

**ASSESSING REAL WEATHER CONDITIONS IMPACTS AND
URBAN AREA THERMAL PERFORMANCE VIA CFD
MODELING: A STUDY ON THE FORMATION AND
POPULATION DYNAMICS OF AN URBAN AREA**

A Thesis

by

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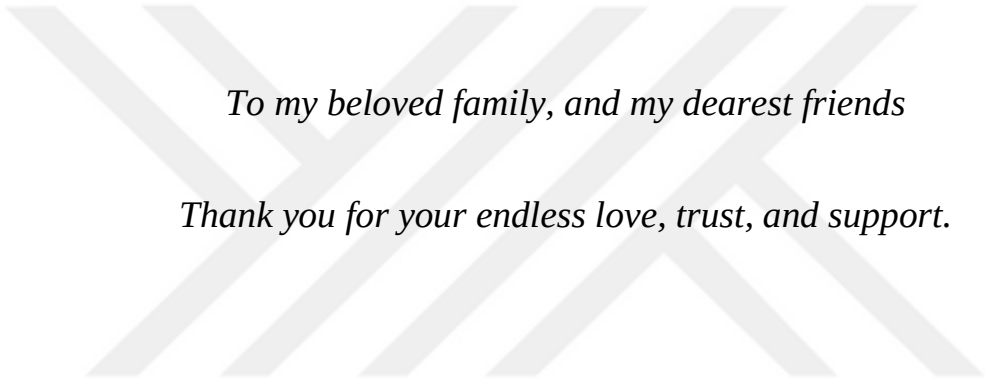
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To my beloved family, and my dearest friends

Thank you for your endless love, trust, and support.

ABSTRACT

This thesis aims to examine the problems that may arise in an urban area and minimize the adverse effects of extreme weather events such as heatwaves. To achieve this goal, different urban configurations with various geometries and material usage are modeled and analyzed in Yesilkoy/Istanbul using a commercial Computational Fluid Dynamics (CFD) program. The models are simulated with weather conditions (extreme and average) obtained from long-term meteorological records measured by the Turkish State Meteorological Service. The overall study encompasses four different case studies.

The first case study focuses on creating a basic urban area with two parameters (albedo and aspect ratio). The second case study involves the effects of different weather conditions on the microclimate and a comparison of the numerical approach and TS 825 standards. The third case study examines the heat fluxes released from the urban area to the environment and aims to improve their performance. The fourth case study addresses the solution to excessive heating resulting from an increasing number of buildings and investigates the wind characteristics in canyons. As a result of the analysis, the highest average building surface temperature value difference between the low albedo and high albedo scenarios is calculated as 2.9 °C at 11 o'clock. With the effect of aspect ratio, the average temperature on the building surfaces decreased by at most 1 degree at 11 am. As a result of the roof design the average temperature difference on the building surfaces is at 1 pm and 2 pm, with a maximum of 0.6 °C. The cool roof strategy, which is used to reduce the negative effect of the population, showed the greatest effect at 1 pm and reduced the average temperature on the building surfaces by 1 °C.

ÖZETÇE

Bu tez, bir kentsel alanda ortaya çıkabilecek sorunları incelemeyi ve sıcak hava dalgaları gibi aşırı hava olaylarının olumsuz etkilerini en aza indirmeyi amaçlamaktadır. Bu amaca ulaşmak için ticari bir Hesaplama Akışkanlar Dinamiği (CFD) programı kullanılarak Yeşilköy/İstanbul'da çeşitli geometri ve malzemelere sahip farklı kentsel tasarımlar modellenmiş ve analiz edilmiştir. Modeller, Meteoroloji Genel Müdürlüğü tarafından ölçülen uzun vadeli meteorolojik kayıtlardan elde edilen hava koşulları (ekstrem ve ortalama) ile simüle edilmiştir. Bu tez dört farklı vaka çalışmasını kapsamaktadır.

İlk vaka çalışması, iki parametrelili (albedo ve en-boy oranı) temel bir kentsel alanın yaratılmasına odaklanmaktadır. İkinci vaka çalışması, farklı hava koşullarının mikro iklim üzerindeki etkilerini ve sayısal yaklaşım ile TS 825 standartlarının karşılaştırılmasını içermektedir. Üçüncü vaka çalışması, kentsel alandan çevreye salınan ısı akışlarını incelemekte ve performanslarını iyileştirmeyi amaçlamaktadır. Dördüncü vaka çalışması, artan sayıda binadan kaynaklanan aşırı ısınmanın çözümünü ele alıyor ve kanyonlardaki rüzgar karakterini araştırıyor. Analizler sonucunda, düşük albedo ve yüksek albedo senaryoları arasındaki en yüksek ortalama bina yüzey sıcaklığı değerlerindeki fark saat 11 de 2,9°C olarak hesaplanmıştır. En-boy oranının da etkisiyle bina yüzeylerindeki ortalama sıcaklık saat 11.00'de en fazla 1 derece azaldı. Çatı tasarımı sonucunda bina yüzeylerindeki ortalama sıcaklık farkı, maksimum 0,6 °C ile 13:00 ve 14:00 olmuştur. Nüfusun olumsuz etkisini azaltmak için uygulanan soğuk çatı stratejisi en büyük etkiyi saat 13.00'te göstermiş ve bina yüzeylerindeki ortalama sıcaklığı 1 °C düşürmüştür.

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CHAPTER I

INTRODUCTION

Global population growth and economic growth have brought along a rapid urbanization process. The world's population has increased more than three times since the middle of the 20th century [1]. While this process results in a large migration wave from rural areas to cities, it causes rapid expansion of cities. This situation affects the global climate system, causing temperature increases, extreme weather events, and changes in the precipitation regime. These two phenomena have adverse effects on the urban climate as well as on the global climate.

