to airport and Torbalı direction. Surrounding area consists of mostly small industrial workshops (furniture and car services) and commercial buildings on the northern and eastern side, Izmir-Cesme highway, new Fuar Izmir and Aegean Free zone on the south side. There is a small hill with and a neighborhood with 2-3 story buildings are located on the western side (Figure 4.2).

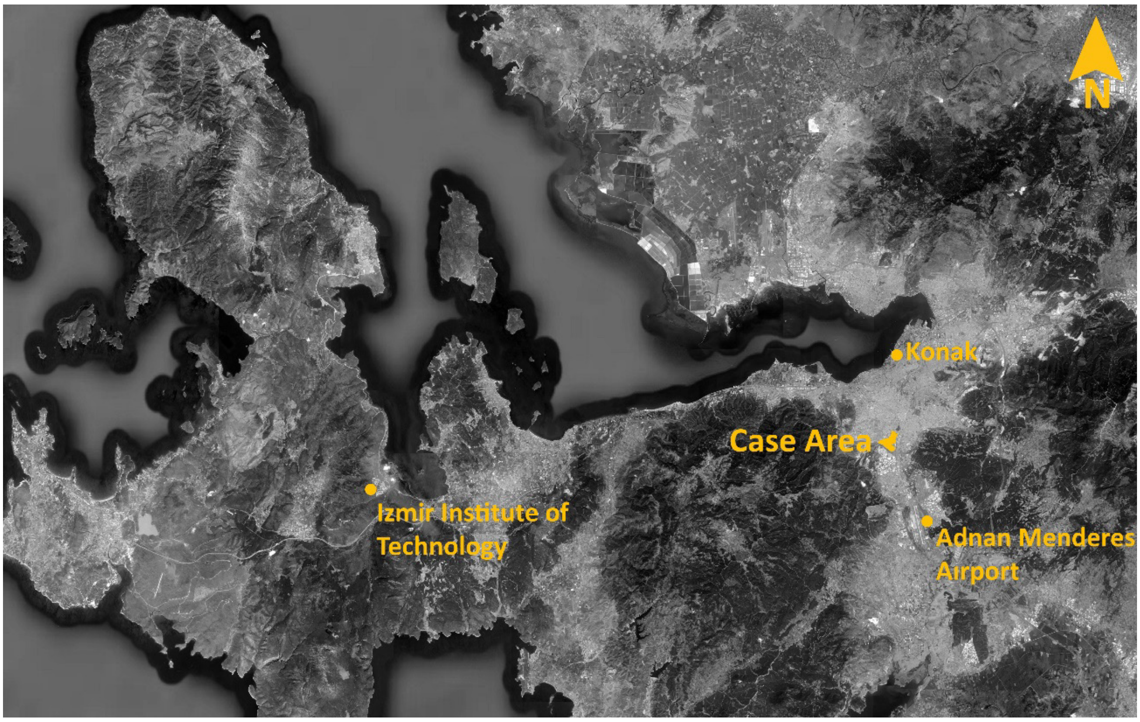


Figure 4.1. Location of case area in Izmir (Source: Google Earth 2019)

Figure 4.2. Location of the case area in Izmir (Source: Google Earth 2019)

Geographically, case area is a hundred meters elevated from sea level, situated in a valley like formation between two higher mountains directing prevailing wind from sea to penetrate inland. Area is quite large (1200000 sq. meters) and significantly affect wind behavior with unoccupied regions behind small residential buildings. There are only a few parks and urban open spaces in the area and existing buildings are clustered near the main arterial road connecting the airport and the city center (Figures 4.3-4.6). Existing building density in this area could be qualified as low (850 square meters land area for a building) concerning other regions of the city since there are only a few options for public transportation. Most of the residents are in low-income category working in industrial or service sectors in the city. Existing building layout is not laid accordingly to regional plans. Buildings are clustered within narrow streets and infrastructure is not renewed by the local municipality because of future development plans.

Figure 4.3. Photograph of the case from south direction

Figure 4.4. Photograph of the case from east direction

Figure 4.5. Photograph of the case area from southwest direction

Figure 4.6. Photograph of the case area showing tight clustered neighborhood

This clustered structure is not suitable for energy efficient implementations since its organization is organically grew to solve only local problems like distance to services and public transportation. New regulations for efficient distribution of infrastructure were not applied and residents of the neighborhood were not penalized for illegal constructions. On the contrary, residents of the neighborhood were permitted by government. Through the 1970’s to 1990’s slum areas increased rapidly and chancing political views with vote concerns, most of the slum areas like these neighborhoods rapidly legalized (Erdem 2019). Municipalities had to recognize the existing layouts as is and did not make any progress on planning these areas until they are redeemed as “Urban Regeneration Area”. These neighborhood types quickly evolve from slum to low density areas when they are not supervised by governments. The case area is a good example of this growth as mapped in Figure 4.7. Pink colored buildings are four story structures, green colored are three story buildings, rarely found purple-colored buildings are two story residential and some commercial buildings.

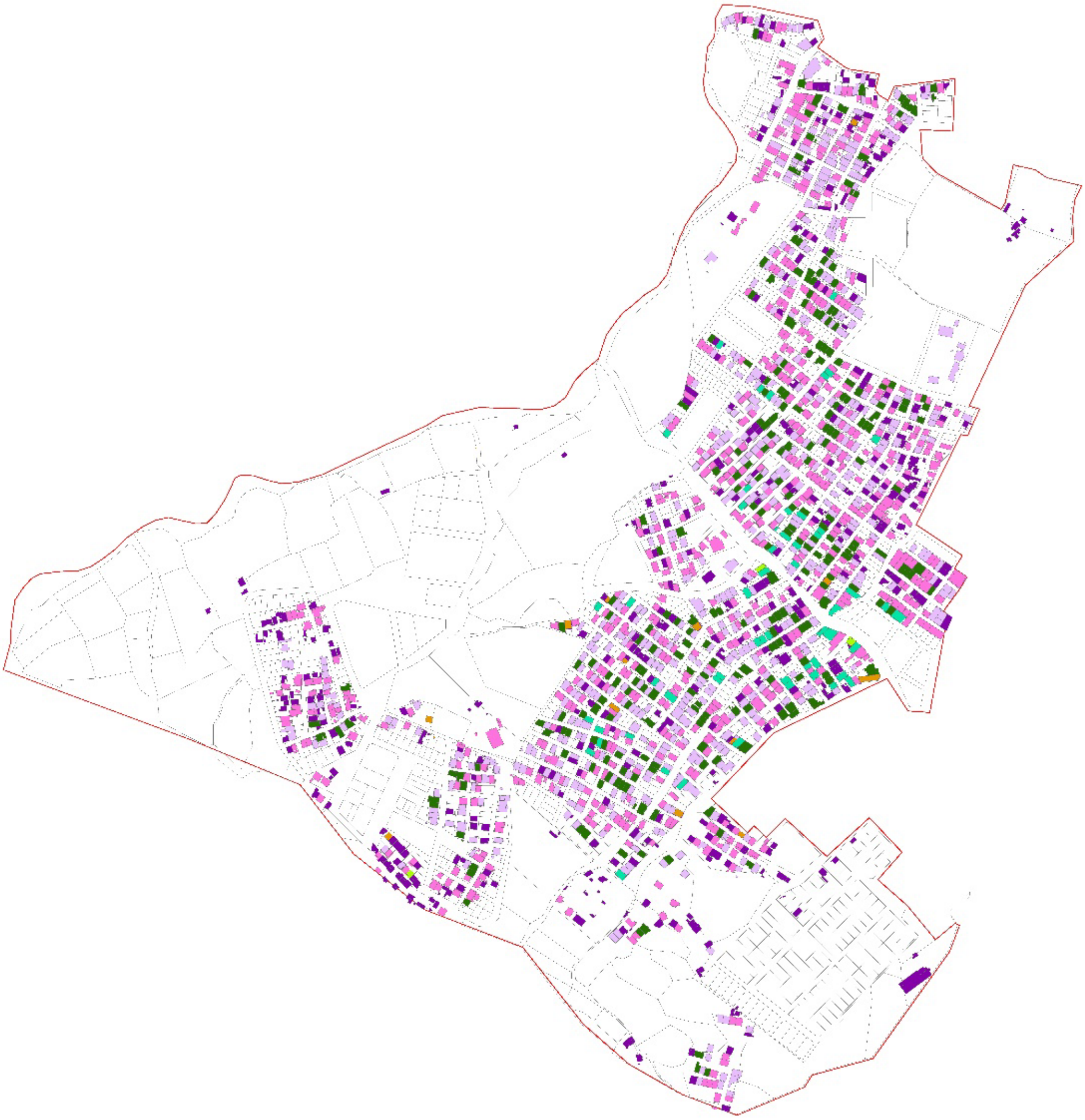


Figure 4.7. Existing building layout

4.2. New Redevelopment Concept Project

New conceptual project of case was proposed by the winning masterplan office of competition held by the municipality's Department of Urban Regeneration and Redevelopment (Bayhan 2015). Proposed project includes more than 2500000 square meter area of residential and commercial buildings, new parks and recreational areas and completely repurposed transportation infrastructure. Urban design concept project proposal is adequately including all residential units required by the municipality guidelines with apartment blocks ranging from six story to fifteen story buildings. Streets were designed wider to sustain heavier traffic loads. Building orientation principle was to align long buildings parallel to each other and gather taller buildings on the central axis of the project. This axis supposedly forms into a commercial district with shops on the first levels of buildings (Figure 4.8).

Figure 4.8. Accepted design of urban regeneration area

The design approach of conceptual urban design was to form inner courtyards with four to six building blocks surrounding them. These public areas attached to crossing streets would serve as recreational green areas and increase the overall value of the neighborhood. Conceptual approach was found sufficient to fulfill the requirements of the future population but also neglected the project area’s climate conditions like sun path and shading, prevailing winds, natural convection to mitigate urban heat island effects. Wind environment is going to be investigated primarily as the case of this thesis. Building features and geometries will be captured in a focus area study to scale down to pedestrian level wind environment

4.3. Focus Area for Sampling

The focus area chosen for detailed simulations is in the central part of the case area. It consists of residential buildings with 3 distinct types and common use area at the center of the city block area (Figure 4.9) Building features like entrance, parking entrance and mechanical shafts have direct access to common use area, and they are directly affected from wind at the pedestrian level.

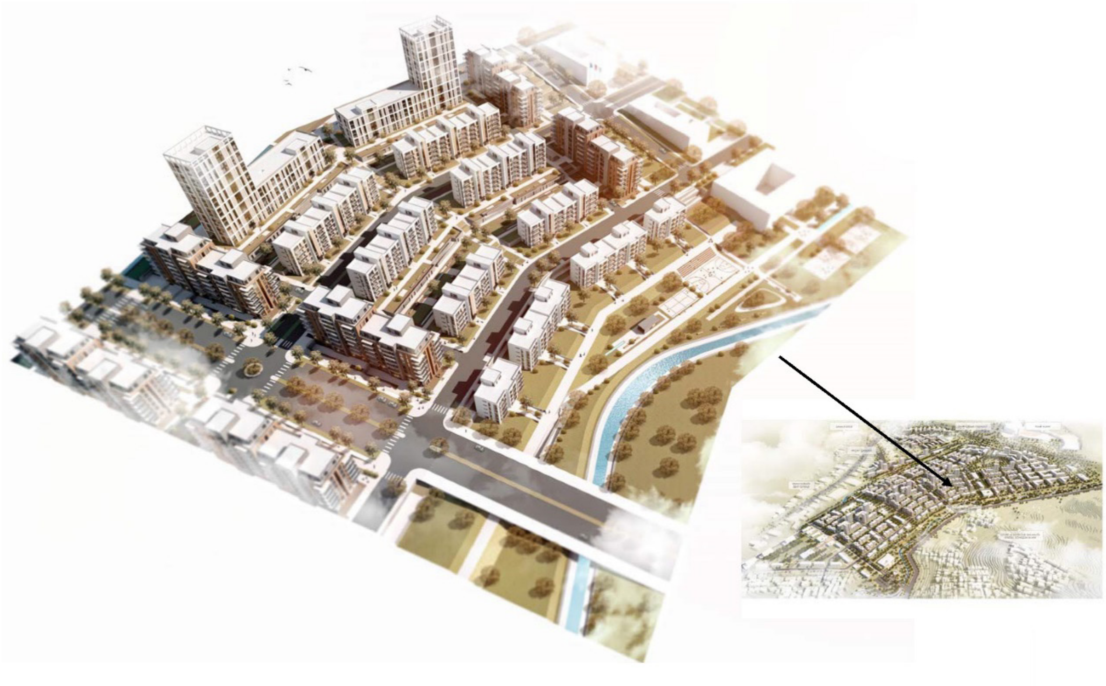


Figure 4.9. Focus area location in the case

4.3.1. Sub-Configuration Buildings

The focus area consists of 3 types of residential buildings. These buildings are repeated to satisfy housing needs of residents who has rights to own land plot in designated area. It is also regulatory issue of providing multiple mid-rise buildings rather than building taller residential units. These buildings form a semi closed courtyard area for recreational activities. This courtyard area is publicly accessed from surrounding streets and passages between the buildings. Buildings are going to be simplified for initial simulations and verification steps (Figure 4.10). Architectural features like balconies, entrances, recesses, or extrusions on the facade will be added on the following steps and compared for pedestrian level wind environment.

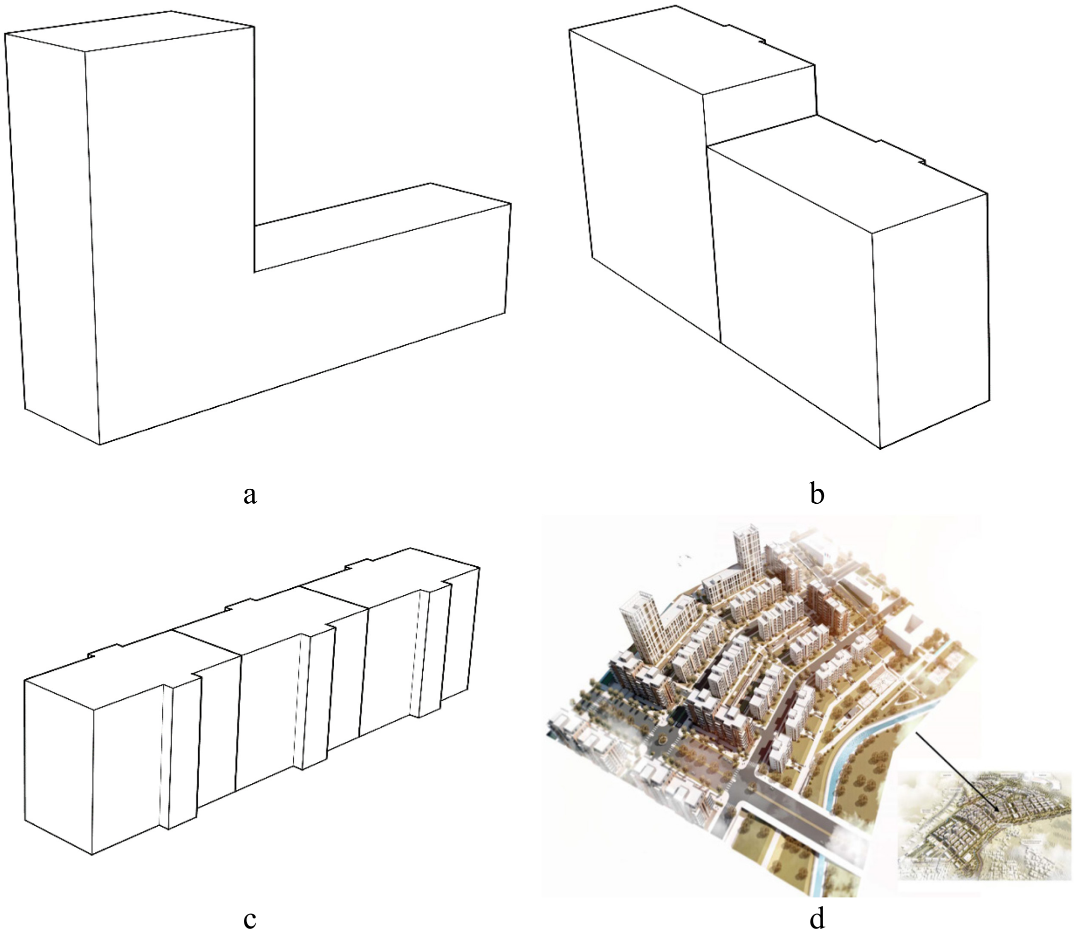


Figure 4.10. Types of generic buildings in focus area a) high rise building, b) two midrise buildings c) three low rise buildings d) location of focus area

4.4. Meteorological Data

Designing new settlements for development projects require well established analysis of microclimate in study area. Seasonal temperature differences, humidity and wind data from term measurements required while conceptual massing decisions. On the latter phases of project development, landscape designers also need the same data for accommodating correct vegetation for the location. These long-term data should be acquired directly from the site for at least a year long period or fetched from closest meteorological stations (Wu and Kriksic 2012).

Case study area has a dense low rise clustered neighborhood and some security issues, so it was not possible to find suitable location for installing a weather station on site. Nearest meteorological stations were in vicinity of five-kilometer radius, so the data from these stations picked for assessing local climate conditions. One of the stations is in Adnan Menderes Airport which indicates that station should be capable of collecting data without interruption or obstruction (Figure 4.11).

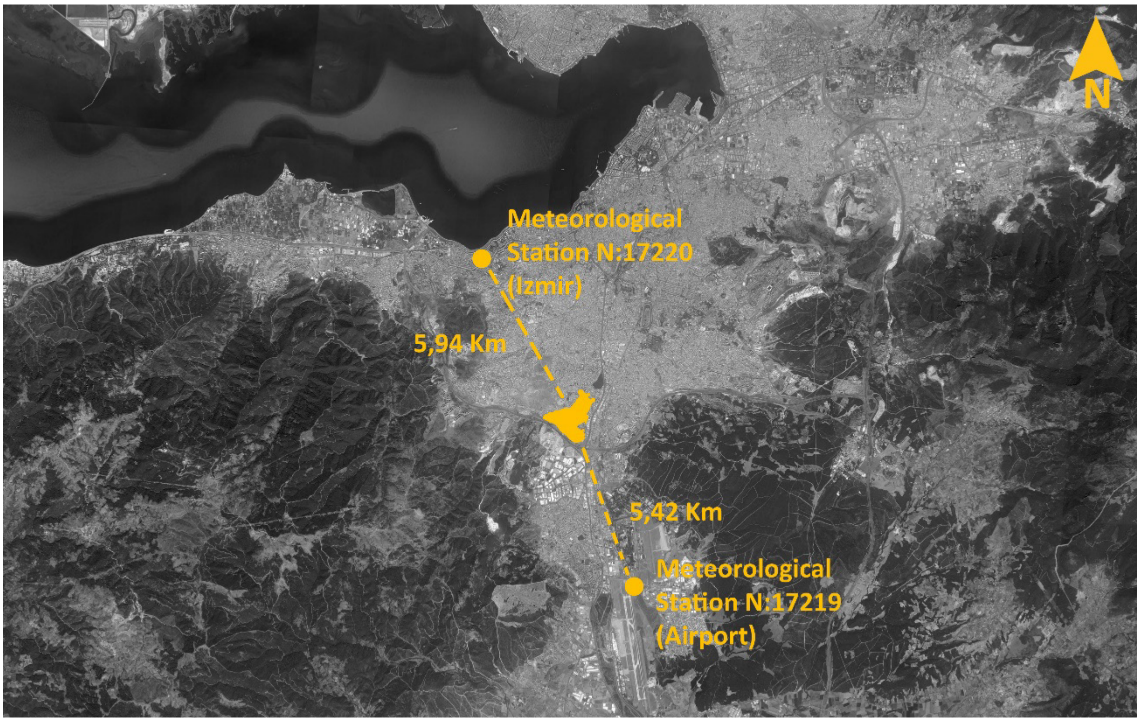


Figure 4.11. Location of meteorological stations (Source: Google Earth 2019).

Long-term data from nearby meteorological stations measuring wind speed, wind direction, dry bulb temperatures, sunshine duration acquired on annually, monthly, daily, or hourly periods from Turkish Meteorological Department. Raw data from stations indicating the mean wind speed and direction are hard to judge by sorting them in data filtering techniques for sixteen directions. Weather stations provide angular based direction data for wind measurements and categorizing the directional data to 22.5-degree pieces of cardinal directions would reveal biased results (Droppo and Napier 2008). In Figure 4.12 wind speed and direction data from same airport weather station of Turkish Meteorological Department used to graph wind rose. Winds from North and North-Northeast have the highest occurrences reaching 1500 hours throughout the year, between 6m/s to 5.6 m/s speeds.

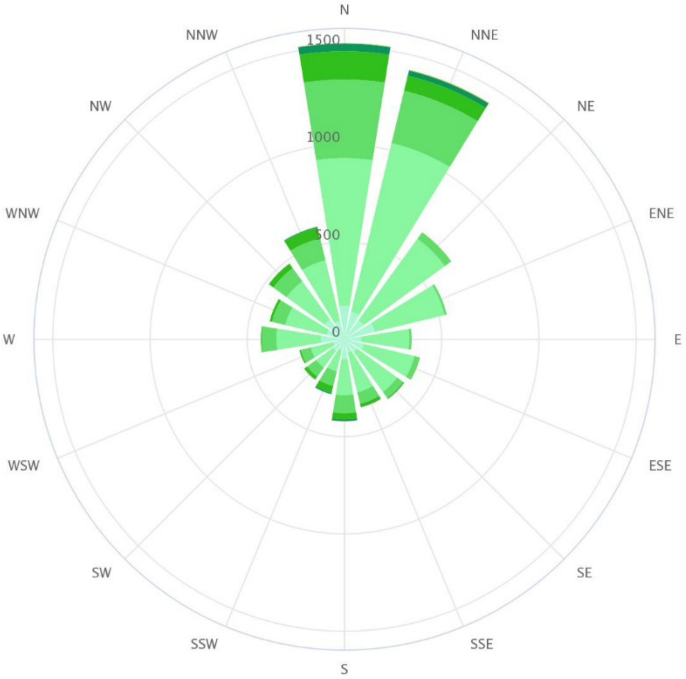


Figure 4.12. Wind speed and direction data of Izmir from weather information website (Source: www.meteoblue.com)

A new methodology is proposed for the analysis of raw weather data. High precision of directional input from station files are converted to thirty-six directions with 10-degree part wind rose graphic with open-source algorithm. This algorithm is purposed for fetching general epw format weather data cache which includes temperature, humidity, solar exposure, rain and wind data. Existing code for graphical representation of all the information modified with coding in user interface and repurposed with analyzing weather station data (Figure 4.13).

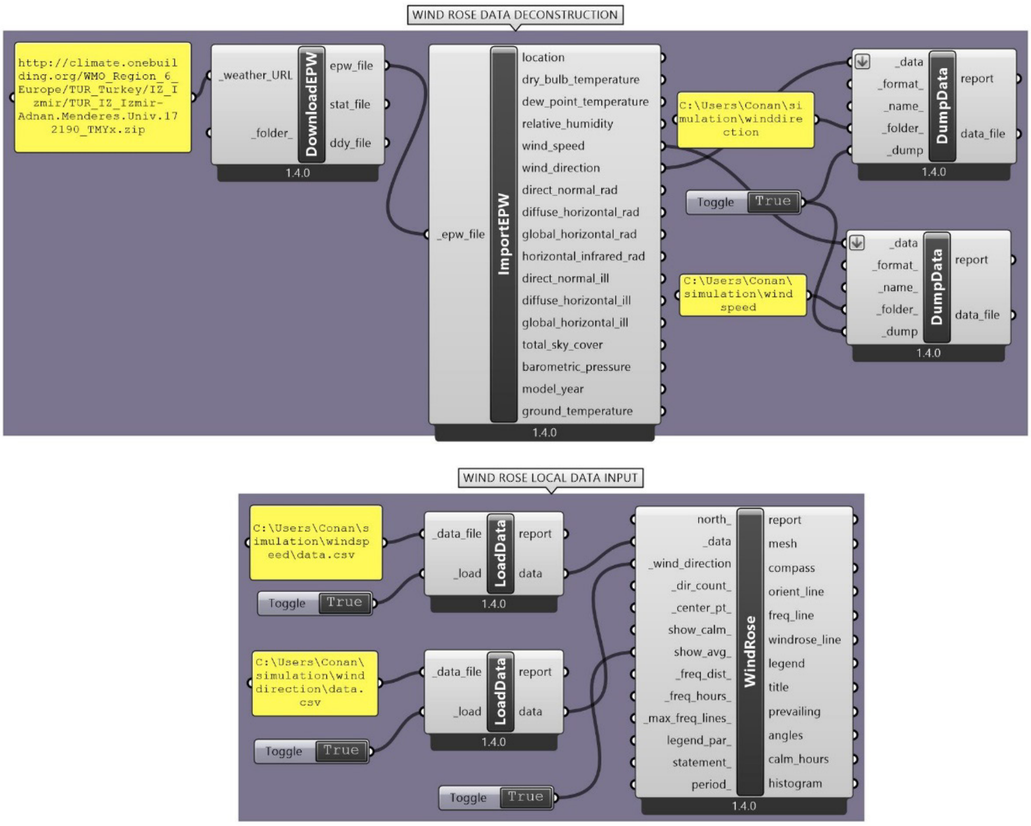
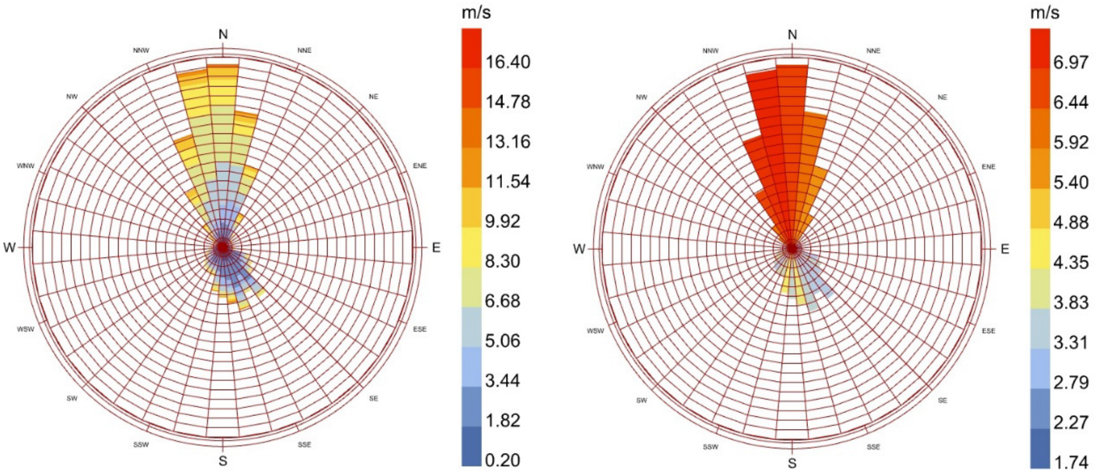


Figure 4.13. Graphic User Interface code for repurposing the tool

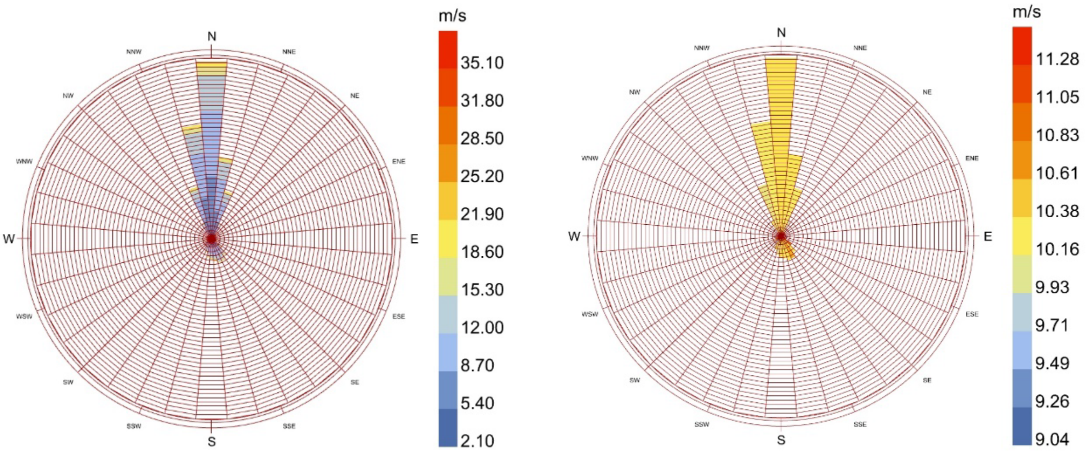
This modification (Mod) is capable of interpreting long years data to easy-to-understand wind roses for local climate decision model and used by architects, engineers, and urban designers. Weather data from airport station are presented in Figure 4.14 and Izmir city center station in Figure 4.15. Airport wind roses indicate majority of north directional winds were prevailing for local climate and reaching up to 16 m/s speeds for inland. On the other hand, Izmir station wind rose shows almost identical direction for prevailing winds but indicate increased speeds.

This weather station is subject to free streams of winds over Aegean Sea where they can keep their energy without any interruptions thus making them available for harvesting wind energy. Case area is more than six kilometers direct air distance to sea, so wind speeds are expected to be lower than the Izmir Bay Area.



a b

Figure 4.14. Wind rose from airport weather station file a) maximum wind gusts and directions b) average wind speeds and directions.



a b

Figure 4.15. Wind rose from Izmir weather station file a) maximum wind gusts and directions b) average wind speeds and directions.

4.5. Simulation Decision Model

Decision model in this study is based on validation with wind tunnel tests of generic buildings in literature (Figure 4.16). This methodology is derived from Blocken et al. framework for simulation methodology and best practice guidelines (2012). It is also widely used in other industries for testing the development phases of design. It is not always possible to find exact matching design of a case study in literature (Blocken et al 2012) Sub configuration approach enables simplifying the working case into basic components and complete simulations with validation to structure final design simulations. This methodology could be used with wind tunnel data in literature and when measurements from case area does not exist.

In this case study, three different types of building masses are simulated for validation with wind tunnel results. These cases are compatible with geometry in wind tunnel data. In this methodology two phase of simulations have been conducted for validation. In the first phase, CFD components of turbulence model, computational domain, grid size and other constants were chosen from parameters of wind tunnel test from literature data. Sample building simulated with chosen parameters to verify the correct parameters. Results are compared to wind tunnel tests repeatedly to reach satisfy wind profiles in data acquisition points. After this phase, sub configuration building masses were prepared for same steps in phase 1.

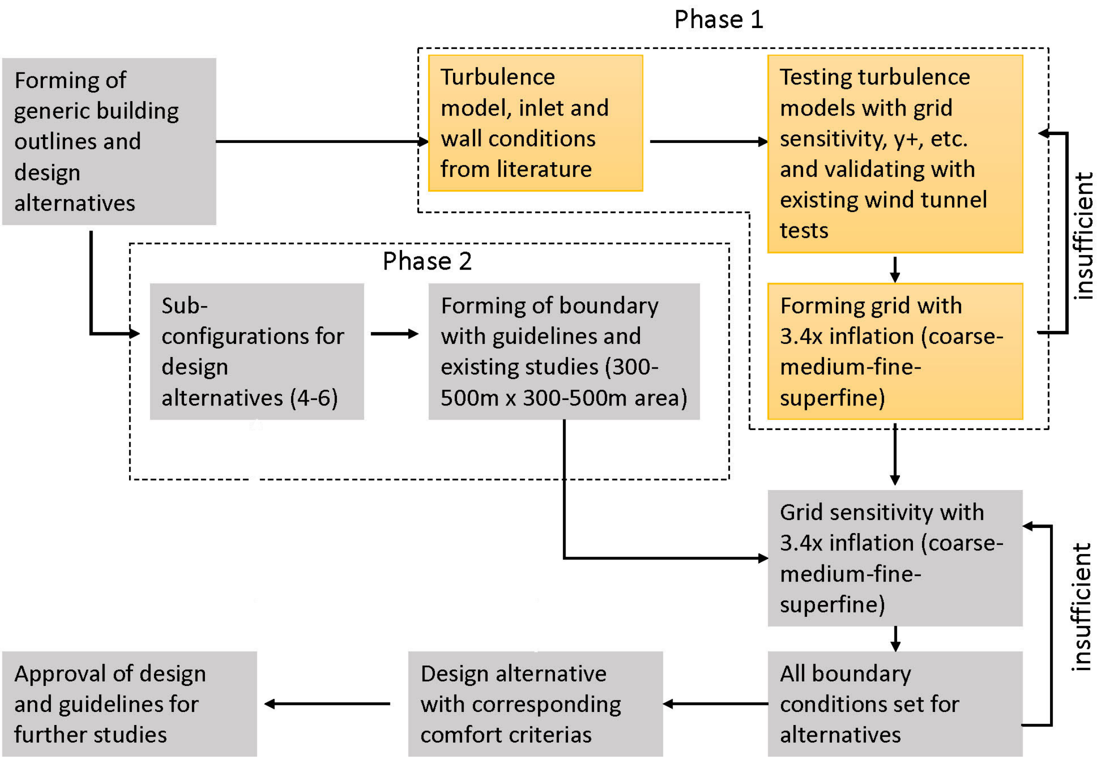


Figure 4.16. Decision model for simulations

On the second phase

building masses will be simulated with output from phase one and results will provide baseline for testing the effects of architectural features. On the final phase buildings will be positioned for testing the layout of focus area. This layout will provide total massing effect on near pedestrian level wind environment.

4.5.1. **Verification and Validation**

The verification and validation of CFD simulations is essential part of all studies in literature to provide statements based on scientific foundations. CFD simulations have been widely used in aerodynamic research since it proved itself as a fast and efficient alternative to wind tunnel tests in last 30 years (Roy and Oberkampf 2016). It requires thoroughly picked simulation parameters to achieve good agreement with wind tunnel test and still requires a methodology to quantify integrity of results (Bert Blocken 2015).

The fundamental strategy to assess credibility of computational simulations is to go through “Verification and Validation” (V&V) phases (AIAA 2002)

CFD simulations incorporate uncertainties and errors that may be caused by computation or user related deficiencies. Quantifying the rate of contradictory results is processed with Verification and Validation principles. Verification is testing the accuracy of model implementation to developed and trusted computational solutions (AIAA 2002). Simulation engines whether its commercially sold and accepted in industry or programmed for specific scenario possibly face round of errors due to complex mathematical nature of CFD (Roy and Oberkampf 2016). Commercial codes are constantly tested and verified by developers or researchers. Important part of verification is using the CFD code accurately for presenting the simulation model (AIAA 2002). Verification does not include the assessments of physical experiments. Main problems addressed in verification is the grid discretization, boundary conditions and consistency of simulations (Roy and Oberkampf 2016).

Validation is the process of comparing computational results with experimental results. It is generally followed after verification work to ensure the results can be trusted (AIAA 2002). Validation provides an approval that verification is done accordingly to ensure results are acceptable, but validation procedure may affect the verification phase by adjusting some variables of verified model (AIAA 2002). There is no strict limit for verification and validation process to end to reach exact solution. Computation power, budget and time constraints are also important parameters for V&V process and significantly affect the given effort for quantifying accuracy. American Institute of Aeronautics and Astronautics (AIAA) provided guidelines for a methodology of V&V and generalize for aerodynamic research, but still there is no consensus on what would make the results of a simulation as the universal criteria.

Verification and Validation (V&V) of case study simulation results are performed with wind tunnel experiments from working group organized by Architecture Institute of Japan (Yoshie et al. 2007) This comparative study incorporates tests of several building types and layouts. Testing parameters of wind tunnel and results from probes in various positions (Figure 4.17) are also included in for detailed analysis (Meng and Hibi 1998). This experiment results provided many validation studies to be performed in literature (Mochida et al. 2002), (Yim et al. 2009), (Tominaga, Mochida, Murakami, et al. 2008), (van Druenen et al. 2019)

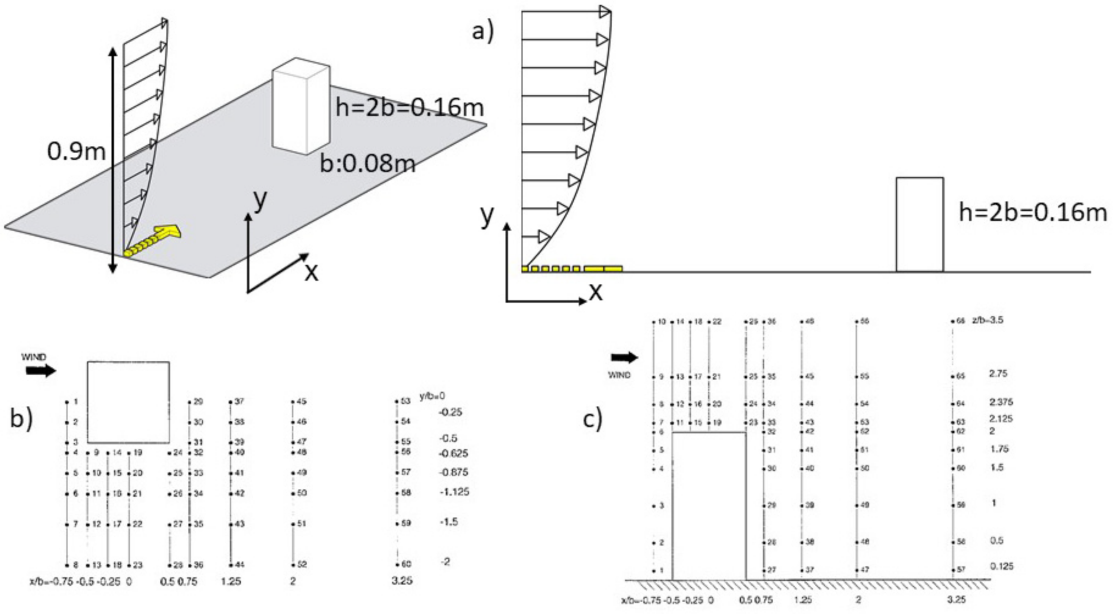


Figure 4.17. AIJ Test case of square prism a) geometric inputs and flow direction b) horizontal data points c) vertical data points

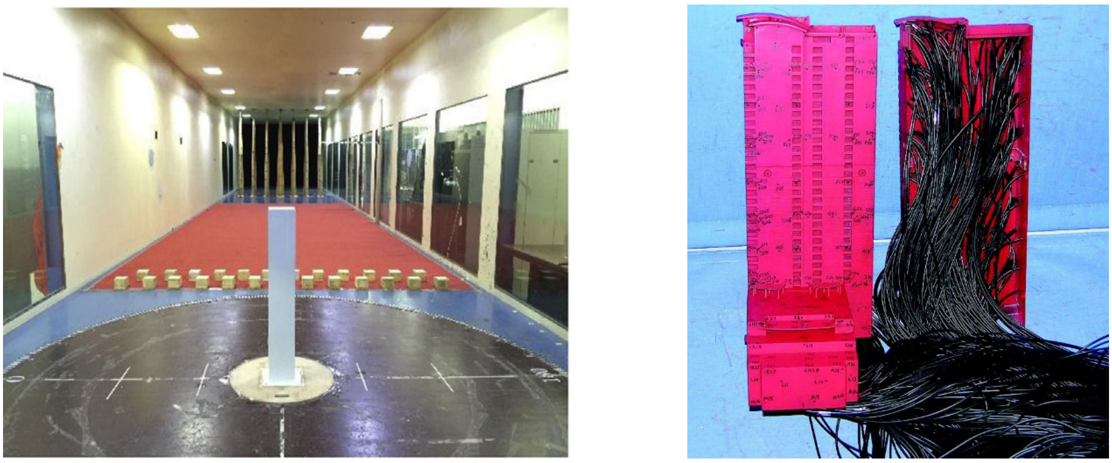
4.6. Modelling and Simulations

New urban design project for the case area included various types of buildings like high rise building (>15 floors) with commercial units on first floor, midrise building (>8 floors) with commercial units on first floor and low-rise building (<8 floors) with residential units only. These buildings were modelled in detail for accurate graphical representation of development project for publicity and design study (Figure 4.18) (Figure 4.19). High level of detail is not feasible solution for unless they are significant for aerodynamic studies. However high-level detailed buildings and building features like recesses, entrance and canopy details, railings or decorative facade elements could be investigated by superposition theory of partial differentiation. This methodology would provide better understanding of complex condition of flow field into several simpler solution clusters providing a detail insight. But for urban microclimate studies, buildings must be in simpler and massive forms to be used in simulations and compare with wind tunnel results (Tominaga, Mochida, Yoshie, et al. 2008).

Figure 4.18. Urban design level model of case area

Figure 4.19. Urban design level model close view

Wind tunnel tests of buildings are maintained with fewer details to investigate wind flow around building without implications of facade details for cases in urban areas. Tall buildings can be excluded in some cases where pressure differences on facades required for investigation (Figure 4.20) (Irwin, Denoon, and Scott 2013).



a b

Figure 4.20. Wind tunnel test of tall buildings a) mass study b) pressure couplings for aeroelastic effects on facades study (Sources: a) Z. Liu et al. 2019 b) Irwin, Denoon, and Scott 2013)

In validation study, wind effects on bluff body were studied to demonstrate wind effects around buildings. It is not possible to investigate every facade detail like balconies or recesses in wind tunnels, so generalized bluff bodies provide baseline for validation studies and other geometric details are added on further investigations. This iterative methodology is used the case study with three distinctive steps. After validation process, architectural details will be added, and finally total layout will be simulated to investigate final form of architectural concept stage of project area. Simulation roadmap is framed in Figure 4.21.

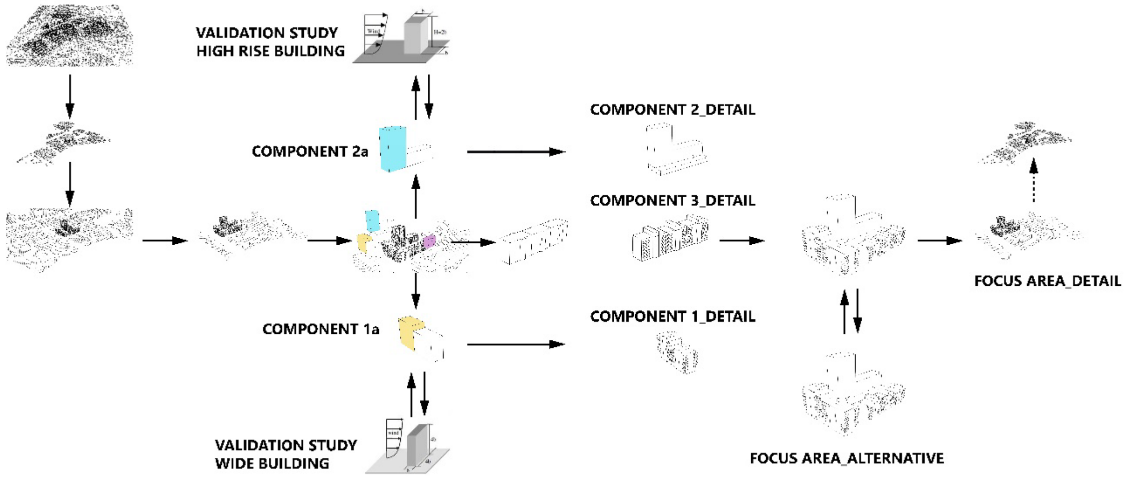


Figure 4.21. Simulation roadmap for case area

4.6.1. **Modeling of the Simplified Base Buildings**

Buildings inside the case area are divided under two groups according to their geometrical shapes. They are color coded for specific type of geometry and studied for sub-configuration approach before simulations of layout. These building forms are free from facade details and applicable to verification and validation study. First type of geometry is the “component a” and color coded with blue in Figure 4.22. This building is chosen for validation which involves good compromise between height width and length ratios to possible design alternatives. Second type is the “component b” colored with yellow. This type involves alternate geometry with lower height but wider front facade. These buildings are converted to mass models for validation study. First component building is picked accordingly with guidelines of Working Group of Architecture Institute of Japan (AIJ)(Tominaga, Mochida, Yoshie, et al. 2008) for wind tunnel tests of Meng and Hibi (1998).

Figure 4.22. Color coded simplified base buildings

4.6.1.1. Validation of Simplified Base Buildings

Base buildings categorized as simplified models are validated with wind tunnel experiments of Meng and Hibi (1998). In pedestrian level wind studies wind tunnel parameters and flow measurements and ground roughness indications should be transferred to CFD simulations (Franke et al. 2004)(Franke 2006) In COST (European Cooperation in the field of Scientific and Technical Research) Action 14, mass studies of different geometries were simulated for provide information about flow around buildings, but detailed methodology was studied by Tominaga et al. (2008) in Architecture Institute of Japan from Franke et al. (2006).

Wind tunnel experiments of Meng and Hibi (1998) provided inflow data of σ_u , σ_v, σ_u , U, and k measurements. U is the mean velocity (m/s), σ is the deviations of x,y,z velocities (m/s) measured with split fiber probes in three directions and k is the kinetic energy (m^2/s^2). Reynolds number is calculated with velocity (U) 4.491 m/s at h_o building height 0.16 m (Figure 4.17). Other wind tunnel properties are calculated with Eqn. 3.7. Reynolds number is calculated 23952 with kinematic air viscosity. U and k inlet flow conditions are interpolated from data. Outlet boundary condition is zero gradient pressure and required to be further from building. Sides and top are symmetry conditions to prevent influence on velocity profiles. On the ground, wall functions should be detailed for simulating suitable conditions to achieve good results.