The parameters such as local topography, building density, and surface materials have affected urban areas. In addition, the urban heat island effect may occur due to dense construction, less green space, asphalt pavement, and energy consumption, which increase heat storage in cities and reduce evapotranspiration. Urban climate research provides fundamental information for urban planning and sustainability strategies by examining the microclimate characteristics of cities and their interaction with the urban heat island.

In order to work on the urban climate and reduce the negative effect, it is necessary to govern the terms of urbanization, climate change, urban heat island, urban planning and urban design, urban climatology and urban microclimate, mitigations strategies, and evaluation parameters to determine their effects on the urban climate.

1.1 Urbanization

Urbanization can be defined as a process of population concentration [2]. While there may be instances where urbanization occasionally halts or even retreats in certain areas, the inherent inclination of society is for urbanization to continue until it is hindered by unfavorable conditions [2]. Urbanization is driven by two primary factors: natural population growth and rural-to-urban migration. These processes contribute to the transformation of settlements of all sizes, including small villages, towns, and cities. However, the cumulative effect of urbanization is the emergence and expansion of mega-cities, characterized by populations exceeding ten million people.

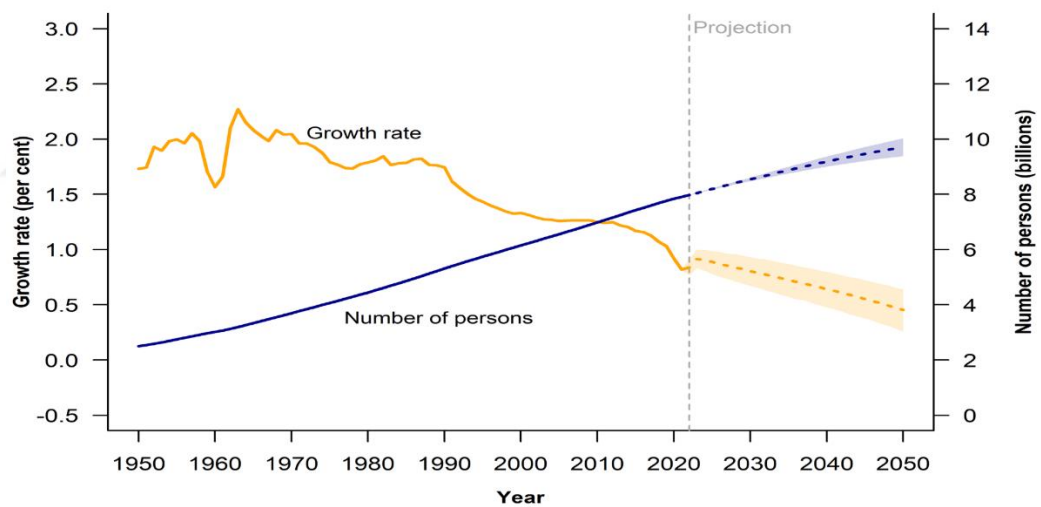


Figure 1: Global population size and annual growth rate: estimates, 1950-2022, and medium scenario with 95 percent prediction intervals, 2022-2050 [1]

The world's population increased in urban areas, with the number of city dwellers rising from 729 million in 1950 to 3.5 billion in 2010. Simultaneously, the global population increased from 2.5 billion to 6.9 billion between 1950 and 2010, as shown in Figure 1 [3]. According to future projections, the global population is expected to reach

8.5 billion in the year 2030, 9.7 billion in 2050, and 2100, 10.4 billion. Additionally, according to Figure 1, the global population in the year 2023 is nearly 8 billion [1]. Urbanization encompasses a wide range of disciplines, including urban planning, geography, sociology, architecture, economics, education, statistics, and public health. This research focuses on urban design, among the disciplines mentioned, and investigates strategies that aim to mitigate the negative impact associated with urbanization.

The uncontrolled and excessive growth of urbanization has led to adverse consequences globally [4]. Urban environments tend to absorb more solar radiation, including direct, diffuse, and reflected radiation, compared to natural landscapes. Also, the convective heat exchanges are significantly reduced due to urban structures, and the release of anthropogenic heat increases in line with population growth. This combination of factors contributes to elevated temperatures in urban areas [5]. In addition to that, when examining the effects of urbanization on the water budget, it becomes apparent that cities experience a partial loss of water permeability, resulting in reduced storage of groundwater and evapotranspiration [6]. The combination of climate change and ongoing urbanization leads to higher air temperatures in densely developed urban areas compared to the surrounding rural regions. Urbanization has been observed to intensify the urban heat island (UHI) effect, which refers to the phenomenon of elevated temperatures in urban areas compared to the surrounding rural regions [7][8].

1.2 Climate and Climate Change

Climate refers to the collective characteristics of long-term meteorological phenomena in a particular location, encompassing factors like temperature, wind, and precipitation [9]. In contrast to weather conditions, which focus on short-term conditions, climate

encompasses the prolonged observation of meteorological patterns in an area. Recent measurements are outside the values of the climate normal, which are defined as reference points used by climate scientists to compare current climatic trends with those in the past or what are considered typical. Climate change is underway, as proved by Climate observations and analyses conducted by the Intergovernmental Panel on Climate Change (IPCC) and national meteorological organizations. According to IPCC report, since 1850, each succeeding decade has been gradually warmer than before. The average worldwide surface temperature between 2001 and 2020 was almost 0.99 °C higher than between 1850 and 1900. The global surface temperature was also about 1.09 °C higher from 2011 to 2020 than it was from 1850 to 1900 [10]. At the same time, the increased intensity, frequency, and length of extreme weather phenomena such as heat waves, droughts, heavy rainfall, storm surges, and rising sea levels globally are already showing the effects of climate change [11].

Although the urban heat island is a significant phenomenon, it is localized and does not play a major role in the broader patterns of climate change, but global climate change can exacerbate the impacts of the urban heat island by imposing an additional thermal burden on urban areas [12]. The occurrence of extreme heat events, resulting in increased frequency, intensity, and duration can be considered as thermal burden on urban areas of global climate change plays a significant role in intensifying.

Concerns regarding urban overheating, which affects thermal comfort, heat-related mortality, and urban energy consumption, particularly during heat waves, have been worse by climate change and urbanization. For the purpose of analyzing the effects of overheating and evaluating mitigation measures in both present and future climates, it is important to create climate predictions that accurately depict the status of the urban

climate, a complex system that contains microclimate phenomena on a regional and global scale [11].

1.3 Urban Heat Island

Urban heat island is a phenomenon which is known as closed isotherms distinguishing the city from the temperature fields of surrounding areas [7]. Basically, Urban heat islands are defined as urban regions that are much warmer than the nearby rural areas. It can be said that, even as a population center experiences growth a bit, it has a tendency to raise its average temperature because there is a relation between urbanization and urban heat island due to materials and urban geometry. It occurs by the relatively higher proportion of incident solar radiation that is absorbed and stored by unnatural materials used in urban areas [13]. In addition to that, even a single building complex will have a different microclimate from a natural piece of land, as the paved surfaces and walls store heat during the day and release it into the air after sunset [7].

Modifications in urban areas can lead to the retention of heat and the redirection or deceleration of air currents, which can either enhance or intensify the overall comfort experienced in urban areas. Consequently, these changes have an impact on the phenomenon known as the urban heat island, as well as the level of thermal comfort experienced by individuals in the region [14].

Numerous researches have shown how urban microclimate affects infrastructure, human thermal comfort, and building energy demand [15][16][17][18][19]. The life quality of people living in urban areas can be developed by understanding the factors affecting the urban microclimate and arranging the shape of the city in accordance with

its location [20]. Also, this study focuses on the changes in the microclimate of the urban area.

1.4 Urban Planning and Urban Design

Urban planning, also known as city planning, is the term used to describe the technical and political process that deals with the development and use of human settlements [21]. As planning can be seen at some of the earliest known urban sites, the history of urban planning and the history of the city are entwined, such as Minoan [22] and Harrapan [23]. Urban planning considers various factors such as population growth, transport infrastructure, housing, public spaces, economic development, and sustainable urban environments. It requires assessing the current situation and imagining potential future development strategies to control urban growth and transformation.

Today the term "urban design" is used to describe almost any design that takes place in any urban setting. Building complexes, city precincts, and entire cities are all examples of multi-building projects that are included in urban design [24]. To produce livable and sustainable urban environments, the built environment must be shaped, including roadways, buildings, public spaces, and landscapes. The goal of urban design is to enhance the quality of life for locals by taking into account how people, buildings, and their surroundings interact. In order to produce cohesive, well-designed urban environments, it takes into account land use, transit, and social dynamics.

In conclusion, urban design is concerned with the precise physical planning and organization of urban spaces, while urban planning is concerned with the comprehensive, long-term management and development of urban areas. To design urban landscapes that are sustainable and practical both disciplines collaborate.

1.5 Urban Climatology and Urban Microclimate

Urban climatology is a multidisciplinary field that studies how urban areas influence climate and uses that knowledge to improve urban planning. Also, by integrating knowledge from different disciplines, urban climatology seeks to develop a holistic understanding of urban climates and promote the development of sustainable, comfortable, and resilient cities [25]. In addition to that, urban climatology is divided into three scales with boundary layers [26], and these scales can be sorted from general to small as follows;

- Meso-scale: involve weather and climate at the scale of the whole city, typically tens of kilometers.
- Local-scale: includes landscape features such as topography but excludes microscale effects and focuses on one to several kilometers.
- Micro-scale: relates to microclimate on the dimensions of individual buildings, streets, courtyards, gardens, etc. and focuses on between less than one meter and hundreds of meters.

A microclimate is defined as a particular set of meteorological conditions that exist in a particular location and differ from the weather patterns that occur locally. The phrase can be used to describe spaces that are a few square meters or smaller, or that are many square kilometers in size. Because climate is statistical in nature and involves the spatial and temporal variation of average values for many parameters, some areas can exhibit and sustain unique microclimates across time.

1.6 Mitigation Strategies

Mitigation strategies are defined as approaches that reduce the adverse effects of UHI and heat waves for livable urban areas. In order to actively combat excessive heat stress, urban planners are progressively implementing sustainable alternatives (such as creative urban landscape planning and infrastructure design). Such strategies encompass energy and water cycles, environmental and socio-economic measures, and common relationships between human activities and natural systems [27]. They aim to address the complex interactions and dependencies in urban environments to mitigate the effects of the urban heat island effectively. Generally, these strategies include developing green infrastructure, selecting surface materials, increasing water surfaces, energy-efficient building designs, and appropriate urban planning. These strategies are applied for purposes such as lowering temperature, increasing air circulation, and protecting the natural environment.

1.7 Evaluation Parameters

Evaluation involves assessing the quality, significance, and value of a subject, and evaluations are the outcomes derived from this assessment process [28]. Evaluation criteria for urban heat island mitigation measures may vary depending on the specific context and objectives of the evaluation. Generally, evaluation criteria assist researchers and city planners in making informed decisions for sustainable urban development in determining the effectiveness, feasibility, and overall impact of urban heat island reduction solutions.

In microclimate modeling, evaluation parameters depend on the urban area used to compare the studies with other studies. Comparison, assessment or validation reasons, temperature-related characteristics in particularly air temperature, have been considered

in the majority of investigations. Wind speed, surface temperature, and average radiation temperature come after this factor [29].