Ground wall roughness length z_0 was not specified in experiments, but it is a requirement for good agreement on results (Franke 2006) (Tominaga et al. 2008). Logarithmic law for shear stress velocity (u_*) is used for finding z_0 (Eqn. 3.10), and shear stress velocity (u_*) is calculated from *k* near wall value from profile. Substituting the u_* value in Eqn. 3.8 with near wall velocity and A= 0, we can calculate z_0 as 1.8e-04 meters. For verification of the approximated values, 2d flow simulation conducted to compare

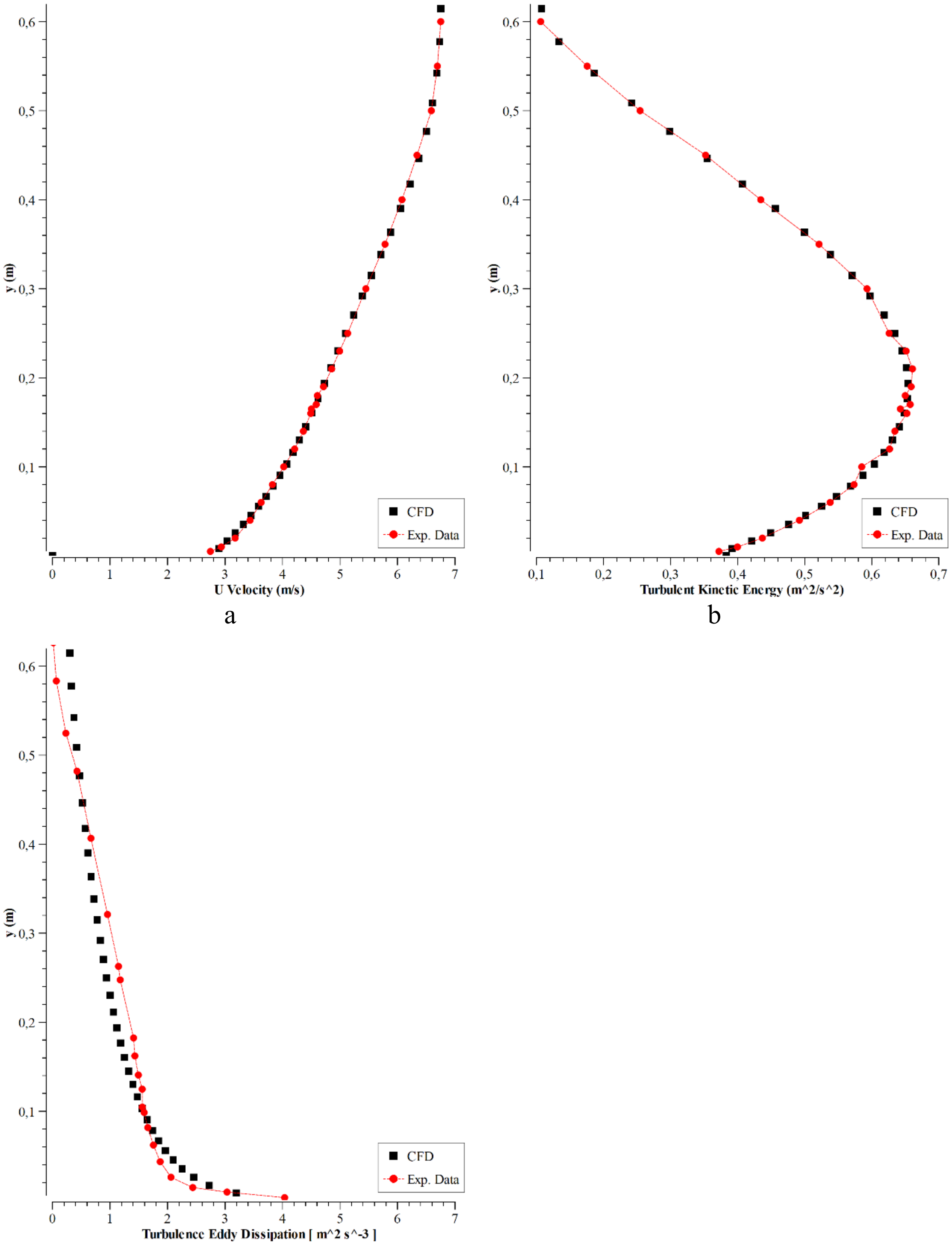
$$u^* \cong C_\mu^{1/4}\sqrt{k} \qquad \text{Eqn. 4.1}$$

$$U(z) = \frac{u^*}{k} ln\left(\frac{z}{z_0}\right) + A \qquad \text{Eqn 3.8}$$

data with wind tunnel inflow conditions. *U*, *k*, and *Ɛ* profiles applied with boundary conditions (Figure 4.23) summarized in Table 4.1. Specific roughness parameter and wall conditions are also used with User Defined Functions (UDF) for simulation environment in ANSYS Fluent simulation tool. This tool is an industry level verified simulation program that can complete RANS equations with high degree of accuracy. It has been used in aerodynamic research and validated with experimental results, so no further verification of programming code needed for this step. Meshing for grid structure is completed on ANSYS ICEM CFD tool, which is another module of ANSYS programming pack (Figure 4.24). Grid with high orthogonality and low skewness required for faster computation. It can also benefit from less errors from angular forces that may have develop with prismatic tetrahedral grid.

Table 4.1 Boundary conditions for 2d simulation

Boundary	Condition
domain size	20b x 7.68b (1.6m x 0.614m)
grid size	40 (x) - 32(y)
inlet	interpolated U, *k*, and *Ɛ* profiles
outlet	zero gradient pressure
side wall	none
top wall	symmetry
ground wall	z_0 as 1.8e-04 m with wall functions
solution scheme	Quick scheme for convection terms



a

b

c

Figure 4.23. CFD simulation input for boundary conditions a) *U* velocity b) *k* Turbulent kinetic energy c) $\mathcal{E}$ Turbulence eddy dissipation

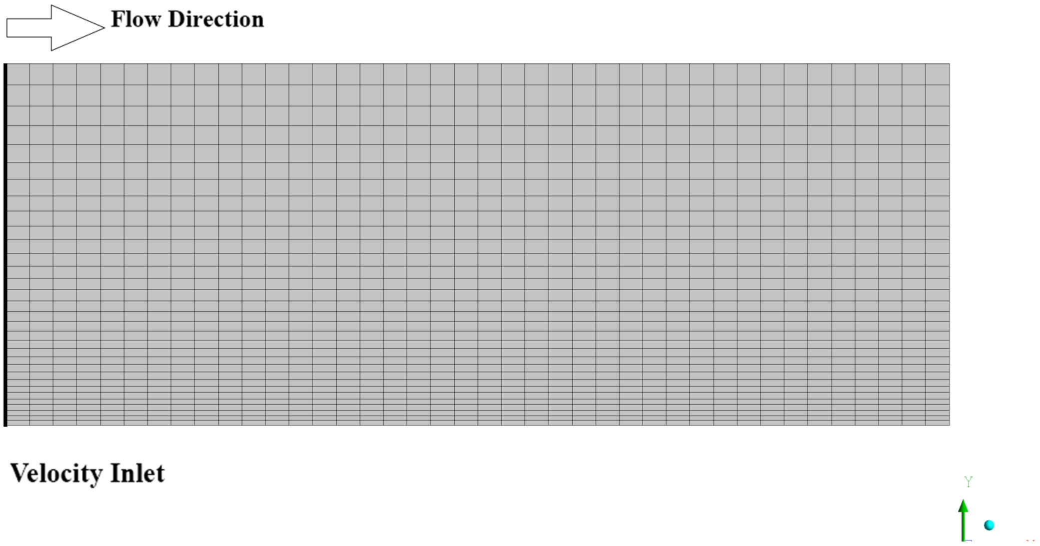
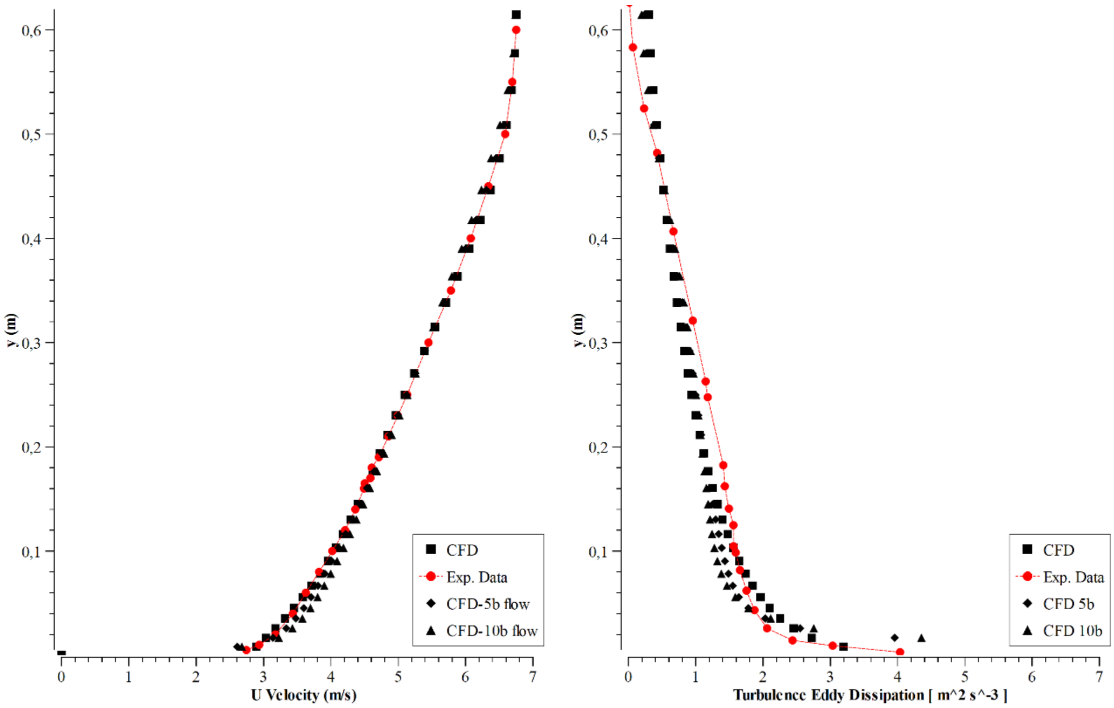


Figure 4.24. Meshing of 2d roughness length study.

Simulations are Profiles from 2d case are shown in inlet, 5b from approach flow and 10b distance from incident flow are compared for roughness influence (Figure 4.25). A higher value for roughness chosen for approximated z_0 value would implicate profiles further away from experimental results. Turbulence eddy dissipation rate is slightly off but captures the results within margin of %10 to %20. These resulting profiles are chosen for three dimensional CFD simulations for verification.



a

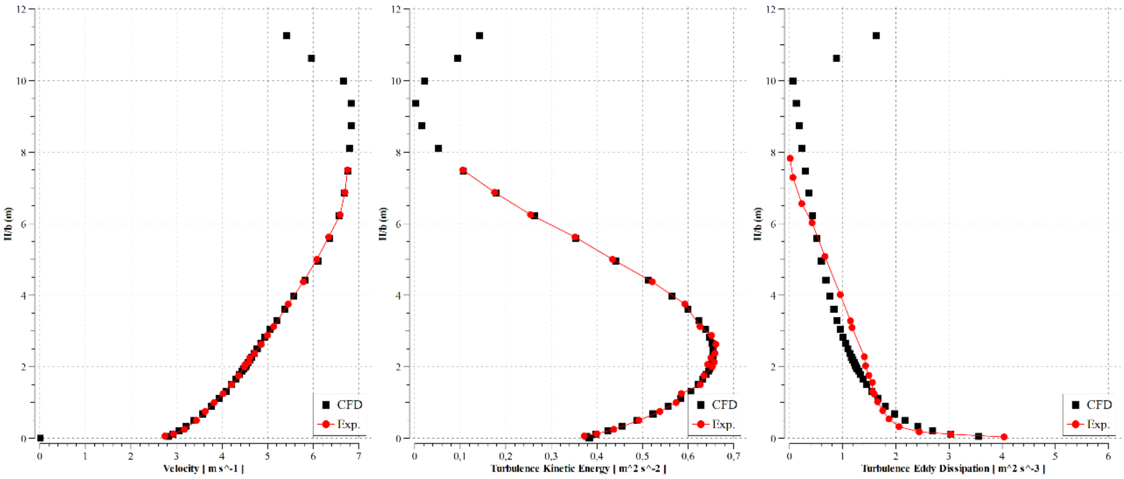
b

Figure 4.25. a) *U* Velocity b) $\mathcal{E}$ Turbulent Eddy Dissipation profiles from inlet and approach flow

2d simulations provided the z_0 and momentum profiles that have been verified with computational data from benchmark results of Architecture Institute of Japan Research Group (2016). These profiles are fitted to new domain and deployed with UDF coding to Fluent program for 3d validation of wind tunnel results (Figure 4.26). Building dimensions and domain size explained in Figure 4.17 with boundary conditions in Table 4.2 used for 3d simulations.

Table 4.2 Boundary conditions for 3d simulation

Boundary	Condition
domain size	21b(x) x 11.25b(y) x 13.75b(z) (1.68m x 0.9m x 1.10m)
grid size	60 (x) x 39(y) x 45(z) 9(x) x 15(y) x 9(z) building
inlet	interpolated U, k, and ε profiles
outlet	zero gradient pressure
side wall	symmetry
top wall	symmetry
ground wall	z_0 as 1.8e-04 m with wall functions
solution scheme	Quick scheme for convection terms



a b c

Figure 4.26. Inlet profiles of validation simulation a) Velocity b) Turbulent kinetic energy c) Turbulent Eddy Dissipation

Inlet profiles for velocity (*U*), turbulent kinetic energy (*k*) and turbulent eddy dissipation (Ɛ) are higher than 2d validation study to include all domain to wind tunnel roof. Full dimensions of wind tunnel test section are 1.1 m width to 0.9 m height. H/b axis in the profile graphics is converted to unitless wind tunnel height/b, reaching top part to 11.25 units. Windward part, in front of the building is 5b and leeward part behind the building is 15b accommodating the guidelines in literature (Bert Blocken 2015) (Yoshie et al. 2007). Wind tunnel test section discretized to 60 x 39 x 45 cells in x, y, z dimensions using orthogonal hexahedral mesh (Figure 4.27). Building corners and surfaces are densely meshed to capture flow separations and downwash effects on pedestrian levels.

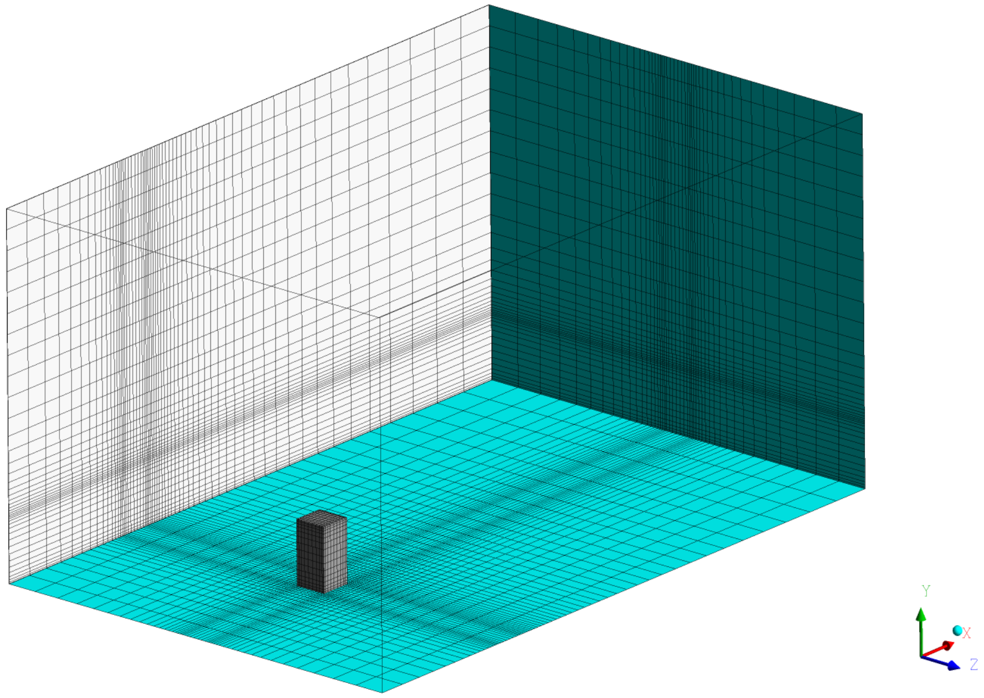


Figure 4.27. Meshing of 3d validation case

Validation simulation completed with domain specifications which are laid out by Architectural Institute of Japan benchmark report (AIJ 2016). Wind tunnel experiment data for specific probe locations are marked in Figure 4.28. Turbulence model alternatives are not investigated since specific *k-Ɛ* parameters are input with UDF code. *k-Ɛ* RANS model sufficiently resolve different parts of the model area. This model provides a good compromise between time spend on calculations to available computational resources.

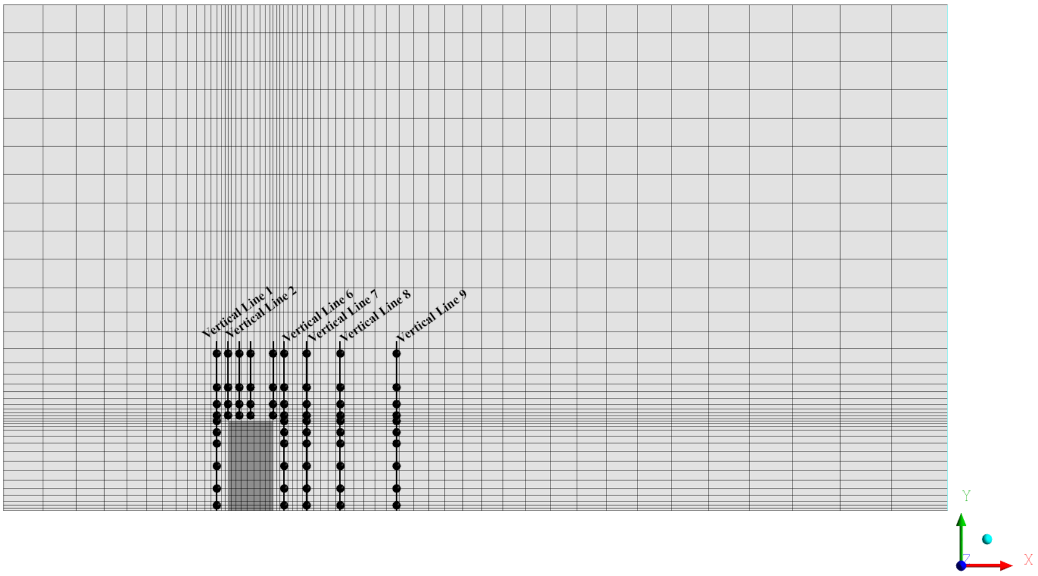
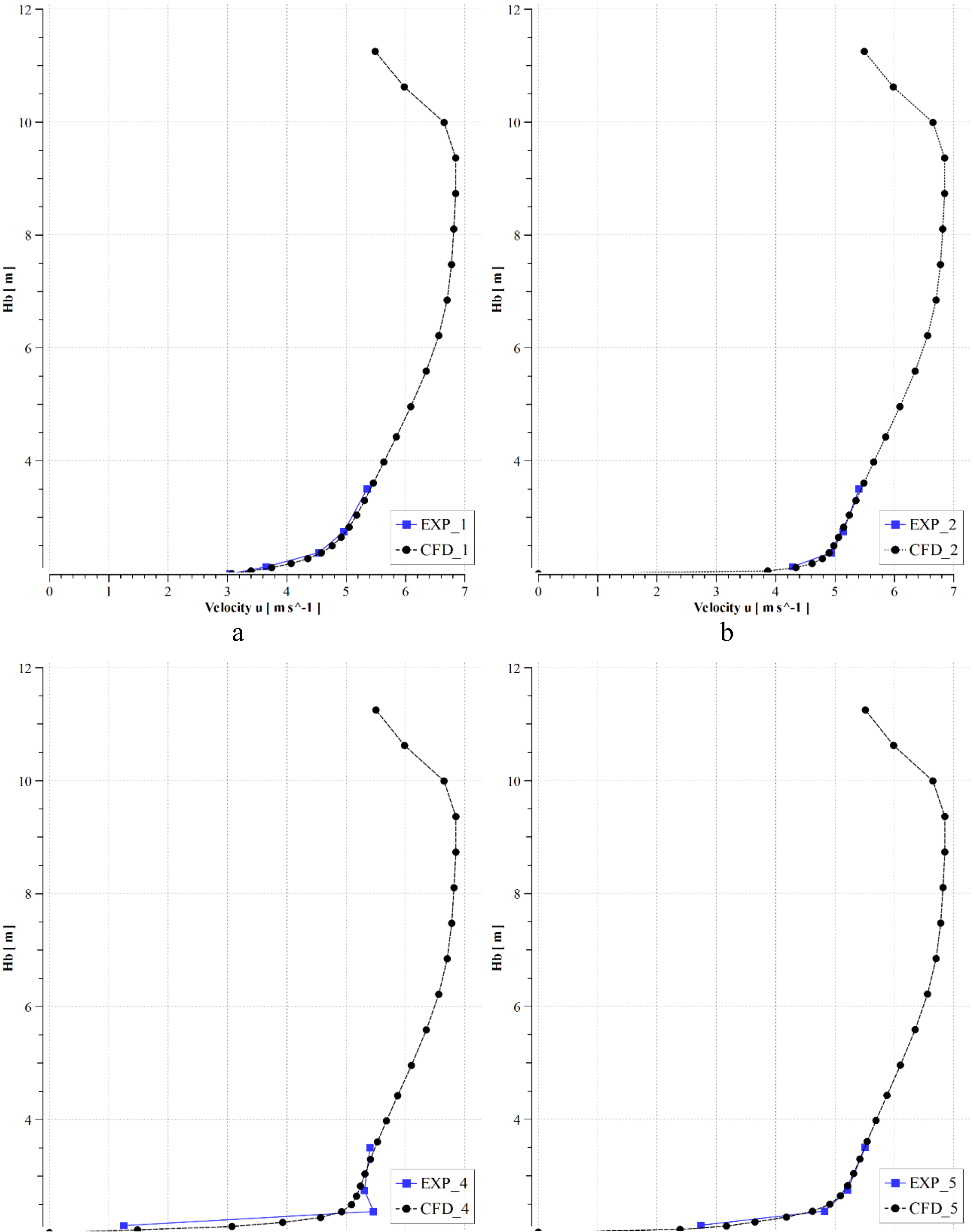


Figure 4.28. Probe locations around the building on vertical plane

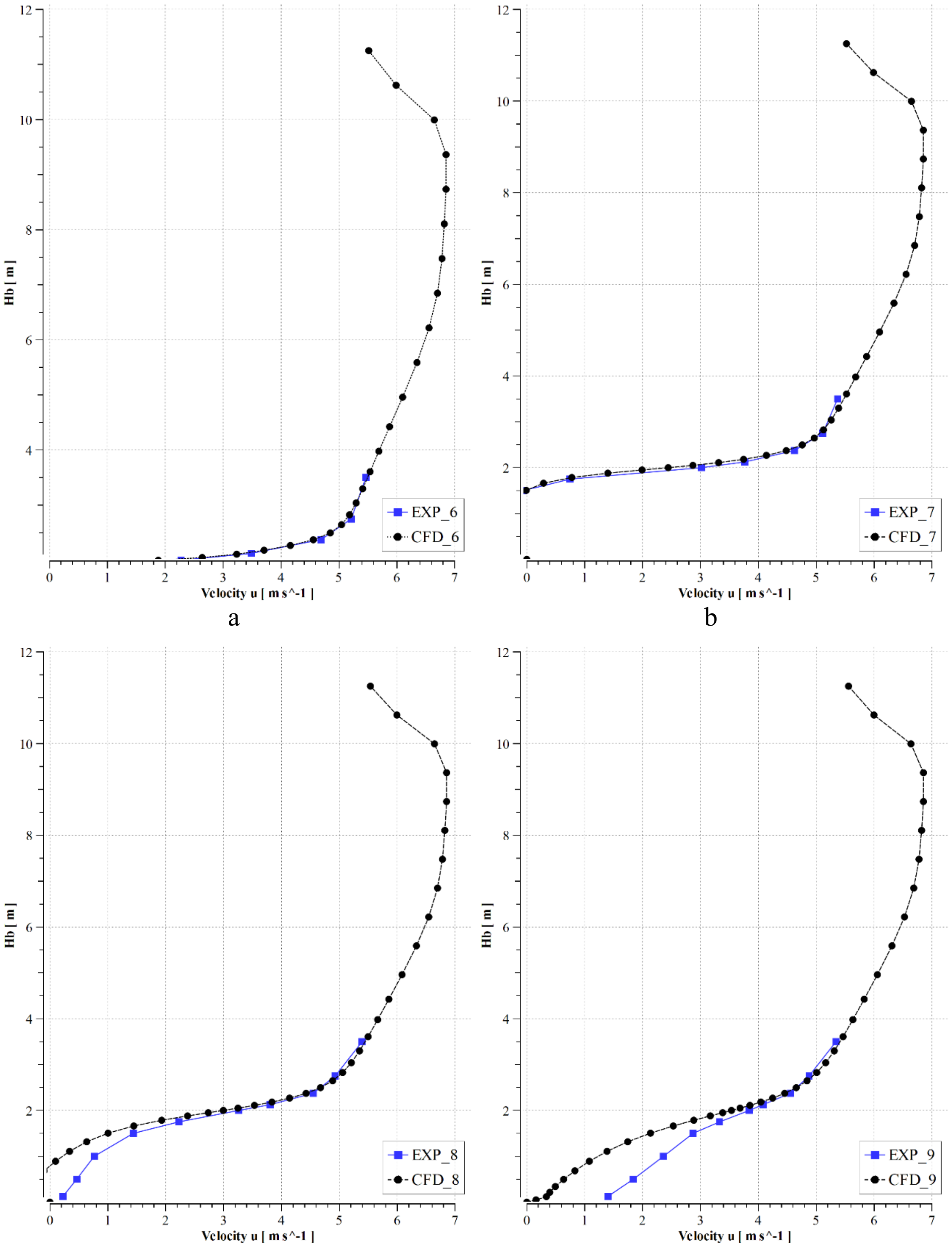
Vertical velocity profiles showed good agreement on in front of the building and through the middle section of the roof part. Figure 4.29 a) and b) charts are the first two lines in probe locations showing acceptable profiles, but in chart c) there is misleading data in the section close to roof end. This could be the specific problem of *k*-*Ɛ* model where reattachments of flow separations are overdriven from experimental studies (AIJ 2016) (Mochida et al. 2002) (van Druenen et al. 2019). It is also possible that there could be a measurement error since there is not enough data to conclude in this part. Following velocity profiles are again capture dependable results in Figure 4.29 d) to Figure 4.30 c) charts, but again in far behind the building, reattachment flow distance is longer than the wind tunnel experiments. This part of the flow area is not a priority location since the pedestrians close to building surface are affected heavily from wind nuisance.



a b

c d

Figure 4.29. Vertical velocity (u) profiles probe locations on vertical a) line 1 b) line 2 c) line 4 d) line5



a b

c d

Figure 4.30. Vertical velocity (u) profiles probe locations on vertical a) line 6 b) line 7 c) line 8 d) line 9

Graphical velocity contour plots of the validation study support the velocity charts and reattachment length errors in figures 4.31 and 4.32. Negative velocity areas from downwash effects in front of the building and wake effects behind the building can be observed. Flow reattachment area behind the building showed in blue color gradients could be resolved with high fidelity LES (Large Eddy Simulation) but using this turbulence model require HPC (High Performance Computing) clusters to solve high density mesh grids. On the other hand LES model could overestimate the circulation area in front of the building (Tominaga, Mochida, Murakami, et al. 2008), which is an important region for this study.

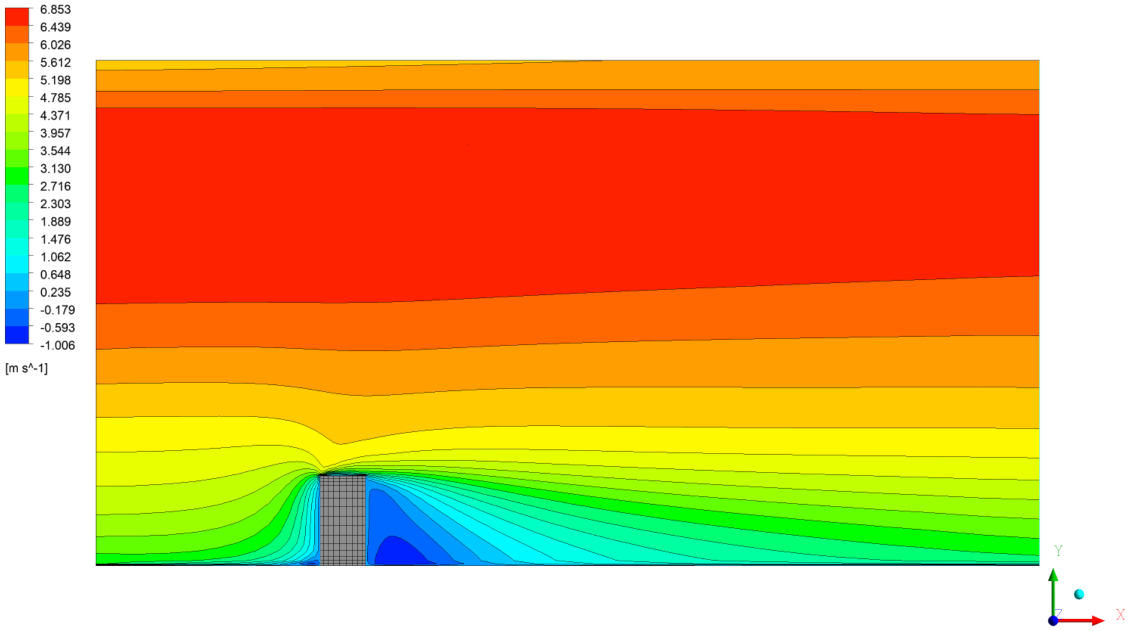


Figure 4.31. Vertical velocity contours of 3d case at z = 0

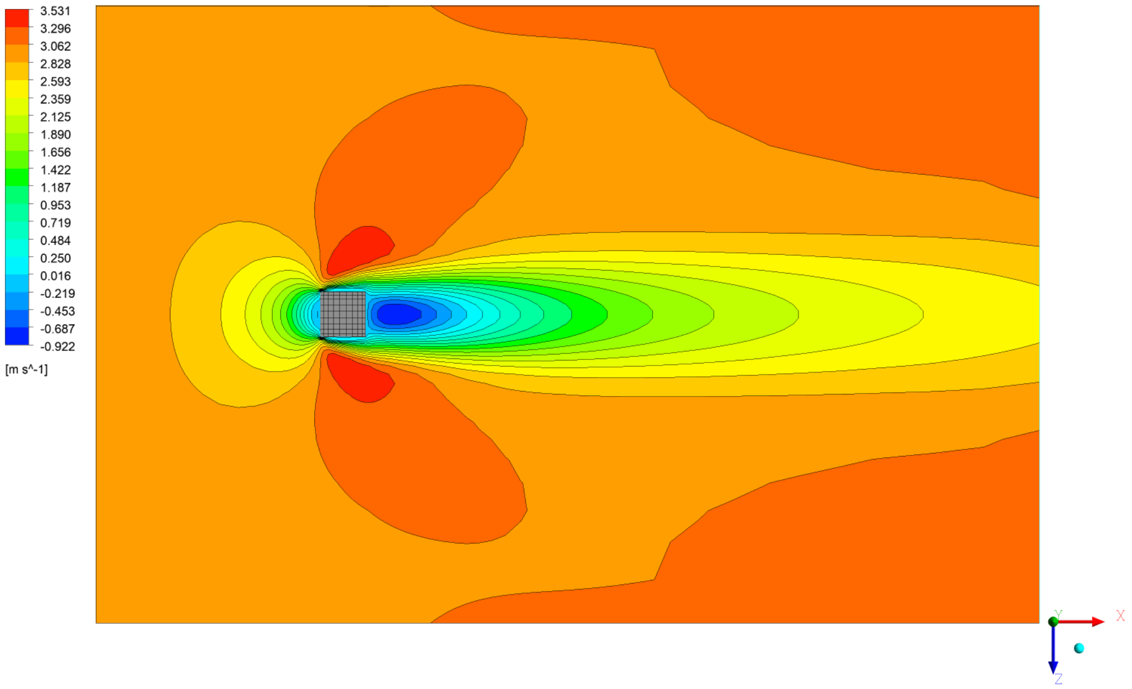
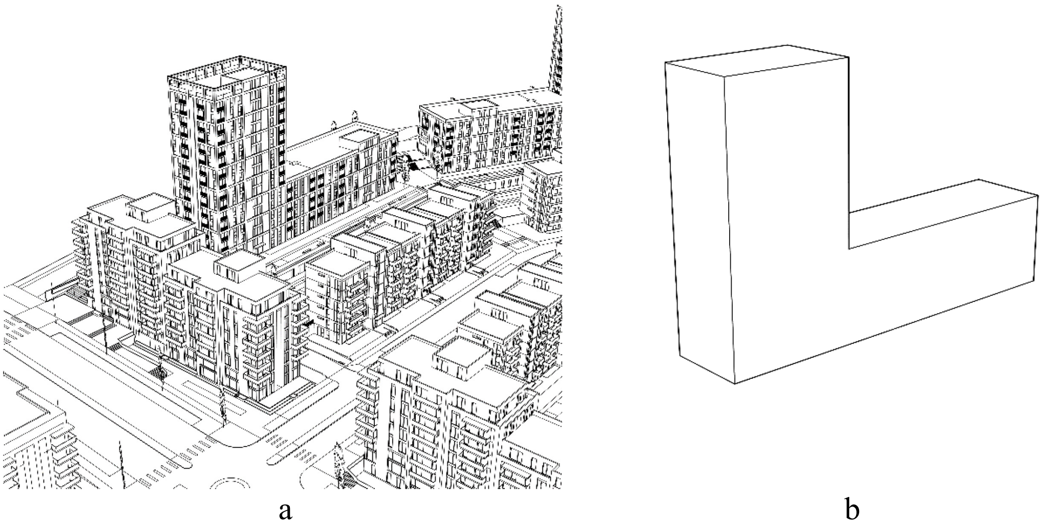


Figure 4.32. Horizontal velocity contours of 3d case at y = 0.1m

4.6.2. **Simulations of Simplified Base Buildings**

Buildings in the case study area were categorized in three distinctive types according to their geometric parameters. First building type is the tallest and longest structure in the layout and named as “component 1” in this study. Component 1 has width of 16 meters and has four times the height (Figure 4.33). Dimensions of the buildings have been converted to letters for clarification and to prevent possible calculation errors. This component was modeled with a x 4a x 4a (width x height x length) geometric ratio and meshed with more layers than validation study (Figure 4.34).

Second building type is midrise building located on the windward direction of the case area. This building has b x 2b x 2b (width x height x length) dimension ratio denoted with letter “b” corresponding to 15 meters. It was named component 2 for category type and separated from component 1 with extensive architectural details. This component is positioned closely to component 1 it in layout and joined with same type, forming a blocking geometry before the inner garden. Third building type is



a b

Figure 4.33. Component 1 a) model with details b) mass model

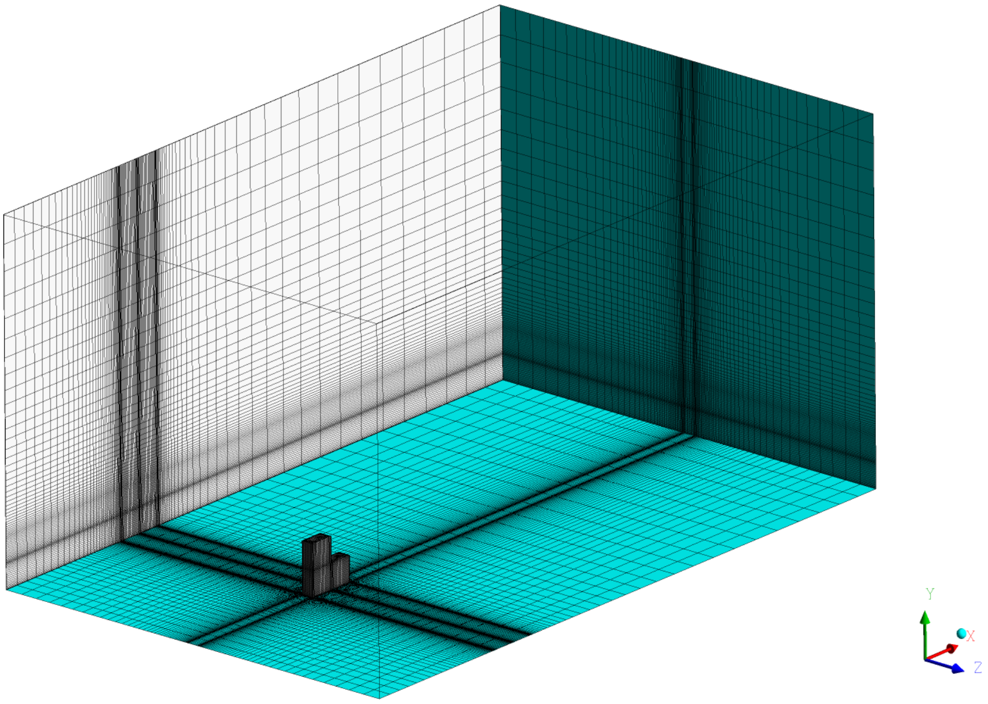


Figure 4.34. Mesh model of component 1

component 3 which is a low-rise type building and share same architectural details with component 2 (Figure 4.35). Dimensions of this type is denoted with letter "c" with c x

1.5c x 2c dimension ratio. but repeated two times, forming a lengthy block along the street side.

This building type had no commercial spaces in ground level so that pedestrians would not approach near the building. Programmatic functions are also limited for this component because of surrounding green patches. Components 2 and 3 are also modelled with more layers on ground level

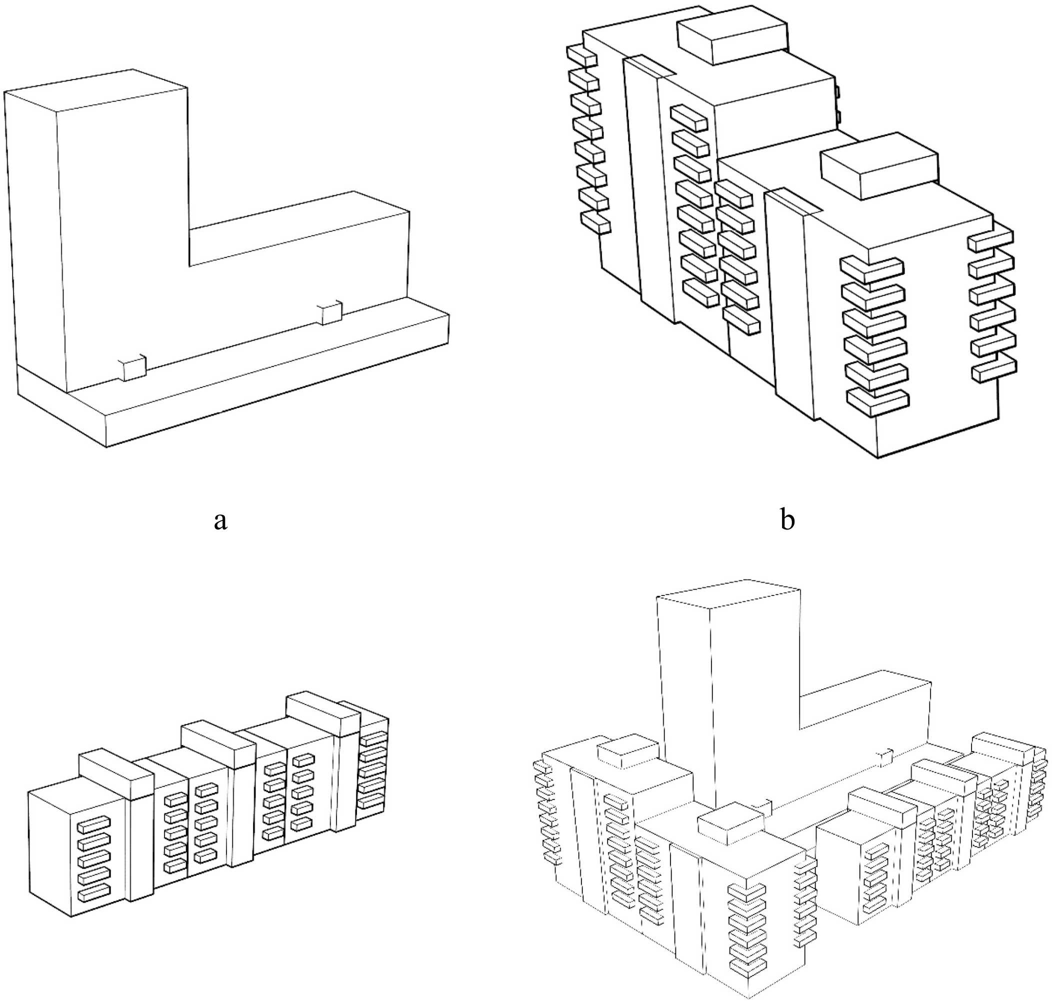
a

b

Figure 4.35. Component 2 (a), and component 3 (c) mass models

4.6.3. **Modeling of Building Features**

Architectural features on buildings facades, like balconies, passages, canopies and entrance spaces are required for functionality of building. These features are located accordingly in terms of architectural design concept, but they could significantly affect wind flow and disrupt the other potential natural ventilation benefits (Montazeri and Blocken 2013). Balconies and canopies have largest impact since they extend from the surface of the building (Figure 4.36). Other features like facade decoration or orientation addons are small details compared to their application area to surface area of the facade.



a b

c d

Figure 4.36. Building features are added to component 1 with entrance and commercial units (a) component 2 with balconies (b) component 3 with balconies (c)

Entrance spaces for building users or shop customers in ground level cannot be ignored also. They are less likely to extend from surface of the building, but their location can be important for safety of users and utilization of functions behind them.

Wind simulations of buildings in this case are maintained with addition of building facade features designed in conceptual phase of the project. Balconies are primarily important for the study because of their surface area and extension length from the facade. Small recesses, french style balcony design and other decoration facade elements like strips, tiles or profiles were not included. Component 1 had no balcony extension therefore its modeled as smooth surface. Components 2 and 3 had corner type and longitudinal balcony shapes and a definitive bump on the entrance side. Both components also had large mechanical rooms on roofs. These features were designed without investigating possible effects on pedestrian level wind environment or natural ventilation for courtyard area.

4.6.3.1. Simulations of Buildings with Features

Building types with architectural features were modelled explicitly to capture the effects imposed by their size and location. Balconies are added for component 1 and component 2 with smaller layers than near ground wall layers (Figure 4.37) (Figure 4.38). Vertical grid is also refined for capturing the corners of balconies. Domain is converted to substantially high detail grid and increased the simulation length twice more than simple model. Computational domain features were not changed since components without the architectural features provided baseline for quantifying difference with or without the included details. An empty domain with inlet profiles also simulated for three-dimensional velocity gradients for comparison purposes.

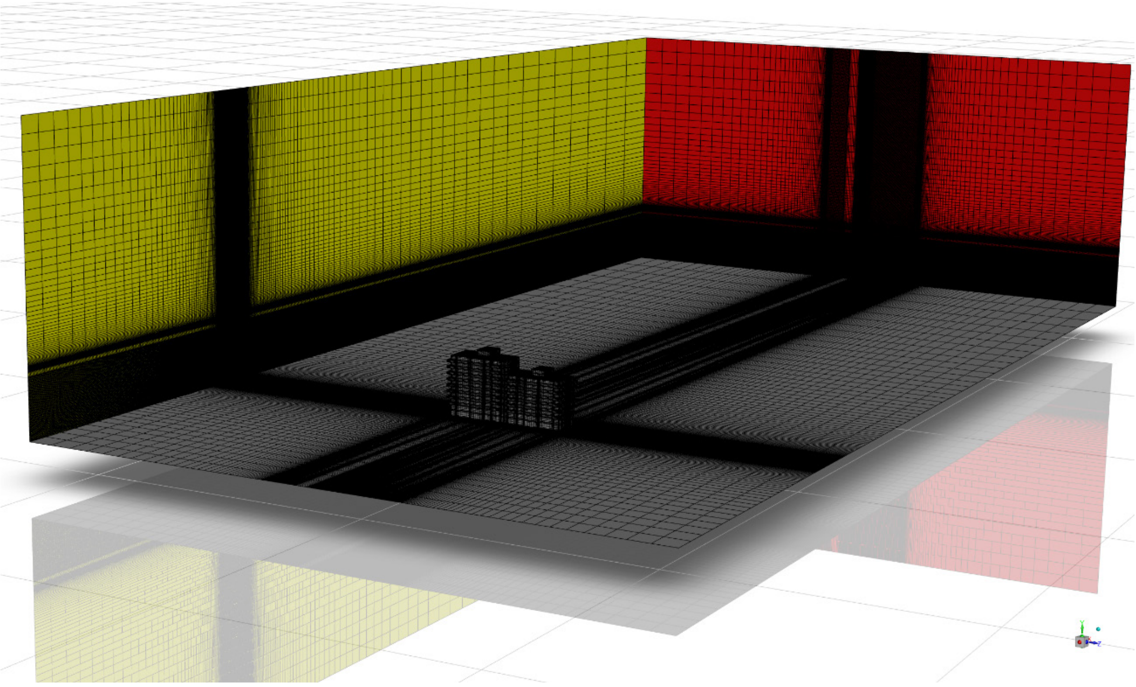


Figure 4.37. Buildings with features simulation grid and boundary size

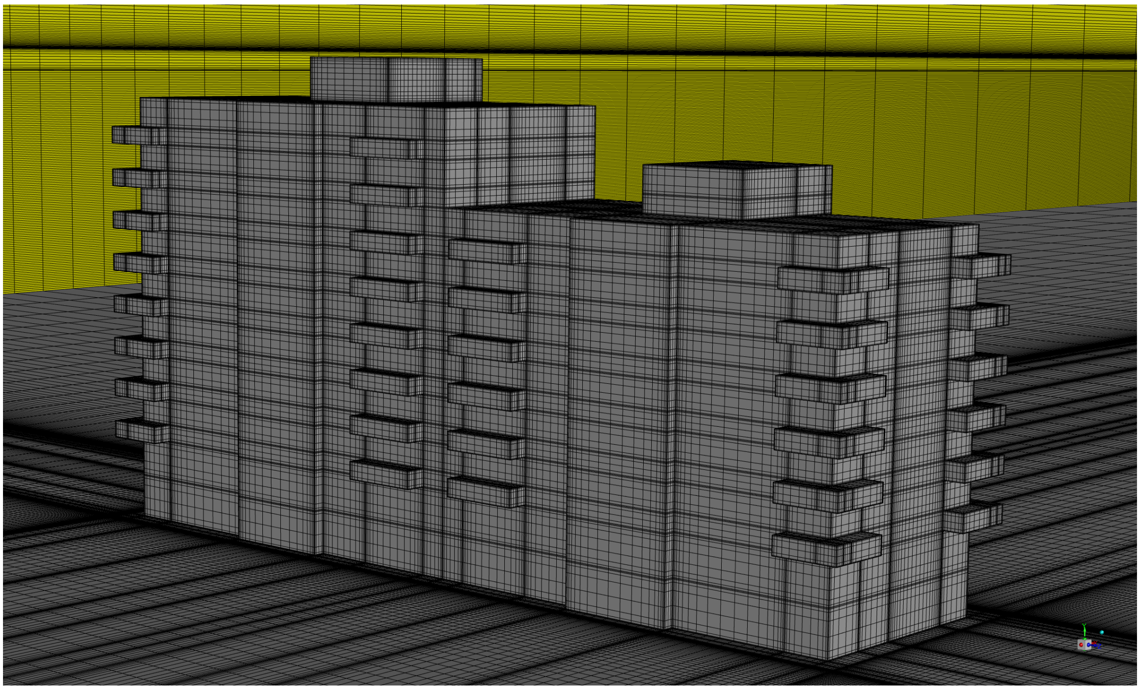


Figure 4.38. Balcony features on component 2 in detail

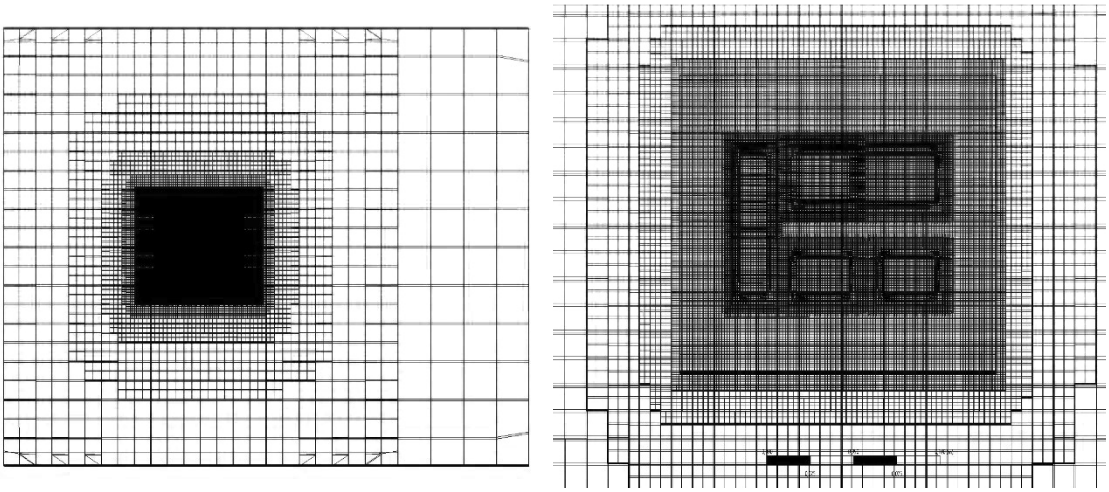
4.6.4. **Modeling of Building Layout**

Case area layout is unique type of combination formed by component buildings. They are located around an inner courtyard which secures more private green area with semi openings to surrounding streets. Limited access to this area is formed by specific locations of component buildings with two passages between buildings and one large opening to leeward direction. Meteorological data stated that this area is subject to winds from north direction which translates to windward direction from the component 2 side. It is protected from direct wind effects but investigating whole building layout is critical for making final assumptions for this area. Component to component interaction is also critical for this layout. Component 1 is located behind the component 2 which is critical considering the height of these buildings. Wind speeds tend to increase between two buildings when a twice higher building is situated in lower building layout. On the opposite side component 2 is higher than component 3 so that wake field would significantly change in passage area. Component 3 is also longitudinal aligned to layout that would increase wind speeds directionally.