1.8 Scope and Outline of the Present Study

The scope of the study is reducing the negative impact of urban heat island on urban areas with mitigation strategies and considering the effect of these mitigation strategies on the thermal and characteristics parameters. In line with the mentioned topics of urbanization, climate change, urban heat island, urban planning and urban design, urban climatology and urban microclimate, mitigation strategies, and evaluation parameters, this thesis aims to accomplish the following objectives:

In Chapter II:

- Providing a literature review for the development of urban climatology and urban microclimate.
- Examining the types and usage patterns of mitigation strategies.
- Definition of the problem statement of the study.
- Evaluation approaches are used actively in the study.
- Location-Specific information about the chosen area is given.

In Chapter III:

- Geometry specifications and details for the different case studies.
- Mesh details are examined, and information on the mesh design techniques are given in this part.
- Boundary conditions used in surfaces and meteorological data are presented.

- Details of the setup specifications are given with a detail examination of heat transfer formulations, viscous model formulations, and solution parameters.

In Chapter IV:

- Solutions are figured out, which are obtained from the first case study. The effect of the albedo level and aspect ratio (H/W) are considered in detail and decided to new primary urban design.
- Simulations are made with two different weather conditions to examine the effect of weather data on microclimate analyses.
- In order to examine the heat fluxes radiating from the urban areas created, an examination is carried out with the control volume.
- With the case studies obtained, thermal changes in an urban area continue to expand, and these changes' effects on the wind character are examined.

In Chapter V:

- The advantages and disadvantages of the mitigation strategies and evaluation parameters are examined depending on the results obtained.

CHAPTER II

LITERATURE REVIEW AND PROBLEM STATEMENT

2.1 Literature Review on Urban Climatology and Urban Microclimate

Studies on urban climates expanded, particularly in central Europe, during the early 20th century. A notable example is Geiger's book, "Climate near the Ground," which was first published in German in 1927 and later translated into English in 1965 [25]. While Manley was the first person who used Urban Heat Island effect as a terminology in 1958, Luke Howard (1833) was the first to offer proof that a city's air temperature is frequently higher than that of the area's countryside, and he mentioned that urban microclimates tend to generate and keep more heat from rural areas [30][31]. Also, Howard's approach became the primary scientific method to determine differences between urban and rural areas' temperatures with the data from observation [25]. As mentioned in Oke's study on the city size and urban heat island, the first investigation, which shows the relation between urban heat islands and meteorological conditions was developed in 1950 by Sundborg [32][33]. Although there are a lot of accumulated evidences for the urban air temperature effect, this evidence is often localized and difficult to generalize for use in different locations [25]. Oke's (1973) research showed that it is possible to eliminate external influences and found two mathematical approach a relationship between the maximum temperature value between urban and rural area and the size of the city in North America and European settlements [33]. In another study by Oke (1981), the universal relationship for cities in different climates is determined using the H/W ratio or the sky view factor rather than population [34]. Up until the early 1980s, studies published with a focus on the

experimental estimation of UHI intensity continued. However, there has been a significant development in terms of continuing climate modeling studies and urban area estimations in this regard. Lowry (1977) claimed that it is inherently impossible to distinguish this specific effect from other climate impacts, such as climate change, because upwind/downwind conditions, the location of the reference rural temperature measurement, and the measurement period can all affect UHI intensity. Since the 1980s, urban climate research has shifted its emphasis toward physical aspects and the development of accurate climate models due to the high level of uncertainty in UHI intensity measurements and experimental estimations.

Towards the end of the 1960s, studies aiming to examine the physical mechanism that caused the urban heat island effect emerged with surface energy balance [25]. The most common expression of the new approach to urban climate research is the equating of sensible heat flux, turbulent heat flux, and conductive heat flux values dependent on the surface of the material to net radiation [35]. Adoption of this strategy made it possible to move from studying the causes of impacts to impact explanations while linking the work to the broader field of boundary layer meteorology, but this field conceptually only determined the nature of surface-air interactions for homogeneous surfaces and developed regulations to predict energy changes [25]. As time progressed, studies have contributed to a better understanding of the causes of the urban heat island and to the development of the surface energy balance model. Oke [36] proposes at larger scales to evaluate equivalent energy flows over an imaginary volume extending from a substrate depth to roof level for total urban landscapes where energy changes are negligible on the observation time scale. While anthropogenic energy is added to the net radiation part, net

advection through the sides of volume and storage heat flux are added to turbulent heat flux part of simple energy balance equation [35].

To summarize the studies done so far, Mills [25] classified studies generally according to temporal periods as follows;

After 1900, urban influences were studied and defined, along with traditional equipment.

After 1960 radiation, sensible and latent heat variations were studied, and statistical methods were used to analyze the results.

After 1970, meteorological theories began to be adapted to urban climates, and computer modeling techniques were used. In addition, a more precise definition of the urban 'surface', urban scales, and observation of urban influences is made.

After 1980, experimental approaches were adopted, scale models started to be used, and flow measurements were started.

After 1990, the effects of real urban forms on the urban microclimate were studied, and field projects were studied.

Since 2000, realistic urban climate models have been developed, and new techniques began to be used.

These six periods demonstrate that a variety of techniques can be applied to study urban microclimate today [29]. Nowadays, with the development of observation equipment and the development of the computational power of the computers used, more detailed studies are carried out. These approaches are divided into two main categories as

observational approaches and simulation approaches [4][37]. Observational approaches may include field measurements, thermal remote sensing, or small-scale modeling, while simulation approaches may include numerical studies using Computational Fluid Dynamics (CFD) or energy balance models (EBM) [18]. In addition to that, in literature there are studies on microclimate analysis with energy balance model and atmospheric modeling tools in mesoscale [38].