4.6.4.1. Simulations of Building Layout

Building layout case is simulated with same boundary conditions and inlet profiles previously used in component simulations. Boundaries are increased due to inclusion of all components but according to blockage ratio of case study, domain walls are extended according to guidelines in y and z (height and width) directions. On the leeward side test section had enough clearance for longitudinal direction so enough space provided for satisfying 5h-15h lengths in CFD according to guidelines (Yoshie et al. 2007).

Grid size in layout study is significantly increased due to inclusion new areas between buildings. Two passages between the buildings are critical for assumptions so that they were reduced to near wall grid size to capture all possible wind scenarios (Figure 4.39). Grid sizes are scaled down close to boundary limits to lower the computation time.



a b

Figure 4.39. Grid sizing of building layout model

CHAPTER 5

RESULTS

CFD simulations of case study were completed with iterative methodology. Starting with simulations of simple building forms and validation to inclusion of architectural features. Simple building forms are compared with their influence of wind flow on pedestrian level. Locations are picked from proximity to buildings for comparing the buildings with architectural features. Finally building layout wind environment is evaluated with inclusion of all building components. Single building results are discussed separately from layout simulations since interaction between the buildings are included. Solution data from probe locations are compared within each case of simplified buildings and added building features. Wind profiles on specific horizontal and vertical locations are charted and supported with contour plots and streamline plots from Fluent simulation software.

5.1. Results of Simplified Buildings

First building, component 1, simulated as mass model and comparison with empty domain CFD simulation results are presented in this section. This building had stepped geometric shape behind the building and 4a height for a size width ratio. Contour plots show the vertical profile in Figure 5.1, represents negative wind speeds in front of the building, stepped roof and behind the building. They are caused by downwash effect encountering with approach flow in the front of building. On the first step roof negative *u* velocity area is larger due to increased wind speeds from vertical boundary layer merging with higher scalar corner effects than the pedestrian level. Horizontal contour plots show the difference between stepped roof level and pedestrian level wind gradients in Figure 5.2 and Figure 5.3. Reattachment length is larger on pedestrian level plot, where we find negative velocities towards the building, but also more velocity gradients on the sides of building due to higher amounts of wake effects behind the building. The back stepped geometry of the model has a larger area of negative speeds than validation case behind the building in total.

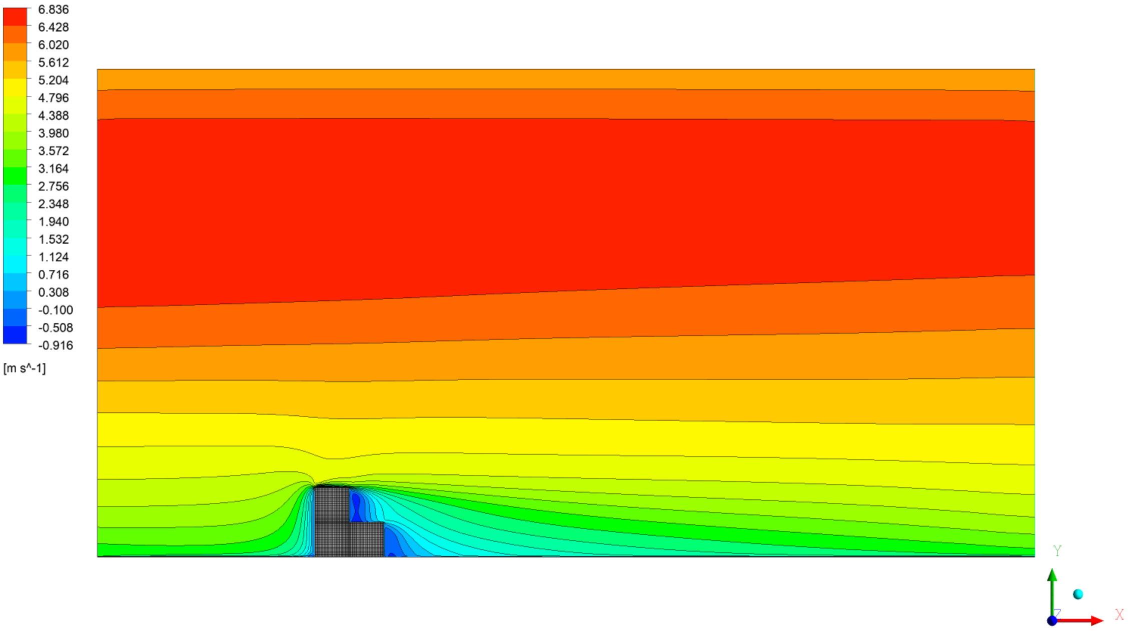


Figure 5.1. Vertical wind profile in center axis (z=0) of the building

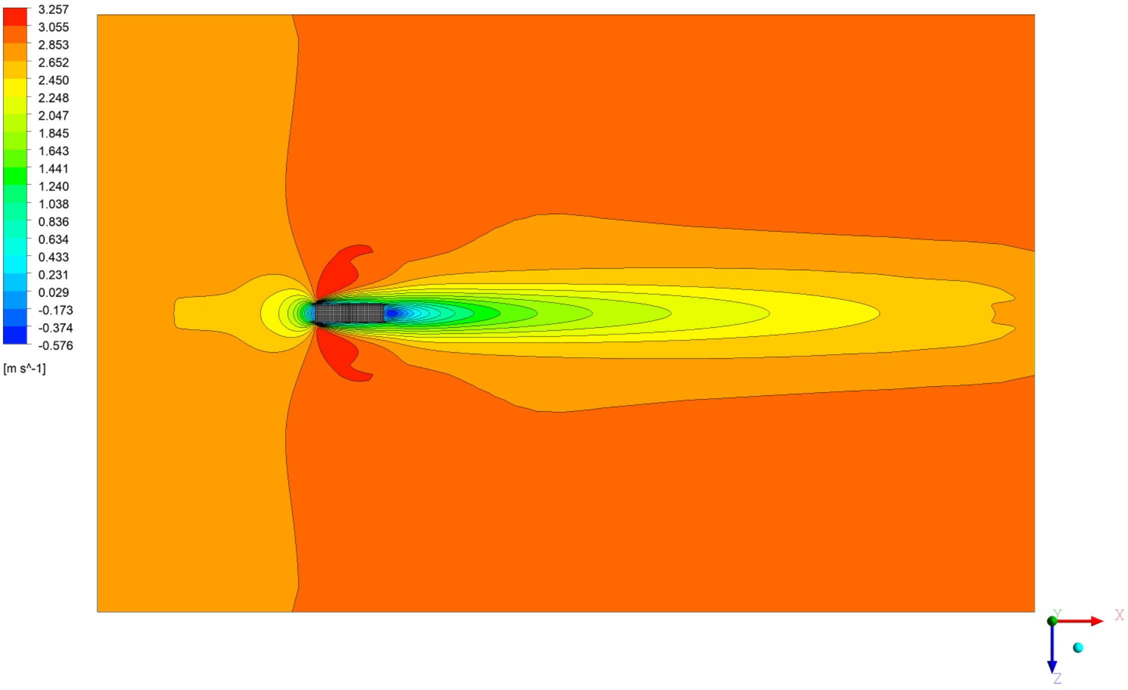


Figure 5.2. Horizontal wind profile on pedestrian level (y=1.75 m)

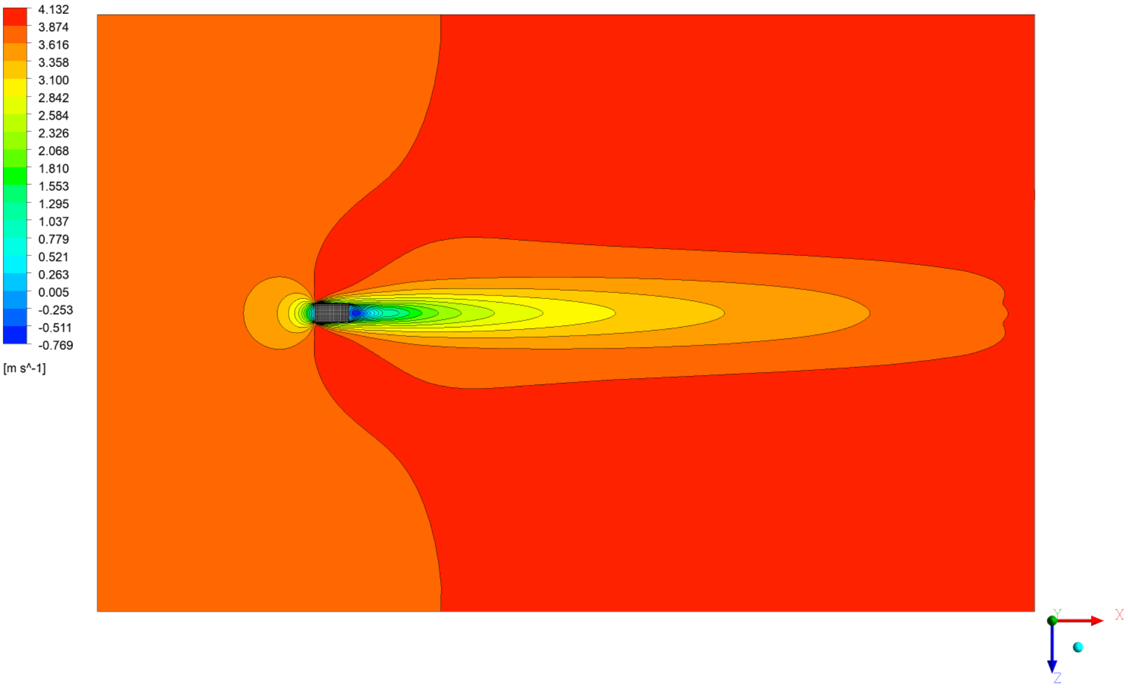
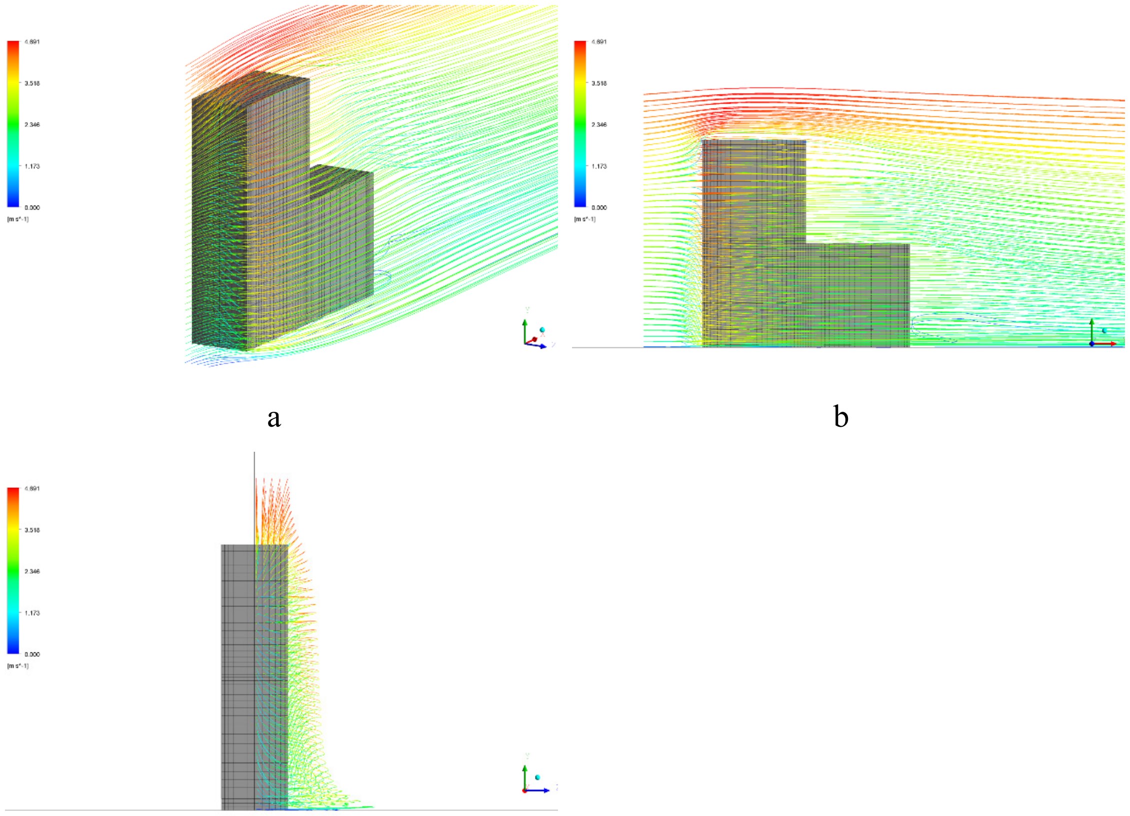


Figure 5.3. Horizontal wind profile on roof step behind the building (y=32m)

Streamline graphics show the stagnation zone where the maximum pressure is reached and wind speed is zeroed in more than 3a (z =48m) ratio higher on the front side of the building (Figure 5.4 a-d). Downwash effect is swelled along the way down to ground thus expanding the area disturbed by corner effects on the pedestrian level (Figure 5.4 c) This area is primarily the problematic area in case of tall buildings. Also, turbulence levels are higher in these levels of atmospheric boundary layer addressing the issues on corners and behind the building. In Figure 5.4 b, lateral view of the streamlines shows eddies behind the building causing negative velocity gradients. Streamlines show only one half of the building to provide easy to follow results rather than crowded view where building velocity field is symmetrical in center axis of the building.



a b

c

Figure 5.4. Wind velocity streamlines around the building a-c) full streamlines from different views

On the pedestrian level wind environment wind speeds are measured along the specific locations around the building. These wind speeds compared to building surface speeds where it reaches 0 on front facade of the building and empty tunnel measurements to investigate influence of tall building. Pedestrian activities divided into 5 meters and 2 meters away from the building. 2 meters distance is used for walking while looking at shop windows, sitting in front of service area of shop, entering/exiting the building. It indicates primary use of building. 5 meters distance is for passing by the building with no activity related to building or interaction proposed by building. These locations are specified in Figure 5.5. They are extended from corners to capture influence of wind flow characteristics but acquire the same height data from results. Flow field charts in front of the building and behind the building are symmetrical and extend to 50 meters away from the building.

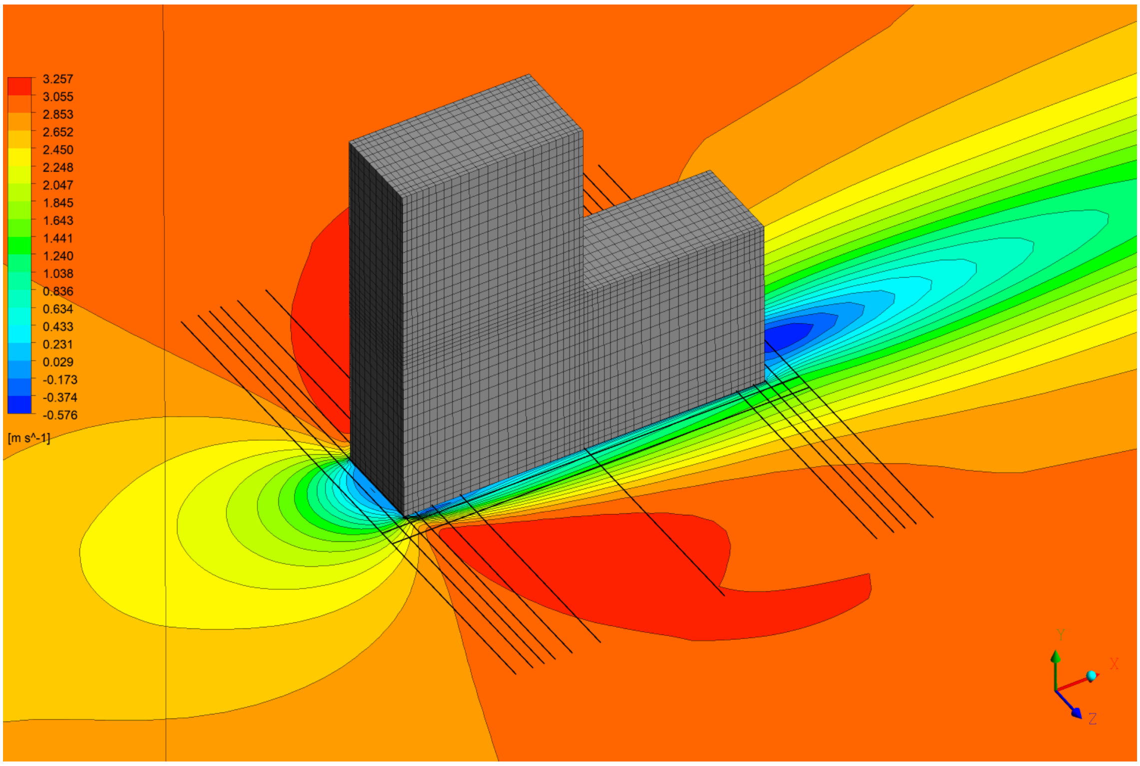
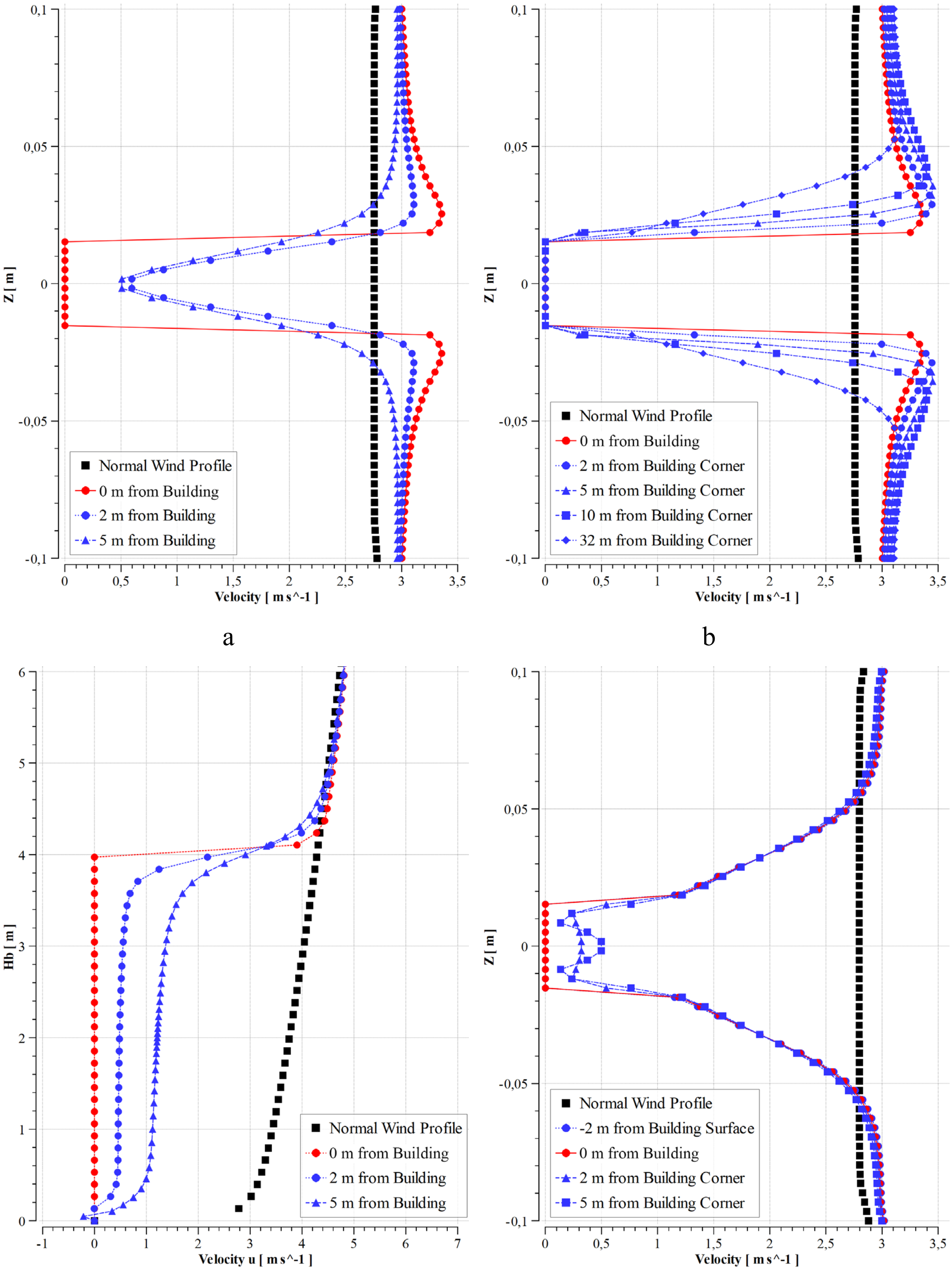


Figure 5.5. Profile locations taken from the model

Investigating the first chart from locations in front of the building from Figure 5.6 (a) we expect to observe negative values of velocity in the central axis of the facade. Data from empty tunnel presented in chart shows a linear profile and data from surface show 0. As move to corner of the building velocity increases suddenly by the merging of downwash and corner effects. Further moving away from surface for 2 meters to 5 meters, velocities smooth down for transition but still contains a significant jump from values. Vertical profile in Figure 5.6 (c) shows the scale of change from normal profile to building specific locations. In Figure 5.6 (b) data points are showing the locations distance from front corner of the building where 32 meters are equal the center of the longitudinal surface. This part of the building is different than front facade as the wind speeds increases quickly and densely layered. This is the diminishing corner effect where vorticity decreases, and smoother transition is observed. Figure 5.6 (d) shows the profiles behind the building. In this part departed wind profiles from corner effect creates a negative pressure and gradually smoothens. We can understand from overlapping profiles that turbulence is lower on the sides of behind the building Negative velocity zone is still observed from graph in the center part with differences.



a

b

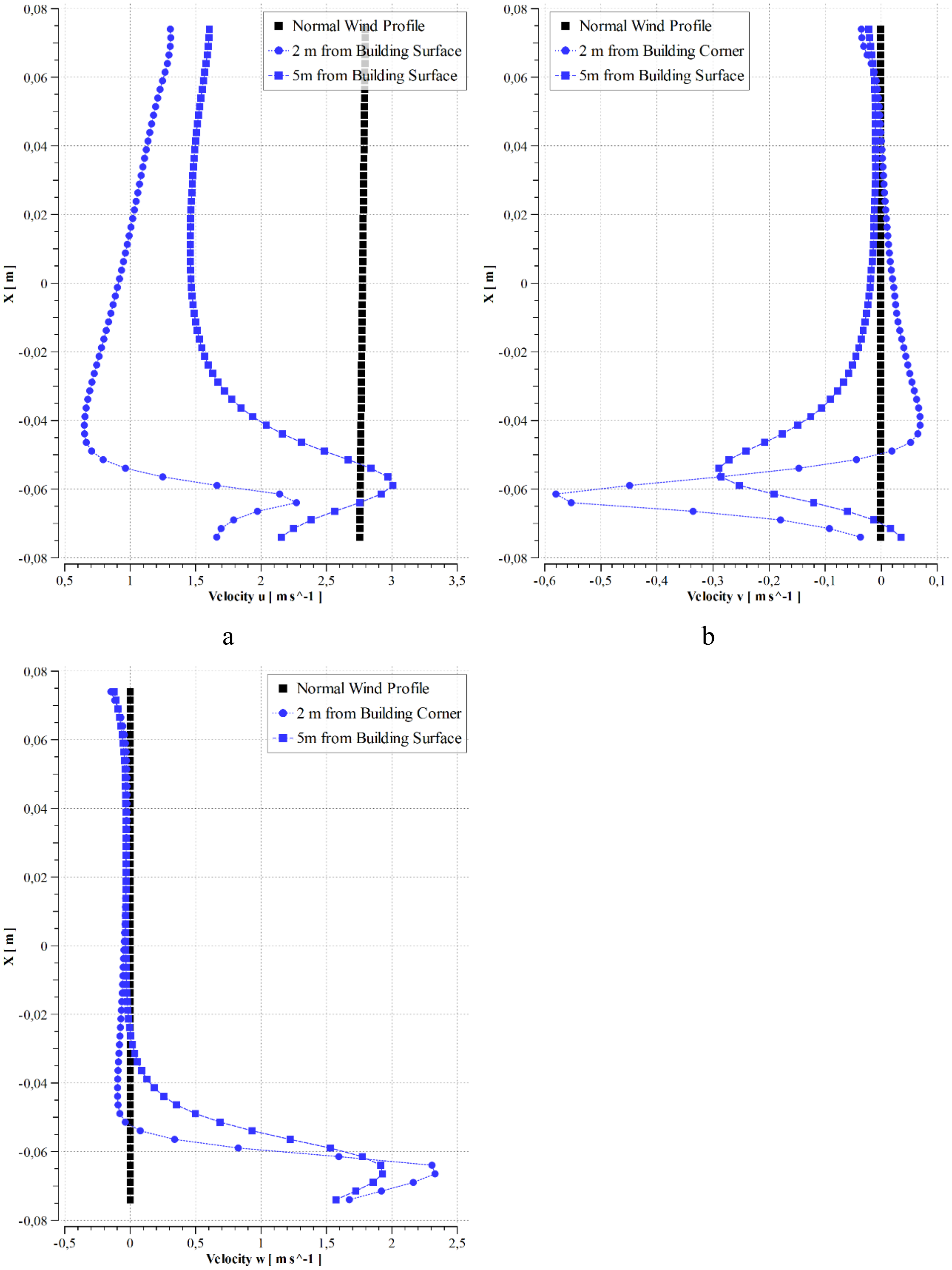
c

d

Figure 5.6. Wind profiles in front of the building (a), various distances from corner (b), vertical profile in front of the building (c) and behind the building (d)

Further away from central part of building from behind was not observed due to mentions in turbulence profile discrepancies mentioned in validation study.

Corner effects are dominant factors of pedestrian level wind flow. Longitudinal path along 2 meters and 5 meters away from building facade analysis charts demonstrates the changes in *u,v,w,* gradients in velocity while passing the corner of the building. Charts illustrate starting from 5 meters in front of the building and moving on straight path 2 meters and 5 meters away from building facade. Graphs show identical disruption point of all means of velocity on -0.064 x direction where it is aligned with corner of the building (Figure 5.7). There are rapid bounces of data from positive to negative in both *u* and *w* charts resulted from sudden change in *v* from downwash effects. Velocity gradient of *v* smoothens to 0 approximately 10 meters further from passing the center of the facade Velocity gradient of *w* conforms quicker 20 meters before the center of facade. Corner effects on *u* gradient dissipates as the wind gains speed over distance passing parallel to surface. It can be observed that velocity fluctuations disappear by moving further away from the facade surface.



a

b

c

Figure 5.7. Velocity gradients of u,v,w parallel to the longitudinal facade away from 2 and 5 meters distances

5.2. Impact of Geometric Features of Buildings

Simplified building models are fitted with their geometric features and simulated again for investigating further in detail. Main geometric feature of the components was the balconies. Balconies are added to corners in component 2 and component 3 with respect to architectural function inside the corresponding area. Contour plots and streamline graphs are presented in this section. Component 2 was a midrise category building with less significant downwash effect on windward facing front side of the building. Balconies diverted the natural flow of downward velocity gradients and produced smaller eddies between floor levels (Figure 5.8). Flow is separated quicker than mass model without balconies and carried the negative velocity *u* gradients further away from building. On the ground level, velocity profile tends to differentiate like smooth wall, but distance was not enough for creating fully developed downwash effect.

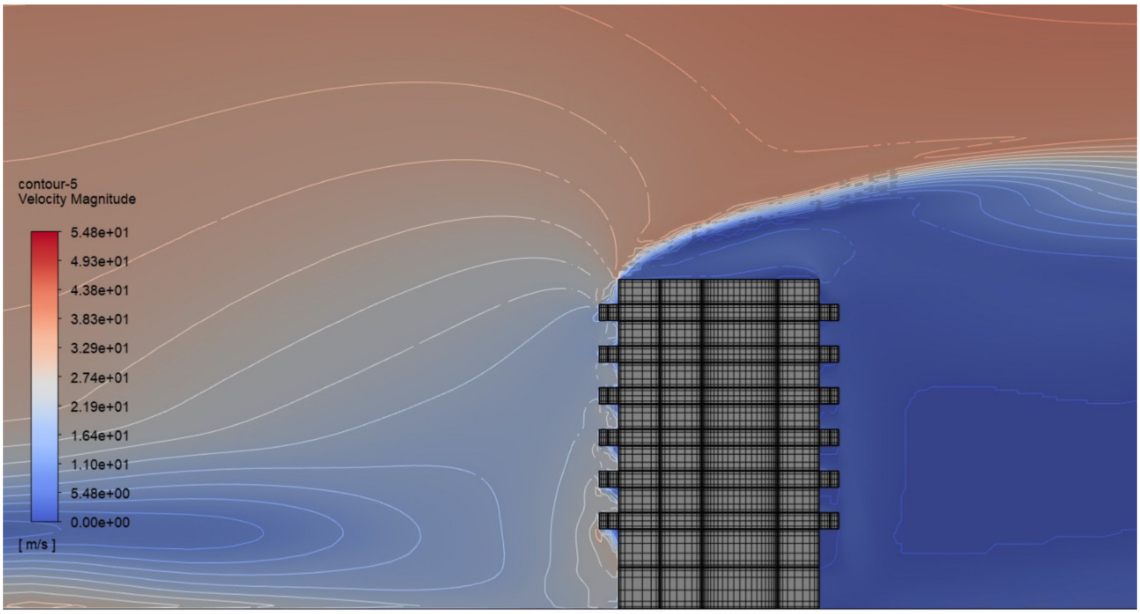
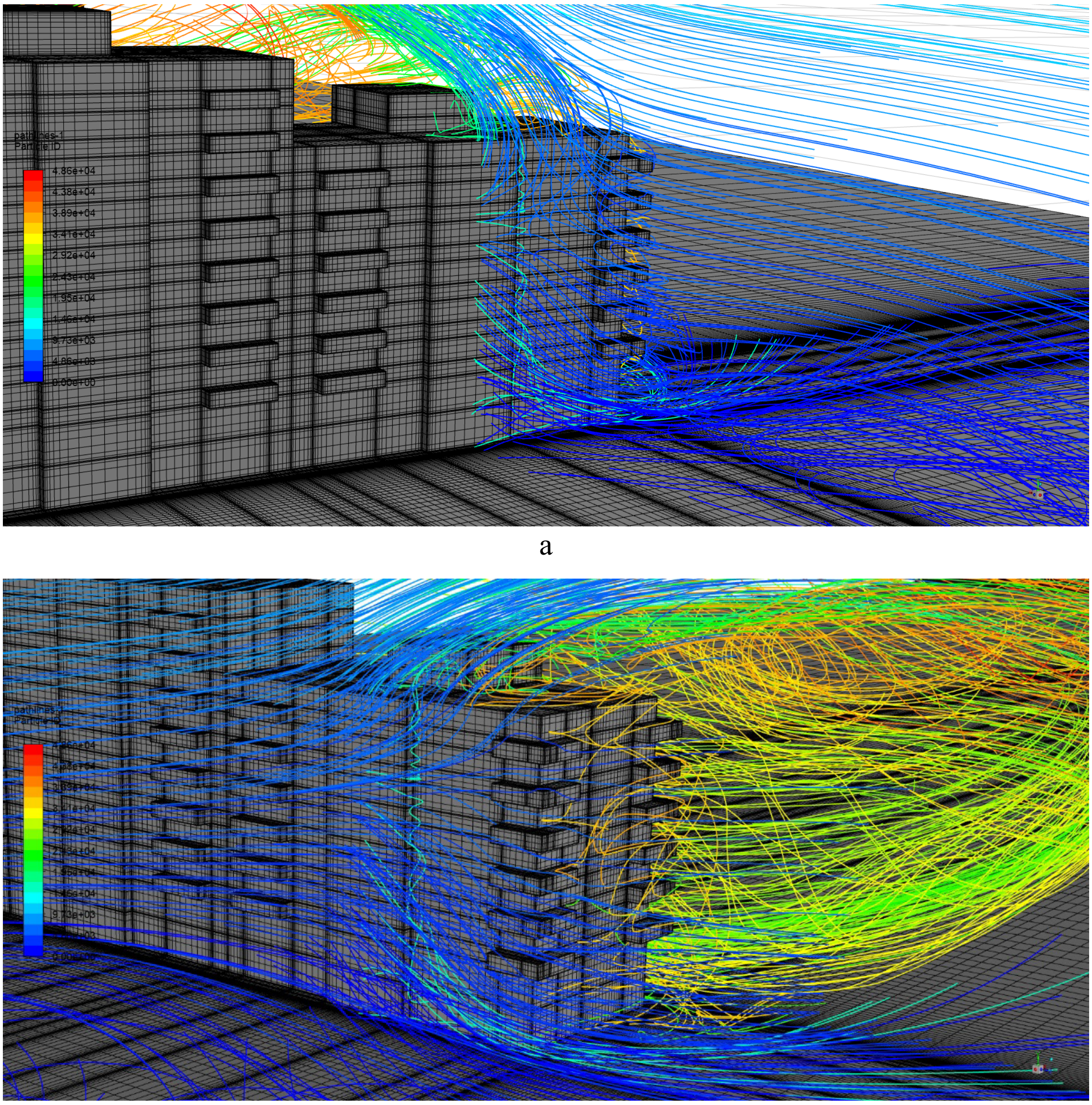


Figure 5.8. Vertical velocity contour plot of balcony added component 2

On the corners of the component 2, balconies created venturi like channel effects in upper levels, where the local eddies gained velocity within confined spaces between levels (Figure 5.9). Velocity streamlines from the symmetry plane of the component 2 divide into two directions from stagnation zone like previously studied models, but after a short travel to building corner, balconies guide streamwise particles to between levels. Downwash effects and corner effects are still valid for the component because of high ground level. Degenerated corner effects produced turbulent eddies with merged streamlines passing through spaces between balconies (Figure 5.10).



a

b

Figure 5.9. Velocity streamlines of corner effect on component 2 isometric view from front left (a) and front right (b)

Negative pressure area which is normally produced behind the building was spread wider along the back surface of the component. Length of reattachment part behind the building is enlarged accordingly but created lower eddies since balconies are added to whole building symmetrically.

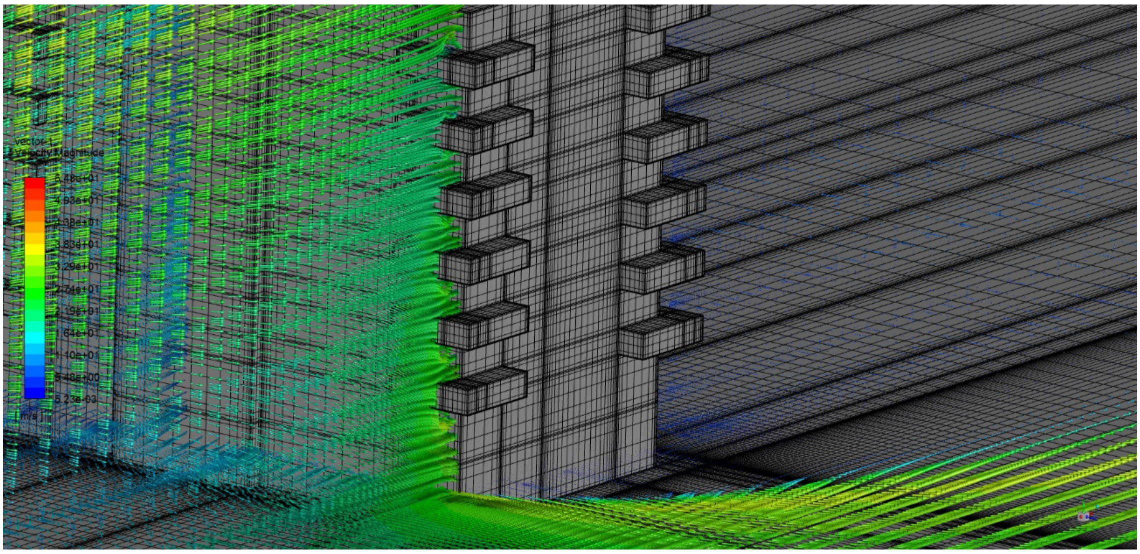


Figure 5.10. Velocity streamlines perpendicular to building facade at the corner

5.3. Results of Building Layout

Building layout simulation was conducted with inclusion of building components positioned in their specific locations. Component 1 and component 2 are closely positioned and expected to be influenced by each other. Component 1 is higher than the component 2 and the gap between them is under influence of two velocity profiles. Seperation flow from the component 2 roof required a longer distance from the building to reattach to ground but component 1 is located very close in leeward direction. Seperated flow component 2 blocked by component 1 and merged with downwash effects. Downwash flow is partially seperated in the corners of component 1 but on the axial location of front facade of the building downwash flow is significantly increased and directed to component 2 (Figure 5.11). This situation creates vorticity between two buildings and amplifying both velocity gradients on facade surfaces (Figure 5.12).

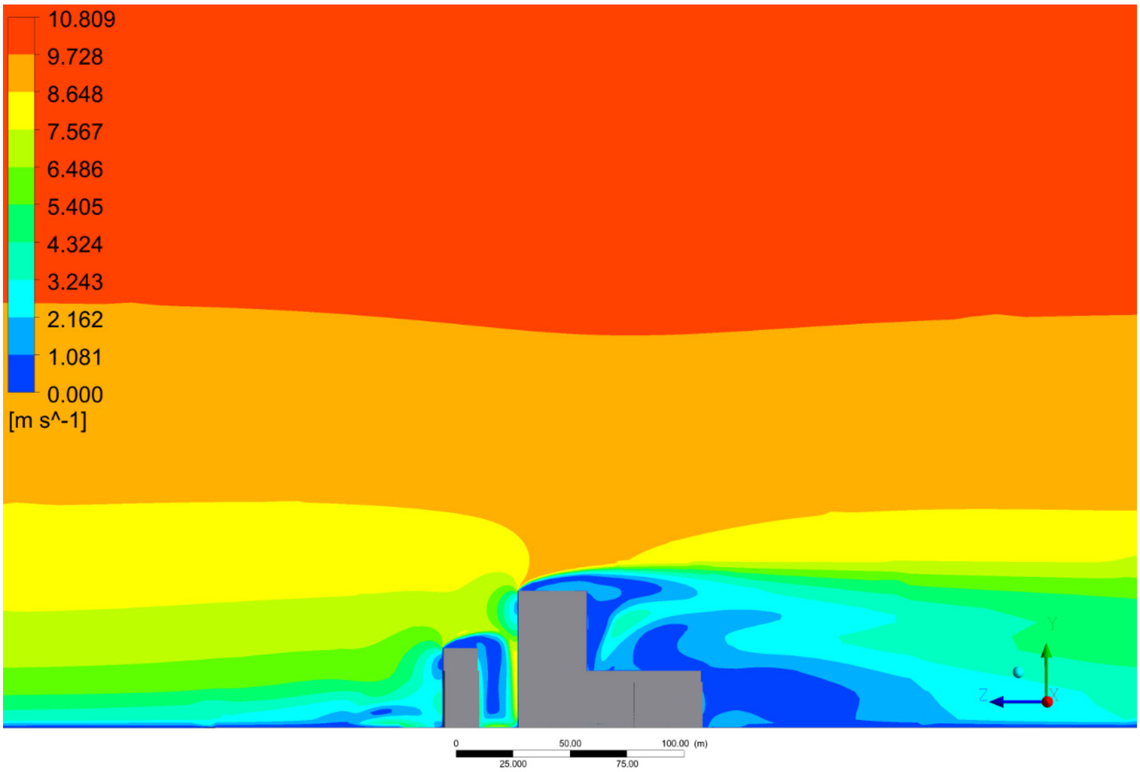


Figure 5.11. Velocity contour plots of building layout model

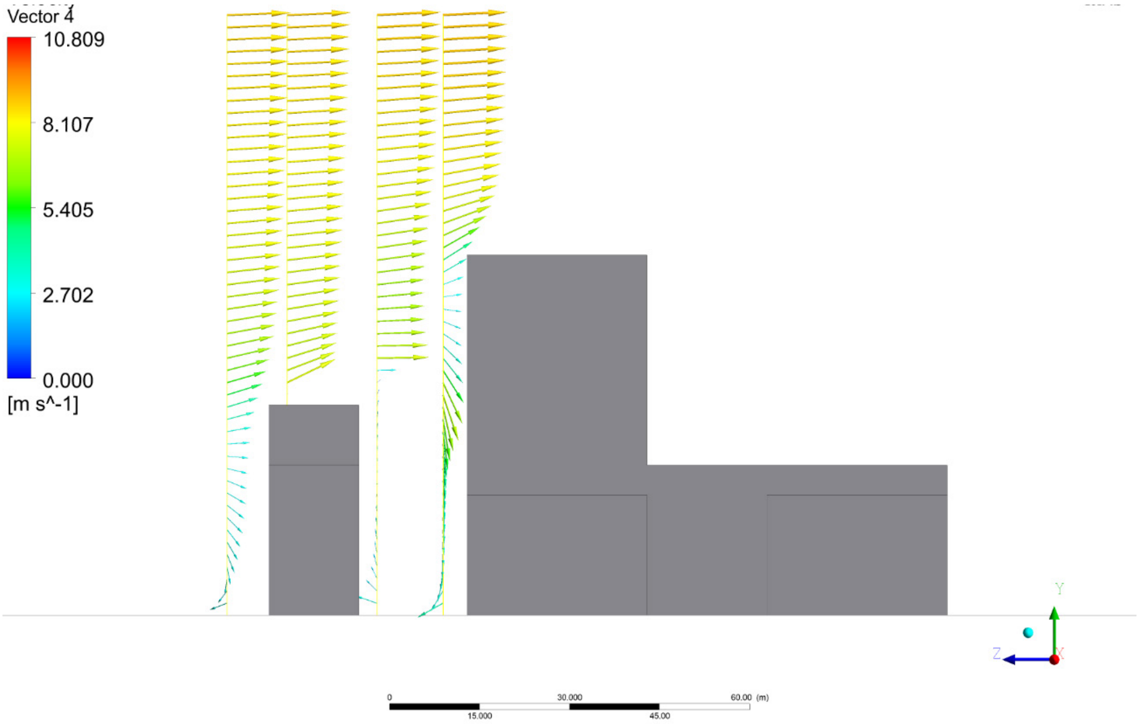


Figure 5.12. Velocity vectors on approach flow to components

5.4. Pedestrian Level Wind Speeds and Categories

Simulations results providing wind speeds and direction vectors are presented in previous sections are valid for only single type of wind flow profile which was input for boundary condition. Normally wind speeds and duration fluctuate certain levels in atmospheric boundary layer. Fluctuations are increased when there is high turbulence as well as effected from terrain (Deacon 1955). Universal wind comfort and safety criteria creation has been an extremely difficult task to account all the variables (Ratcliff and Peterka 1990). Earlier studies without wind tunnel experiments were based solely on observations and hard to quantify (Murakami et al. 1980). Compared from previous works, Hunt et al. experiments included a methodology to investigate different forms of wind (Hunt, Poulton, and Mumford 1976). This methodology analogizes wind flow type to corresponding criterion (Table 5.1).

Table 5.1 Pedestrian wind criterions by Hunt et al.

Wind flow type	Condition
Steady uniform wind	
$u < 6$ m/s	For comfort and little effect on performance
$u <$ 13-15 m/s	For ease of walking
$u <$ 20-30 m/s	For safety and walking
Non-uniform winds	(If u varies by %70 over a distance less than 2 meters)
$u < 9$ m/s	To avoid momentary loss of balance and to be able to walk straight
$u <$ 13-20 m/s	For safety (requires lower values for elderly people)
Gusty winds	
$u_s < 6$ m/s	Comfortable and little effect on performance
$u_s < 9$ m/s	Most performance unaffected
$u_s < 15$ m/s	Control of walking
$u_s < 20$ m/s	Safety of walking

Comfort and criterions were divided into three flow types, steady and uniform wind conditions, non-uniform winds and gusty winds. Non-uniforms winds could be witnessed on locations around hard corners of tall structures, where increased wind speeds joined with ground level vortices and direct to lower pressure area, thus turning corners. Walking away from the corner of the building we could observe sudden changes in wind speed. These areas could be dangerous if wind speeds increase due to gustiness. Gusty wind flow type is calculated with Eqn. 2.3 applied with mean wind speed and turbulence intensity. It is possible convert velocity contour charts to examine building components and layout to support pedestrian level criterions of given in literature. Previous chart of velocity profile in front of the building area was converted to satisfy criteria ranges with fewer contours in Figure 5.13 and close-up view presented in Figure 5. 14..