Many general observations related to different parameters such as wind speed, cloud ratio, and population have been made within the scope of urban heat island studies [35], but other research conducted in the past has shown conflicts between these observations and the cause of these inconsistencies is due to the statistical analysis's limitations in presenting a number of physical events [4].

Field measurement approach is used for the first time by Howard to examine the urban heat island in London. In the area measurement approach, the near-surface temperature pattern in the urban area is often compared to the rural area on the basis of pairs of fixed or mobile stations or groups of stations. The outcomes are frequently used to determine the density and spatial distribution of the heat island within an urban area. Nevertheless, data analysis is difficult due to the large number of parameters that can affect urban heat island formation, and simple correlations between measurements and urban heat island properties are insufficient to make consistent generalizations [4]. Arnfield provides a summary of the number of stations, the impact on the climate, and the comparison process [35].

Remote sensing has been widely used in UHI research recently since it can completely characterize a city's thermal environment at a certain time [8]. This approach

involves observing the temperature of urban surfaces, which is influenced by the balance of energy exchanges occurring at the surface [39]. This method uses sensors installed on satellites, aircraft, or ground-based platforms to measure the thermal energy released by urban regions. The resultant surface temperature, surface albedo, turbulent transfer from the surface, and surface emissivity can all be determined using this method [40]. However, there are some significant limitations to thermal remote sensing. One of them significant limitations of this method is that it only accounts for upward thermal radiation patterns in terms of surface temperature measurements made by the sensors, and another limitation is that a significant part of the urban area cannot be seen due to its three-dimensional structures [4].

According to the literature, small-scale modeling is defined as substituting an urban area with a prototype for the purpose of conducting more in-depth research [41]. The prototypes are tested in wind tunnels or outdoors. That's why, as with other observational approaches, there are various disadvantages in the application of UHI studies with small-scale modeling. It is costly and complex to establish thermal stratification experimentally. In case there is a similarity between the model and prototype, small-scale modeling is frequently utilized in UHI investigations to verify, calibrate, and improve mathematical models, despite its limitations [4].

In addition to observational approaches, computational techniques are developing rapidly, and among these, computational fluid dynamics (CFD) and energy balance models are the most reliable [4][27]. Recently, there has been a considerable rise in the use of numerical simulation methodologies due to the rising availability of computational resources. The ability to conduct comparative assessments based on several scenarios is the major benefit of numerical simulation approaches over their observational

counterparts [29][42]. Numerical simulations can also provide information on any researched variable throughout the full computational domain, whereas measurements are often only made at a small number of points in chosen area [12][43].

Today, the basis of the studies on the energy balance model is based on the previously mentioned urban energy balance modeling (EBM) formulas developed by Oke [36]. Subsequently, many studies have used EBM approaches for validation and model development purposes [44][45][46]. The energy balance equation for a control volume with two nearby structures yields the urban canopy model (UCM), and the urban canopy's surface and ambient air energy exchanges are taken into account by the model [4]. It provides acceptable accuracy for large-scale energy consumption studies, but the lack of air velocity information is the main flaw in this model because air velocity information is important to understand atmospheric phenomena and to study heat fluxes.

In addition to these, there are differences between energy balance model and computational fluid dynamics, and these differences arise from the difference in approach mechanisms to the problem. While computational fluid dynamics (CFD) is capable of simultaneously solving conservation of mass, momentum and energy equations throughout the urban area, the energy balance equation is used the urban canopy model to represent the exchange of energy between surface and air temperatures within a defined control volume. As a result, CFD provides more precise outcomes in terms of urban heat island (UHI) distribution within the urban area compared to the urban canopy model [27]. In comparison to EBM, the second benefit of CFD is its capacity to resolve flow fields at finer scales [42]. In small scales, CFDs model and solve the wind flow and heat transfers in that region, while EBMs calculate over the values in a control volume, revealing the

difference[47]. Due to this solution difference, it can be said that CFDs are more suitable for single buildings and urban canopies.

In the literature numerous guidelines [48][49][50][51][52] have been developed as the use of CFD in urban physics has grown in popularity in order to enhance simulation quality and reduce numerical and physical modeling errors. Toparlar et al. separated simulations into categories such as scale, configuration type, considered parameters, time solver, and validation [18].

There are four different scales to be used in thermal performance studies in urban areas, and these are meso-scale, micro-scale, building scale, and indoor scales [12][42][43][53]. Meso-scale is generally referred to as less detailed urban or regional surveys between 2 km and 200 km areas, while the area covered by micro-scale includes more detailed modeling from a few hundred meters to a few kilometers [26]. While building scale provides a more detailed analysis opportunity compared to meso and micro scales since it covers an area of only a few hundred meters, an indoor scale can be used to model the ventilation inside the buildings and evaluate the thermal change [54].

Another specification on the CFD studies is configuration type. Microclimate studies are separated into two different geometric models. One of them is called the real urban area, and the second model is called the generic urban area [18][55][56][57][58]. The most significant differences between these two models are geometry and topology. Real urban area studies may cover a few buildings or a part of the city, while generic urban area studies are carried out on the urban areas formed with simply designed buildings. The aims of these two different geometries or study types are different from each other. According to Toparlar et al., CFD simulations in real urban areas are used as

practical case studies or, in the case of a validated study, to explore the limits of CFD [29]. On the other hand, the purpose of the generic urban area is defined in the same study as follows; early CFD models used for microclimate analysis are considered general areas for model development and validation purposes [29].

Considered parameters are also significant specifications in the CFD studies on urban modeling because all the considered parameters cause a negative impact on the thermal environment of urban areas. According to Oke [59], scattering of reflection in urban areas increases due to more absorption of short-wave radiation [18][60], increased long-wave radiation gain from the sky related to extra radiation depending on air pollution [18][60], decreased long-wave radiation loss due to reduced sky-view factors [18][60][61], rises on the anthropogenic heat sources due to human activities [61], increased sensible heat storage in urban area related to amount of construction materials [18][60], reduced potential evapotranspiration because of lack of moisture availability [18][60] and decreased turbulent heat transport due to the reduction of wind speed [18][60][61][62] are shown as seven causes of UHI in canopy layer of urban areas.

Time-solver type is also a critical chose for modeling CFD studies. There are two different time solvers which are called steady [57][62][63] and unsteady [18][61][64] (or transient). The basic differences between steady and transient solver types are time dependency, computational time, and accuracy. Transient analyzes can model dynamic behavior for airflow, temperature, and other initial conditions, taking into account changes in variables over time. Due to this situation, it gives the chance to examine time-dependent phenomena such as daily cycles. However, steady-state simulations make the assumption that variables remain constant over time. That's why it is not usable for the examination of long-term behavior. Also, transient simulations require more

computational time than steady simulations because steady simulation is stopped when the analysis converges to steady-state. In addition, the accuracy of the results is significant differences in time-solver types because the accuracy of transient analyzes is 10% higher than that of steady-state analysis in exergy analysis in buildings [65]. As a result, it is thought that the values obtained from transient analyzes are more usable to consider urban areas.

The last category which is used on the classification of CFD studies is validation. According to the studies in Toparlar's review article, it is seen that almost 60% of the analyzes made on the generic model are not validated and while the studies with the basic generic urban area are initially done to develop and validate the models. Later studies focused on air flow and heat transfer to understand the general mechanism in urban areas in the future [29]. The situation is similar in CFD studies using real urban areas. Urban area CFD studies without validation usually compare various urban configurations within the same urban area. As in the generic urban area, more than half of the articles using real urban area examined in the review study by Toparlar et al. are unvalidated [29]. Because high-quality experimental data must be compared with the outcomes of the simulation for CFD validation [42]. However, obtaining high-quality experimental data is not available without adequate equipment. So, equipment requirement is a significant limitation for validating CFD studies. For instance, the data from the experimental investigations on convective heat transport in street canyons that are now accessible are typically not of a high enough spatial resolution for CFD validation purposes, or information pertinent to CFD validation is lacking [66].

2.2 Literature Review on Mitigation Strategies

Urban heat islands have begun to form in urban areas as a result of the increase in population in the world, rapid urbanization, and climate change. This phenomenon raises a number of challenges, including the reduction of greenhouse gases, the comfort and quality of the interior and outdoor environments, the security of the energy supply, and public health [67]. The methods used to reduce the adverse effects of these urban heat islands are called mitigation strategies. Different mitigation strategies can focus on various approaches like urban geometry [14][57][68][69], albedo level [14][70][71][72][73][74][75], green roof [14][67][70][75], cool roof [67][72], roof design [69][76][77][78][79], aspect ratio [19][57][69][71][76][80][81], trees and park [14][75][82], water bodies [14][83][84], and coverage ratio [15][85]. This study focuses on four different mitigation strategies, and these are albedo level, cool roof, roof design, and aspect ratio.

According to the literature, the interaction of the external environment with the building envelope is the main cause of the heat load of detached residential buildings in warm and hot climates [86]. The reflectance and absorptance ratio of material is related to the albedo level directly. A surface with an albedo value of 1 ensures that incoming radiation is fully reflected to the sky, while a surface with an albedo of 0 ensures complete absorption of incoming radiation. Therefore, the definition of albedo can be made as "the ratio of incident beam to outgoing" or "the ratio of radiation reflected by a surface" [14]. However, using surface materials with high albedo level is not exact strategy to reduce urban heat island effect because reflective pavements should only be utilized in urban canyons with aspect ratios no higher than 1.0 [87]. In literature, albedo level is used in

the study with various range. For example, a study done in Brazil found that a surface with a 0.8 albedo can increase the solar gains on east façades and roofs to 259 kWh/m²/year and 67 kWh/m²/ year, respectively [88]. Another study shows that the maximum daily air temperature in Colombo, Sri Lanka, can be decreased by 0.3° C and the nighttime temperature by 0.6° C by increasing the albedo of buildings in dense urban areas by 0.3 [89]. Additionally, in a study conducted in Izmir, it was observed that replacing materials with low albedo levels (0.19) with materials having high albedo levels (0.5-0.6) reduced the potential air temperature in the shade by 1.55 °C [90].

There are two different ways that roof is gained heating as convection and radiation. The impact of these types of heat transfer is changing due to thermophysical specifications such as incoming solar radiation, the reflectance and absorptance of the surface, and temperature differences. As seen in the literature, there are various values for reflectance or albedo level of a surface from 0.1 to 0.9 with different colors and materials [14][86][91][92]. As mentioned article of Santamouris [70], there are four different stage for albedo level of materials. The first generation of cool roof materials comprised readily available natural materials with a relatively high albedo, generally not exceeding 0.75. The second generation of cool roof materials used artificial white materials with albedo values close to or exceeding 0.85. In the third stage, colored high-reflective materials, which aimed to have both color and a high reflectivity value in the infrared spectrum, are created, and they exhibited more overall reflectivity than conventional materials of the same color and led to substantial energy savings when utilized in urban areas. Lastly, fourth-generation reflecting materials, such as PCM-doped cool materials or thermochromic paints and tiles, have been produced. According to a study conducted in Singapore, installing cool roofs all over the city may mitigate daytime heat stress but offer

only small benefits at night when the tropical UHII is at its highest [93]. Another study states that peak load can be reduced by 5% to 35% when roofs with an albedo level of 0.9 are used [86].