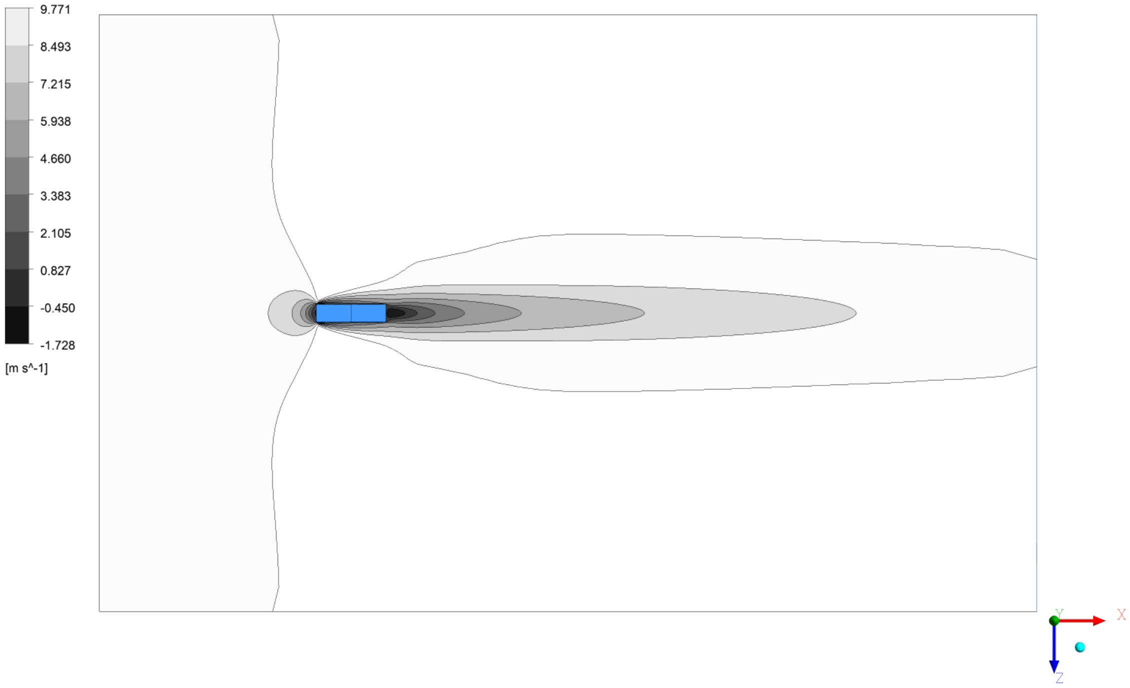


Figure 5.13. New velocity contour plot with matching comfort criteria speeds applied

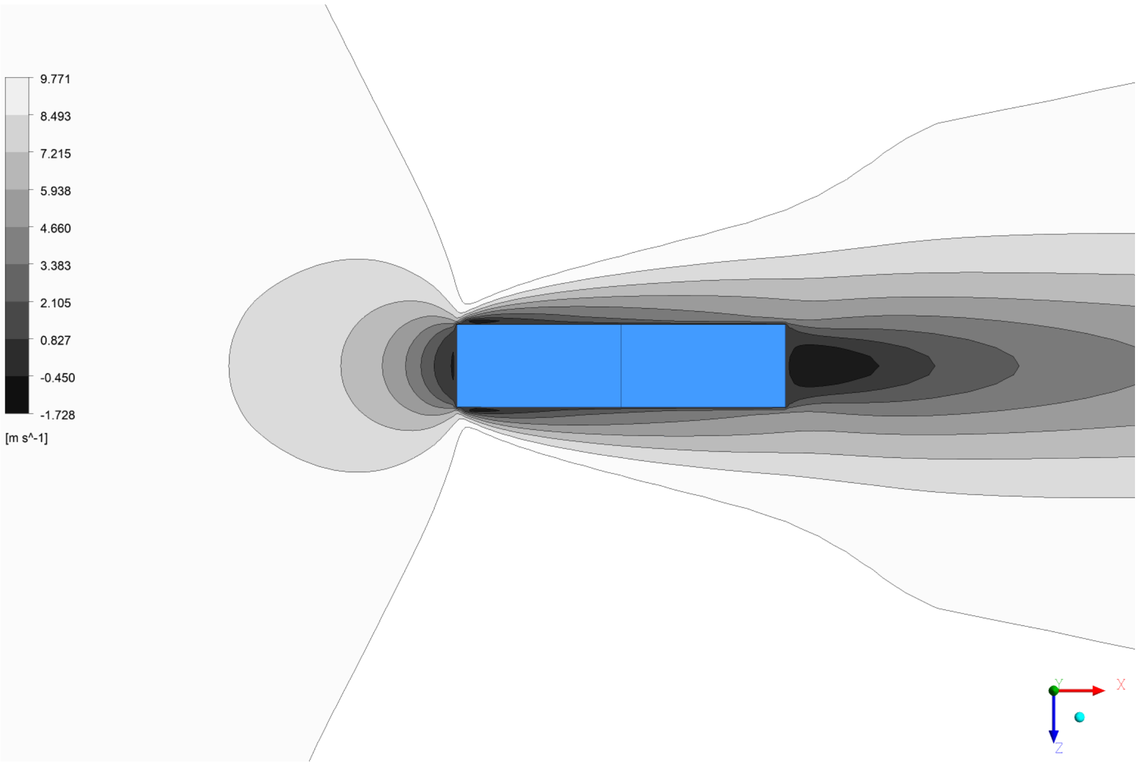


Figure 5.14. Close-up view of new velocity contour plot

Study area near the high-rise building presents a transitional zone from comfortable to disturbed levels in vicinity of windward direction and even closer to corners of the building (Figure 5.15). This zone expands from more than 10 meters from windward direction, but range gets close to less than 2 meters in corners where flow type category changes to non-uniform. Hunt et al. (1976). Non uniform flow type categorizes wind speeds lower than 9 m/s for convenience of pedestrian walking activity. High rise building in the study area presents 8.4 m/s to 9.7 m/s wind speed in this vicinity thus special attention should be given in this location. Wind speeds lower than 6 m/s does not present significant effect on walking activity on steady wind flow categories which also is not witnessed near walking along the longitudinal sides and leeward side of the building. Although zone transition is parallel to the facade of the building, enabling pedestrians to safely walk in front of the storefronts, some disturbance could be felt while walking away from the building.

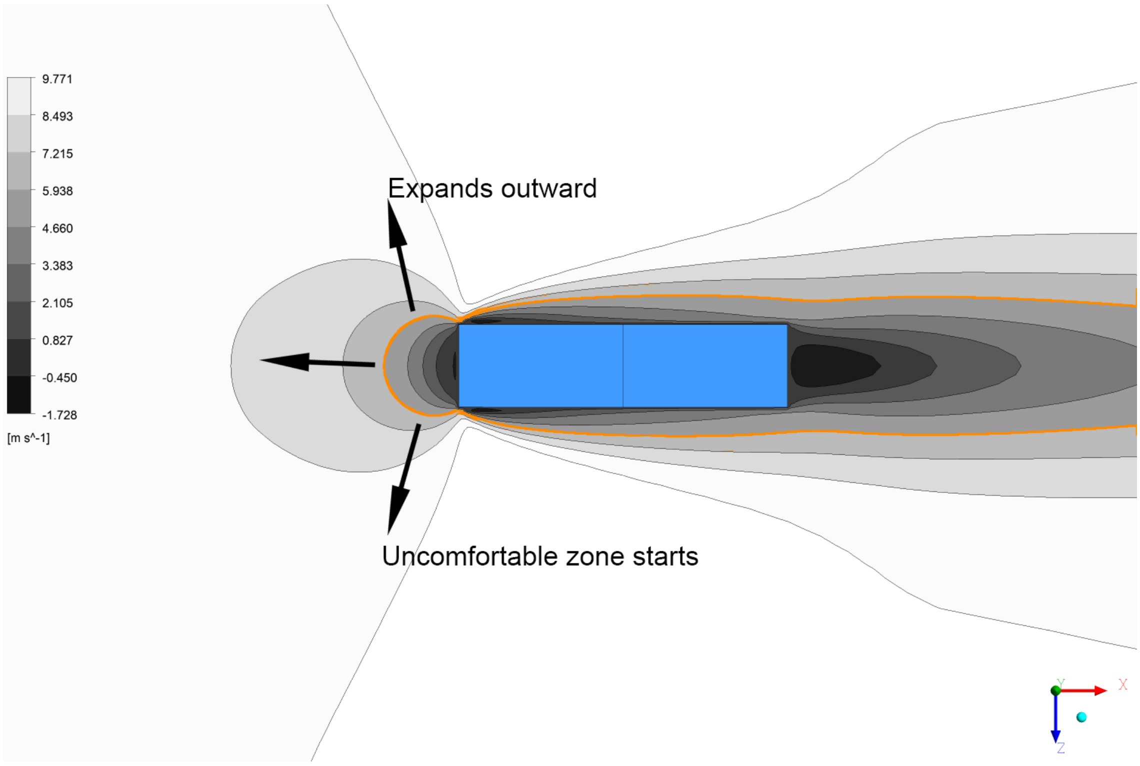


Figure 5.15. Comfort limits localized for Hunt et al. criteria

Comparative studies showed that NEN 1800 standard (Table 2.4) is frequently used in pedestrian level wind environment research (Blocken 2012, Blocken 2015). This standard categorizes wind velocities of 5 m/s and 15 m/s with their occurrences and grades with three pedestrian activities sitting, strolling and traversing. Wind comfort category divided into five grades and wind danger divided into two grades.

Table 2.4. Dutch NEN 8100 standards

Wind Comfort			Activity Descriptions		
Grade	Mean Wind Velocity	Threshold Probability Exceedance	Sitting	Strolling	Traversing
A	5 m/s	2.5%	Good	Good	Good
B		5%	Moderate	Good	Good
C		10%	Poor	Moderate	Good
D		20%	Poor	Poor	Moderate
E		>20%	Poor	Poor	Poor
Wind Danger					
Limited Risk	15 m/s	0.05% - 0.3%			
Dangerous		> 0.3%			

Wind environment around the high rise building in the study area did not present dangerous conditions where wind speeds exceed 13 m/s to 15 m/s for design proposal (Figure 5.16). Surrounding area of the case study was composed of low rise and mid-rise buildings but development plans proposed taller buildings with wider streets that would enable channeling effects on streetwise directions. Prevailing wind measured from airport is around 6 m/s and blows more than %50 of time. It is understandable that open area of the airport does not have same boundary layer with dense city centers thus would not be suitable to link two different environments.

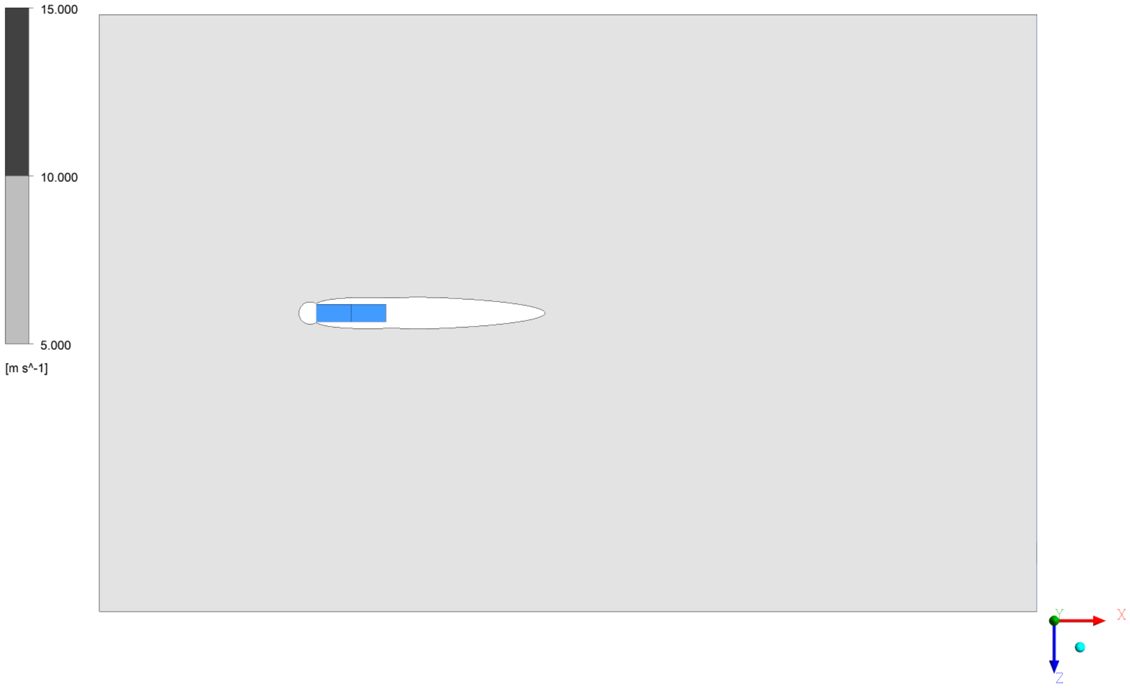


Figure 5.16. Outline of cautionary zone for pedestrian activities

Design proposal included a possible scenario of building high rise units with higher alternatives. In the early stages of design, it is convenient to investigate alternatives and have insight about final conditions before irreversible changes are made. Design alternative of "a x 4a x 4a" (width x height x length) geometric ratio building changed to "a x 5a x 4a" dimensions. Output of the simulations are presented with velocity contour plot accordingly in Figure 5.17 and Figure 5.18. Wind contours are fairly close to design proposal, but wind velocities are higher due to geometric effect of the building. Higher design alternative stagnation zone higher than the proposed building so that wind speeds built up more until reaching the ground level.

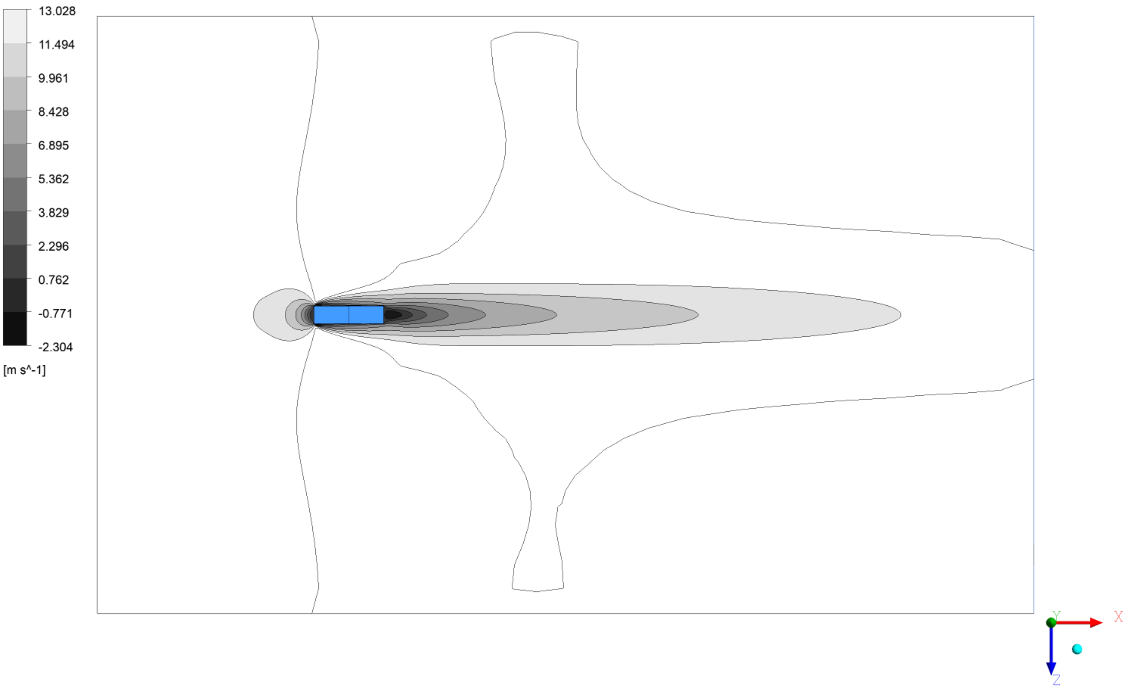


Figure 5.17. Velocity contour plot for higher building design alternative

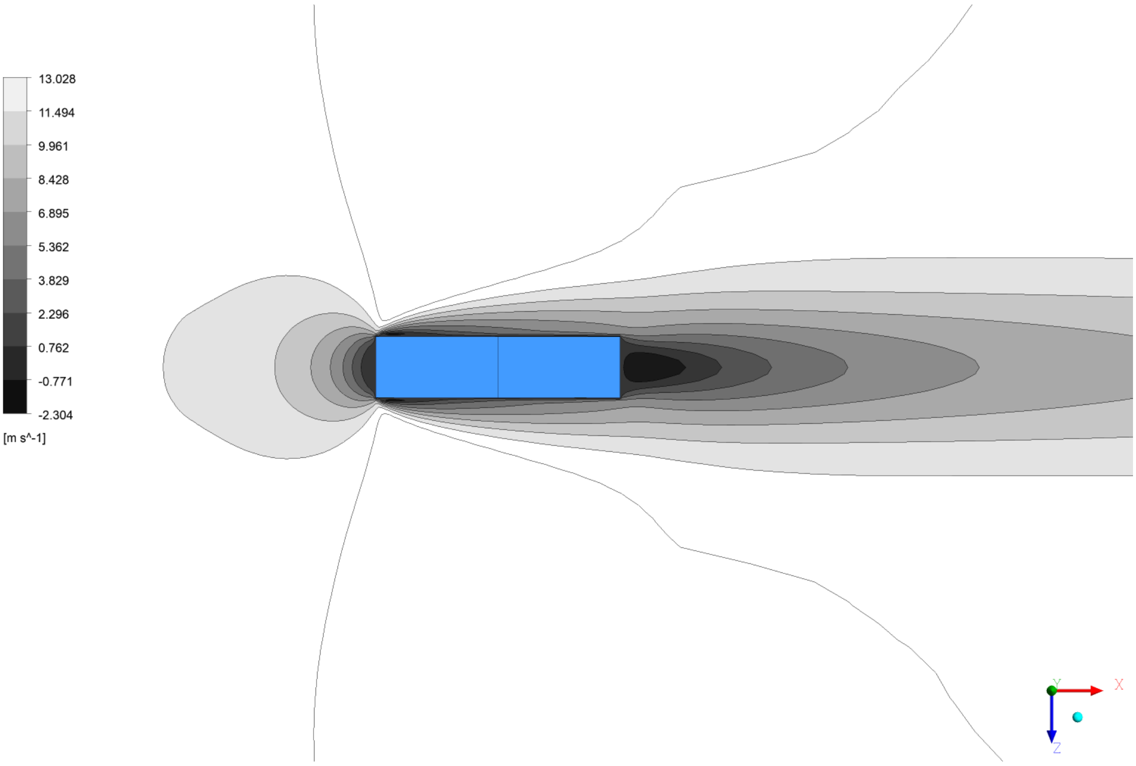


Figure 5.18. Close-up view of velocity contour plot of higher building alternative

Design alternative of the proposal presents a cautionary zone in vicinity of the building. Previously stated transition to uncomfortable zone is quite close to building (Figure 5.19) and corners are again, critical locations that can affect pedestrians while traversing. Dangerous conditions affecting the pedestrians are high wind speeds that could create force to knock a walking person, especially elderly and children. Lateral force can also cause falling from bike or other means of transport that require balancing which could be exerted by wind while traversing the location. Handling loads while passing these areas are also dangerous and could cause injuries.

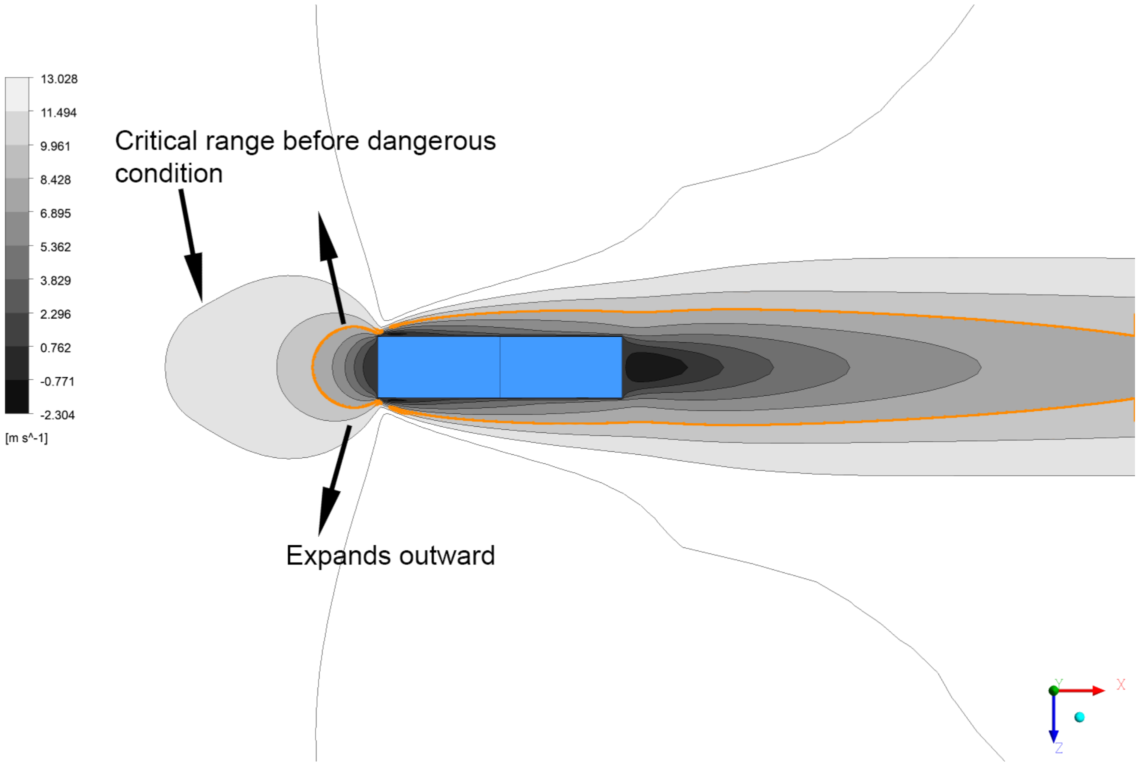


Figure 5.19. Comfort and safety limits localized for Hunt et al. criteria

Wind speeds that are higher than local climate normal are possible and could be inevitable due to climate change. Dangerous levels of wind speeds are initiated from 13m/s to 15m/s speeds and commonly used for defining problem areas Design alternative presented a cautionary zone around the building according to Dutch NEN 8100 standards (Figure 5.20). Pedestrians around this zone could be seriously injured if necessary, precautions are not provided.

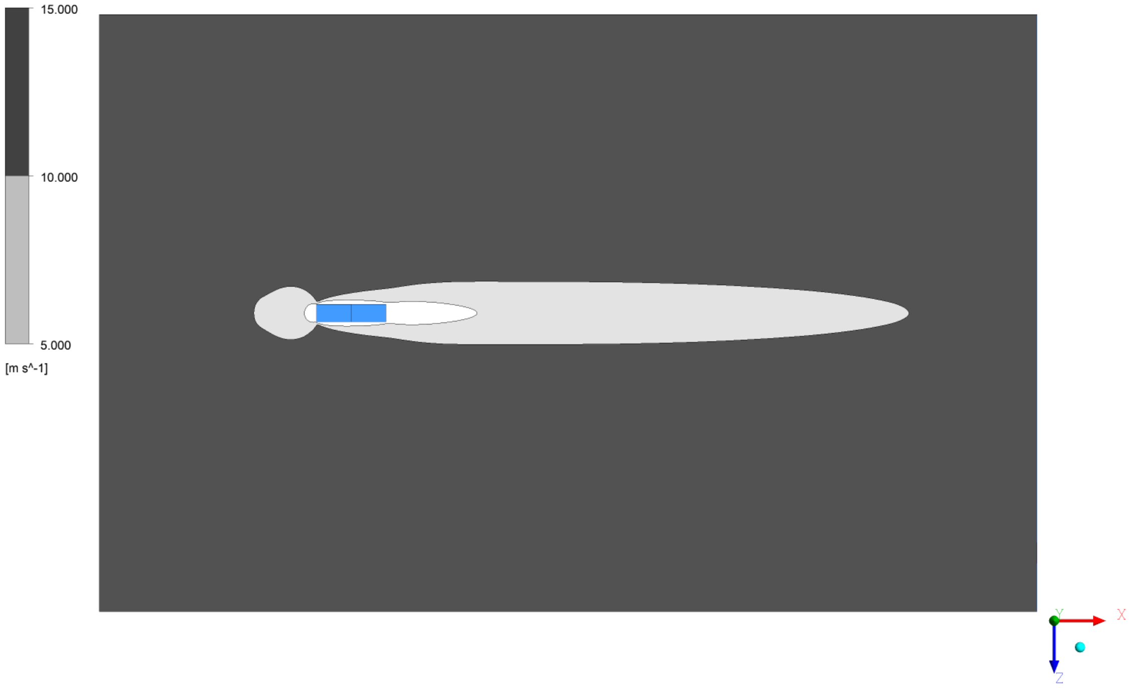


Figure 5.20. Outline of cautionary zone of higher building alternative for pedestrian activities

Windward side of the component 1 building has critical importance in terms of flow field in pedestrian level. Corner effects combining with downwash vortices create highly turbulent area with possibility of effecting activities according to Hunt et al. wind comfort criterias. Moving further away from the building facade from 2 meters to 5 meters, conditions are worsened at the corners of the building. This type of wind profile has a large area of influence in terms of high wind velocities. Although other locations investigated in previously did not show this type of excessive turbulence conditions, points where sudden change of velocity vectors could deliver problems if wind speeds are increased.

CHAPTER 6

DISCUSSIONS AND CONCLUSION

In this study, mechanical effects of pedestrian level wind environment in an urban regeneration area were investigated during early design phase of project. CFD simulations of new buildings and new proposed layout for the case area modeled in mass forms and building geometry effects are compared with detailed models with architectural details. Results are laid out as wind velocity profiles and possible wind comfort categories corresponding to wind profiles investigated for assessment.