Different roof designs or roof shapes affect the air flow direction directly, so the amount of air entering the canyon can increase or decrease. Also, The impact of roof slope and canyon aspect ratio on-air exchange between the street canyon and the higher atmospheric boundary layer is studied by Badas et al. [94] using RANS numerical simulation. To enhance heat dissipation in forced convective flows, Allegrini [69] investigated various roof designs and heights, as well as changed the lengths of the street canyon structures. According to the study, there are strong lateral flows for low buoyancy conditions if the upstream street canyon building is taller than the downstream street canyon building, while an increase in the height of the downstream street canyon building results in a decrease in the air temperatures inside the street canyon [69]. Another study by Garau et al. [76] shows that when the street width in the model increases to 3 times the height of the building, the exchange rate on flat roofs increases at the rooftop level, while it remains almost constant on the globe (45° slope) roofs. The comparison demonstrates that, regardless of aspect ratio, the gable roof's presence encourages airflow [76].

In dense urban areas, the landscape consists of streets flanked by buildings, creating a canyon-like structure. This configuration is commonly represented by the canyon aspect ratio (H/W), which is the ratio of building height (H) to the width between buildings (W) [95]. The aspect ratio of the street canyon (building height to street width) and ground/building facade heating as a result of solar radiation absorption in summer are the most important elements influencing ventilation and pollution transport/dispersion

in urban environments [96]. This means that an inefficient aspect ratio value can both affect ventilation and pollution transport/distribution in urban environments and negatively impact the urban area and increase radiation trapping. Oke mentioned that trapping more solar radiation into the canyons results in more short-wave radiation gains, resulting in an urban heat island [59]. Also, the capacity for passive night ventilation cooling in moderate climates can be greatly reduced due to global warming and heat waves, which could lead to even higher temperatures in urban areas [19]. While in an unsuccessful urban model with an inefficient aspect ratio, natural ventilation is further reduced by the effect of buildings and increases the urban heat island effect, the ideal H/W ratio for canyons resulted in up to a 35% increase in wind speed and a 0.7°C decrease in air temperature [97]. In another study in Singapore, it has been found that the shading produced by large aspect ratios can enhance outdoor thermal comfort on urban streets, and 3 can be utilized as a threshold number for H/W in 5 different H/W ratios (1-2-3-4-5) [98]. However, since each location has different climate and external effects, urban heat island effects can be successfully reduced in urban areas by finding the threshold H/W ratio for each urban area, as in the study conducted in Singapore. In another study conducted in India, the effects of five different aspect ratios (0.6-1-1.5-2-2.5) and five different street orientations (0°-5°-15°-30°-45°) on microclimate in the streets are investigated, and it is observed that a directional angle of 30-60 degrees and an aspect ratio of 2.5 could reduce the afternoon Physiological Equivalent Temperature (PET) values by 5-9°C [99].

2.3 Problem Statement

According to empirical studies on urban overheating, average temperature increases can reach 4-5 °C, and at their highest point, they may exceed 10 °C [100]. The same study also explains how ambient temperature rise has a negative impact on local comfort, energy demand for cooling, heat-related mortality and morbidity, urban environmental quality, and power demand. These adverse effects are separated into two fundamental groups as health [16][101] and economic [102][103]. Increasing construction materials in urban areas increase the heat storage capacity of urban areas due to the materials' thermal properties used on buildings. That's why buildings that are heated by radiation all day cannot reflect the heat that comes from the sun and sensible heat storage in the structure. In addition to that, inefficient urban physic design has a negative influence on the wind characteristic, and it prevents buildings from cooling due to reduced wind speed. In the literature, Yao et al. have demonstrated that apart from the urban heat island phenomenon, urbanization also influences the occurrence of heat waves during the summer season due to humidity [104]. Furthermore, according to a study by Kovats and Hajat [16], it has been noted that hot weather poses a natural risk to human well-being, with prolonged periods of high temperatures having adverse effects on human health. Consequently, the prevention of fatalities caused by heat waves, commonly referred to as extremely high temperatures within the community, has now emerged as a public health concern [16]. In past, 2000 deaths in Athens in 1987 are associated with the heat wave [105], and during the middle of July 1995, a brief yet intense heat wave resulted in 830 fatalities across the country, with Chicago alone accounting for 525 of these deaths [106]. Nowadays, mortality still continues affected by extreme heat and heat waves. In 2006, a heat wave lasting for 18 days occurred in France, and during this period, there were 5000 excess

deaths [107]. Also, the summer of 2022 surpassed all previous temperature records in Europe, and the intense heatwaves during this period resulted in extreme temperatures, drought, and heightened fire activity [108]. Study by Ballester et al estimate that there are overall 62,862 fatalities in Europe in 2022 attributed to heat; out of these, 61,672 took place from May 30th to September 4th and the most notable deaths associated with high summer temperatures [108]. In addition to high-temperature values and heat waves, energy consumption is another negative effect. Studies show that energy and electricity consumed by buildings for cooling are more than 1/3 of total energy and more than 1/2 of the total electricity consumed in European countries and the USA [109][110][111][112][113]. According to the literature, the rise in the cooling load per degree of UHI is found to range between 0.5 and 8 kWh/m²/C/y depending on the actual or projected influence of urban overheating on the energy consumption of the city and building [100]. The minimum coefficient of performance (COP) value of air conditioners may be reduced by up to 25% due to higher ambient temperatures, while it is demonstrated that the potential of natural ventilation is significantly reduced due to the significant decrease in wind speed in the urbanized area [17].