6.1. Effects of Building Geometries on Areas Around Buildings

Building geometries indicated by size three-dimensional size parameters and size ratios are distinctive properties in case of environmental impact of redevelopment projects. Neighborhood level projects which are pursuing wellbeing of the community should be evaluated with local climate conditions. General approach for evaluation generally consists of a brief report evaluating the architecture of buildings and site orientation with a narrow perspective. Architectural qualities of buildings should be investigated by its interaction around closely.

Architectural forms of buildings comprised of three-dimensional width, height and length measurements. Every building has a unique form that could be described by these dimensions. In neighborhood layouts, where multiple buildings come together and oriented, it is beneficial to use a representative letter to identify a coefficient. Building dimensions can be defined with coefficient to represent same category buildings. Buildings influence on pedestrian level wind characteristics could be defined by its coefficient and scalar magnitude of it. In case study of redevelopment area in Izmir, multiple buildings are investigated according to their categories. Three distinctive building types designated for forming a layout with 4 x 4 x 1 ratio high rise building, 2 x 2 x 1 midrise building and 2 x 1.5 x 1 low rise buildings.

In single building and layout of buildings cases, high rise building effected the wind velocities in ground level significantly. Downwash and corner effects in front of the building undeniably change the velocity profiles and created unpleasant points for human activities. Downwash effects were also responsible for vortices on ground levels of other buildings. When buildings are gathered in layouts, single building assumptions changes. Two buildings considered situations, gap between these buildings highlights great importance among other parameters. Front building wake effects merge with downwash effects creates vortices faster than single solutions wake fields. It is advisable to separate these buildings for less turbulent flows. Changing the shape of one building could provide benefit depending on the building. If the building behind is changed and increased in height, vortices problem in the gap increases proportionally. Buildings that are proportionally longer among the other formations are also found problematic by means of increased wind velocities around buildings. Change in wind velocity does not have to be on the same direction, velocity gradients are also responsible for turbulent flows near ground layers. Building height is found as the most effective geometric feature in buildings. Height related flow characteristics like increasing speed from stagnation zone to ground level, corner effects and larger ground level vortices between two buildings are observed. These characteristics are also found closely related to design guidelines in literature (Krautheim et al. 2014, Fadl and Karadelis 2013)

Flow characteristics around buildings are found valid between literature and case study. Corner and Downwash effects are primarily effective on tall buildings, which has width to height to ratio more than two. It always advisable to conduct case specific CFD simulations rather than making assumptions from similar buildings.

6.2. The Comfort and Safety Quantification of Pedestrian Level Wind Environment

Pedestrian level wind environment is highly dependent on parameters of specific location. Terrain roughness, surrounding buildings in the location, local climate regarding prevailing wind effects are main concerns in this regard. This complexity causes obstacles for accepting a universal wind comfort and safety criterias regarding to pedestrians. Engineering means of safety criteria is finding the tolerances. Tall buildings are constructed with structural integrity to withstand these tolerances for the comfort and safety of users. These tolerances are tested in wind tunnels and CFD simulations and validated.

Wind safety and comfort criterias have been studied since 1970's and different scales had been proposed for different activities (Ratcliff and Peterka 1990). Wind tunnel tests of pedestrian activities were also conducted to understand tolerances of people with different age, sex and body type. Resulting scales for pedestrian activities have large margins for different categories. Wind profiles extracted from CFD simulations of buildings and layouts were not comparable to proposed criterias in literature. Turbulence, gusting time, occurrences throughout the day, month or year had to be known for making assumptions. CFD data wind profiles provided mean velocities and turbulence values are calculated to best fitting criterias proposed by Hunt et al. Corners of proposed buildings on pedestrian level wind environment in the case area found highly turbulent locations that significantly effect pedestrian activities. Safety criteria were not reached in this study, but it is discussible that wind profile used in this study is low or not compatible for fitting the criterias. However, wind profiles around buildings show high deviances from one point to another in proximity. These sudden changes studied around buildings showed non-uniform flow characteristics and could be considered as criteria indicator.

Wind comfort and safety criterias are hardly considerable as standards since they heavily rely on expertise and rather than promoting an agreed ground. Dutch Wind Standard NEN8100 is accepted as appropriate scale for pedestrian level wind environments (Janssen, Blocken, and van Hooff 2013). This standard match appropriate levels of wind categories acceptable for Netherlands but depends on time cycles of wind occurrences. This situation leads to meteorological data requirement from the site. Velocity profiles from CFD simulations used in this study were sorted to display very high differences in 2 meters to 5 meters horizontal displacements. These locations indicated disturbing points for pedestrian activities. Horizontal gradients of wind velocities are also used in proposed equation to find turbulence categories for gustiness in the study area. These two indicators showed agreeable results compared to other criterias in literature and could be further developed with inclusion of local climate measurements.

6.3. Conclusion

Architectural and urban design projects require comprehensive understanding of environment to provide functional, comfortable and adaptable solutions to users. Chancing climate of the environment requires designers to investigate more passive and resilient solutions in early design stages. Simulations, energy modeling and prototype tests are valid methods to establish appropriate design alternatives for assessments.

This study introduces wind environment investigation case for a new redevelopment area in Izmir. Buildings proposed in the concept project modeled for CFD simulations to explore the effects of different geometric parameters of buildings on pedestrian level. Results revealed that building height is significant concern for designing neighborhood scale projects concerning the comfort and safety of users. Clusters of buildings should be carefully evaluated in this scale of projects since building type cannot be solely held accountable for wind effects on pedestrians. Buildings assembled in closely to each other or locating a taller building behind a half size building inversely effects the wind characteristics in gaps between them. Corner effects, downwash effects and wake effects are significant categories of flow types occurring around the buildings. High rise buildings with smooth sharp corners created problematic regions around the corners of the building. Balconies and canopies are applicable architectural design features to overcome the high velocity wind flow problems in pedestrian level. It is not always recommended to block wind flow in a building layout since it could increase the pressure difference factor and result in higher velocities to overcome.

Comfortable environment in pedestrian level is achieved by using appropriate wind criterias for studies around buildings. Most wind criterias investigated in this study were not sufficiently explain the comfort and danger tolerances, since they could not be taken as universal guidelines. Wind profiles laid out by CFD simulations fitted with using calculated turbulence data are presented for methodology to review comfort criterias in literature. Another criterion derived from velocity profiles is inspecting the marginal variations in flow profile in short distances. Resulting points are the problem areas that would react to wind gusts poorly and cause danger for pedestrian activities depending on the approach wind profile.

CFD simulations presented itself as a valid and rapid methodology to overcome design problems with quantifiable results. Complex nature of the wind flow could not be predicted with assumptions solely based on literature examples. Case should be modeled specific parameters and validated with wind tunnel tests to reach acceptable results. It is also impossible to find exact model definitions in literature for validations. Sub-elements forming the total design project could be investigated to make assumptions. CFD simulations provide benefits over wind tunnel testing in early design stages to rapidly identify optimum solutions.

6.4. Future Studies

Wind aerodynamics is still a developing field with many industrial applications. New cases are being investigated for better representation of wind environment around buildings in urban areas. Case studies simulated in this study will provide data for design teams for similar building layouts and building geometries. This data will also be included in official Environmental Impact Assessment Report for future stages of urban regeneration area. Since next stages of this project will require new simulations of building layouts, so it is possible to extent the number of buildings investigated in this thesis. Besides, whole area with inclusion of further stage buildings can be studied for understanding neighborhood level wind environment. This data would provide a baseline for comparing the total change in wind speeds after the constructions are completed. Wind measurements taken in the area would also be beneficial for comparisons. It is always possible to broaden the research of building types and provide substantial data for developing a national pedestrian level wind comfort and safety standard for Turkey.

CFD tools are preferable choices to wind tunnel option for engineering teams. These tools are continuously developed with current technological opportunities and integrated to CAD design software. Wind rose representations in this study are generated with similar tool nested in CAD software and can be used by other researchers when shared in open software development platforms. It also possible to complete wind simulations in the same CAD environment and can be interacted with weather data from the wind rose tool. These two separate workflows can be joined to one component which would clarify the complex assessments that are made during CFD with simpler user interface for architects.

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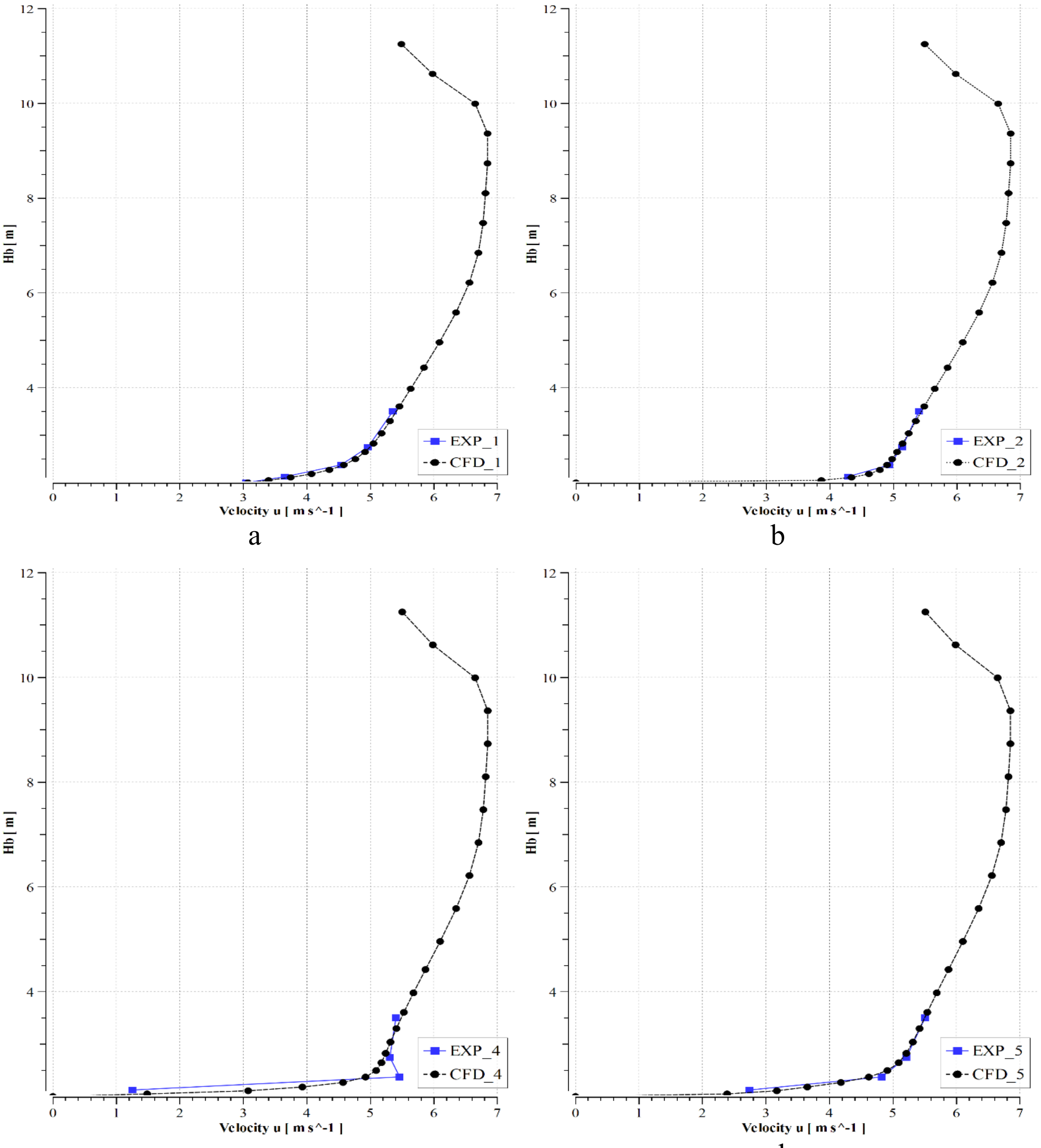
APPENDICES

APPENDIX A

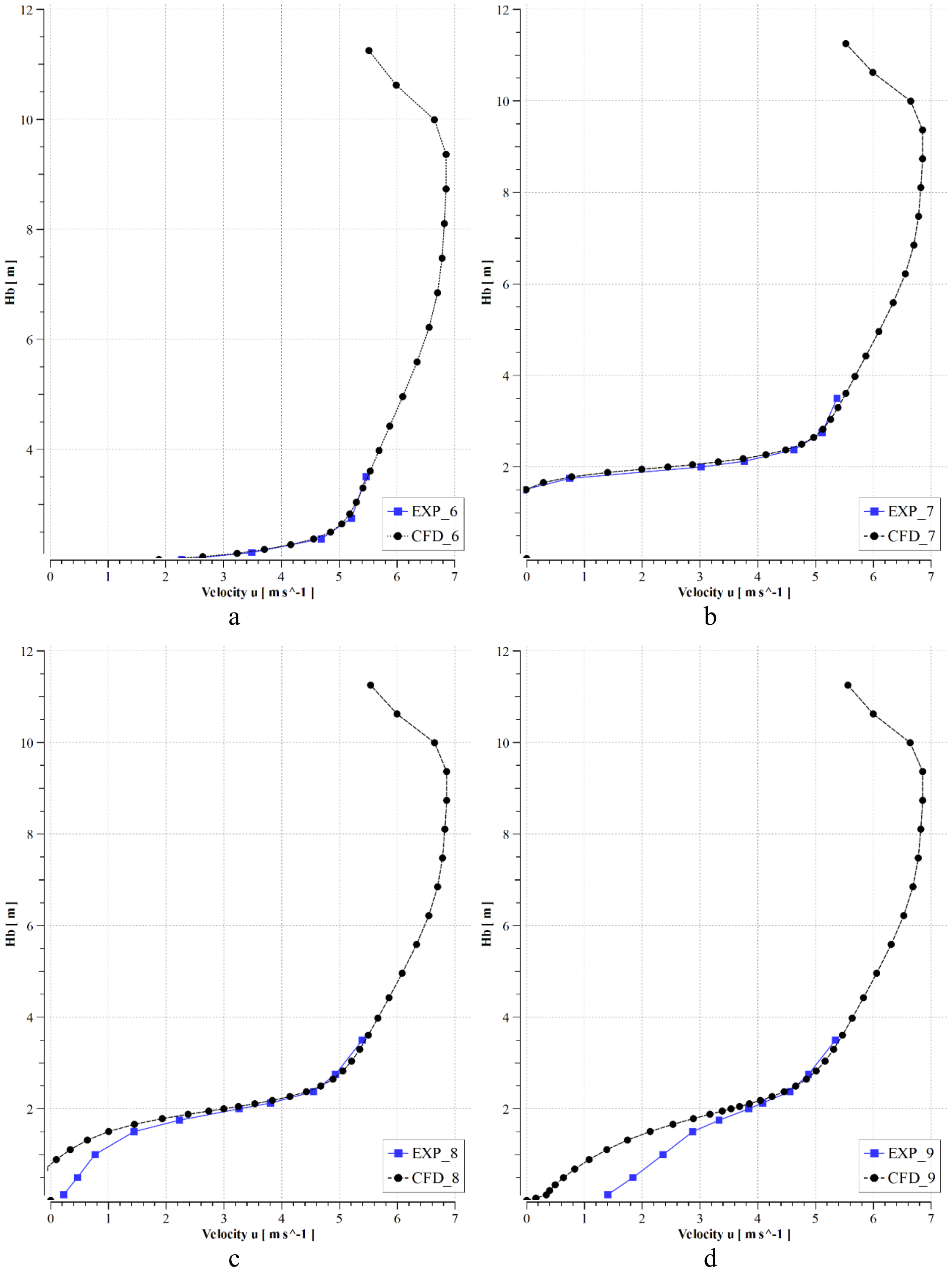
GRAPHICAL RESULTS



a b

c d

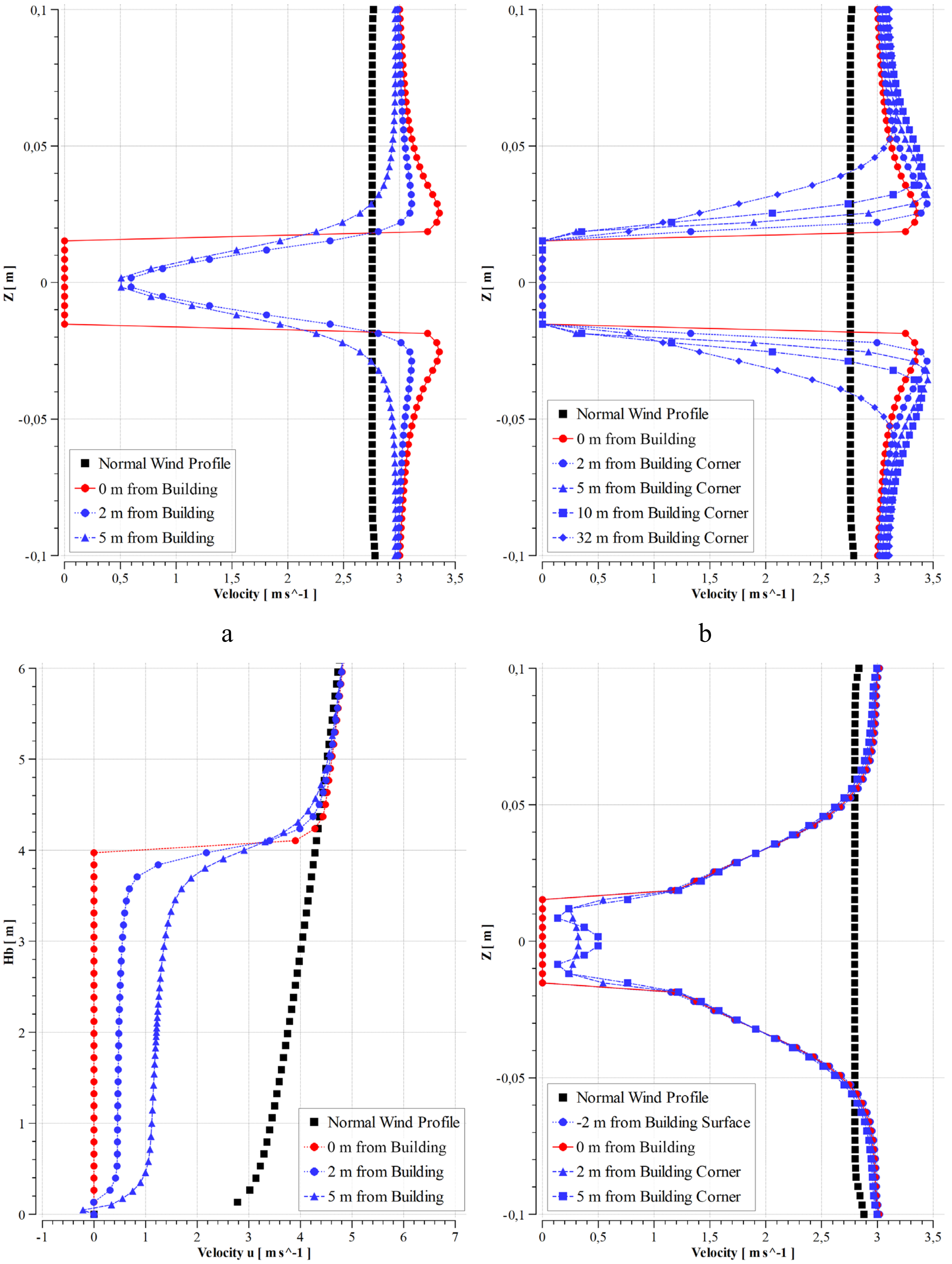
Figure A Vertical velocity (u) profiles probe locations on vertical a) line 1 b) line 2 c) line 4 d) line5



a b

c d

Figure B Vertical velocity (u) profiles probe locations on vertical a) line 6 b) line 7 c) line 8 d) line 9



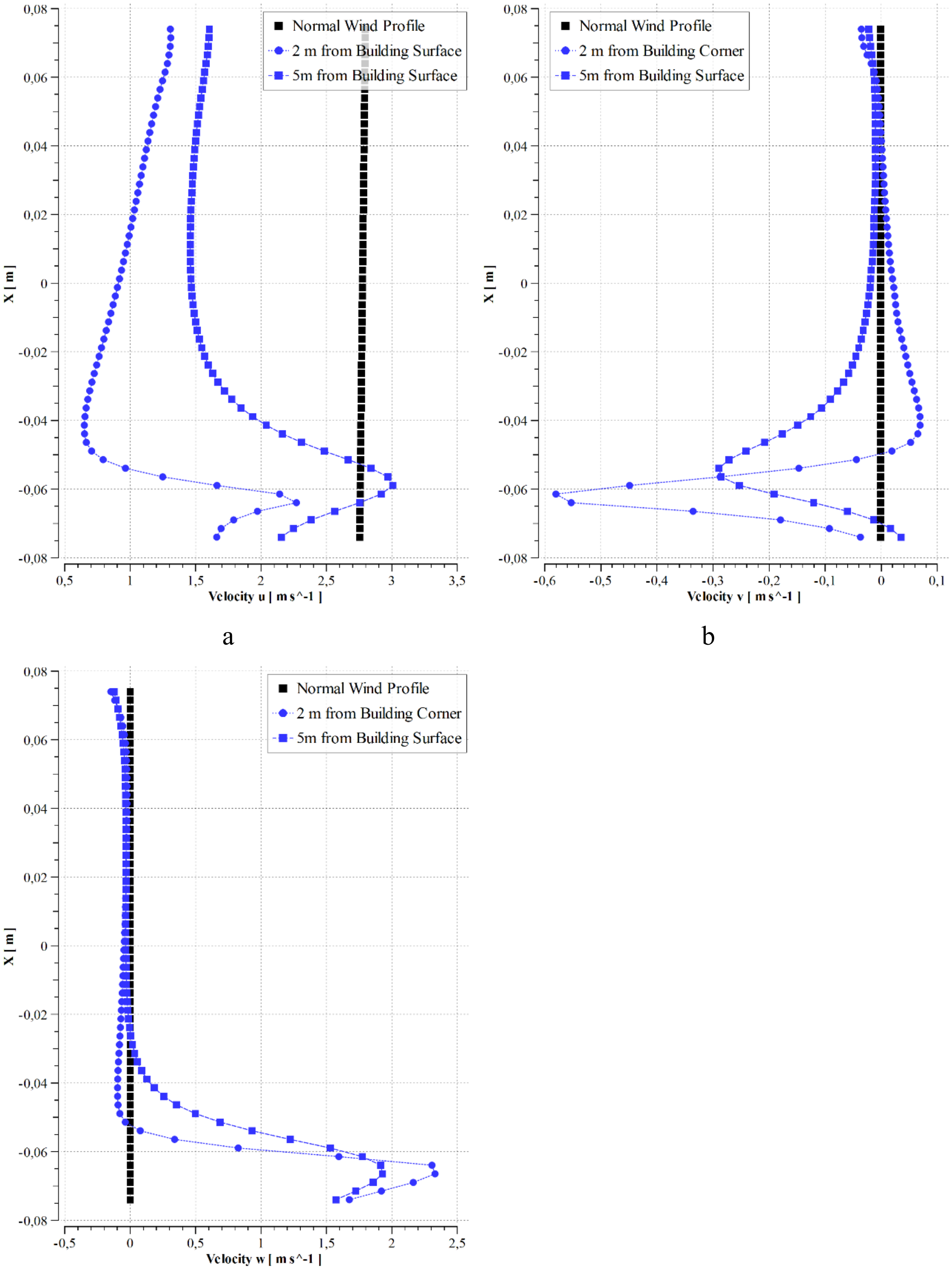
a

b

c

d

Figure C Wind profiles in front of the building (a), various distances from corner (b), vertical profile in front of the building (c) and behind the building (d)



a

b

c

Figure D Velocity gradients of u,v,w parallel to the longitudinal facade away from 2 and 5 meters distances

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Mimed 2006 – Finalist, 2006

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