People have been attempting to solve UHI-related thermal performance problems through experimental and numerical calculation programs. As mentioned before, this study focuses on four mitigation strategies from the literature, albedo level, H/W ratio, roof design, and cool roof with the four different case studies. While colors with different reflectivity are used to check the albedo effect on the average surface temperature of buildings, the H/W ratio is used as the strategy to evaluate the urban physics effect that depends on shadowing and ventilation. Likewise, the different roof design is a parameter that affects natural ventilation by changing vertical wind speeds in urban areas. In

addition, the use of heat flux values as a parameter gives the opportunity to examine where the heat from the urban area leaves the area. As a last mitigation strategy, a cool roof is selected to change the temperature on the roof part of the building and affect the wind character on the street.

This research conducted time-dependent analyses on a 3D generic urban area at a microscale. These analyses evaluated the consolidated short-wave radiation gain, increased long-wave radiation gain from the sky, reduced long-wave radiation loss, increased heat storage, evapotranspiration, and reduced turbulent heat transport. Although time-dependent analysis requires more computational power than steady-state analysis, transient simulations are capable of modeling dynamic conditions such as urban heat island and wind flow patterns. In line with the time solver type and aim of the study, real meteorological data which are obtained from Turkish State Meteorological Service (TSMS) (Yesilkoy/Istanbul) are preferred instead of parametric meteorological data such as constant wind speed or temperature as input [66]. To mitigate the UHI effect, the thermal performance of the urban area is analyzed, and strategies are quantified.

2.4 Evaluation Approaches

Different evaluation methods are preferred for case studies used to examine the urban heat island effect in urban areas and its negative effects. This part of the study shows general information about the evaluation methods used, and details about the models created for cases are shared.

In the evaluation part, ten different parameters are used to analyze the impact of the mitigation strategies. These assessment methods are average temperature values on building surfaces, surface temperature values in urban areas, temperature values on the

street at the 1.5 meters height, wind velocity value at 1.5 meters height, monthly cooling cost ratio, unit heat flux values on control volume surfaces, average temperature differences values on canyons, gradient Richardson Number (Ri), average density values on canyons, and wind speed on the x-y-z directions through the canyons.

In the studies, the process from the first formation of an urban area to its expansion under extremely hot weather conditions is examined, and solutions are produced in response to the negative effects that arise. The albedo level effect is first examined for an urban area to be created in the first stage of the study. The average temperature values on the building surfaces are used as the evaluation parameter in the comparisons. The model with the lowest average temperature values is selected according to the albedo level parameter. Afterward, the effect of the H/W ratio increasing or decreasing on the urban area in the design, which is selected as the best model according to the albedo level value, is examined. In the examinations made among five case studies, the average temperature on the building surfaces, the temperature at the height of 1.5 meters on the streets, and the wind speed values at 1.5 meters height are used as evaluation parameters. In addition, the pedestrian wind pattern comfort criteria are also used as evaluation parameters according to the wind speed values at the height of 1.5 meters.

In the second stage of the study, the effects of weather conditions in the urban area are examined by using two different weather conditions on the five urban designs. The average temperatures on the building surfaces are used as evaluation parameters in the analysis comparing Extreme and Average Weather Conditions. In order to evaluate the need to use CFD software in studies to be carried out in urban areas, the results are compared with the TS 825 standards. In this comparison, the monthly cooling cost ratios are used as the evaluation parameter. In addition, lastly, the wind speed values at the

height of 1.5 meters are examined, and the effect of the conventional heat transfer is evaluated.

In the third stage of the study, urban areas created by adhering to the albedo level and aspect ratio parameters are used. Two more models with different roof designs are added to the five urban models owned in the first case study. In the results obtained from seven case studies in total, the average temperature values on the building surfaces and the unit heat flux values on different facades are used as evaluation parameters.

In the fourth stage of the study, the results that will emerge due to the increase in the population in the urban area consisting of 16 buildings with an albedo level of 0.6 and a H/W ratio of 1 are examined. It is assumed that with the increase in population, the number of buildings increases, and the city expands horizontally. In order to examine the negative effects caused by population growth, the average temperature value on the building surfaces and the air temperature values at a height of 1.5 meters are used as evaluation parameters. Cool surface (cool roof) is used on the roofs of the buildings to solve the high-temperature problem in the urban area, depending on the population. In order to examine the effect of the cool roof on the urban area with 64 buildings, the average temperature on the building surfaces, the average temperature difference at different heights in the canyons between the two scenarios, and the gradient Richardson Number parameters are used as evaluation parameters.

In light of the outputs obtained from the case studies and scenarios created and the different evaluation parameters used, the effect of the changes made in the urban area on the general mechanism is examined.

2.5 Location-Specific Information

Istanbul (Turkiye) is the pilot location for this study. Istanbul, where approximately 15.5 million people lived in 2020, is in a very critical position in terms of population compared to other cities, and therefore it is chosen as the reference location for this study.

In addition, studies in the literature show that the population affects the development of temperature values [33]. Also, study by Unal et al. evaluates UHI effect in Istanbul and shows that UHI got stronger as the city grew larger as a result of the city's growing population [38]. In the same study, urbanization led to a decline in green space and an increase in construction, both of which raised UHI. Based on surface temperature, the predicted urban heat island (UHI) in urban areas reached 8 °C during the day and 6 °C at night [38].

Although Istanbul seems appropriate to study the UHI effect, geographically, it is a city that deserves special attention because of its hills and canyons. The location of the weather data collection station is very important as these hills and canyons affect the weather data obtained by the Turkish State Meteorological Service (TSMS). Care is taken to ensure that the data collection station from which data will be taken is on flat land and is not affected by the surrounding hills and canyons.



Figure 2 : Map of the chosen location

For this reason, Atatürk Airport ($40^{\circ}58'34''\text{N}$ $28^{\circ}48'51''\text{E}$) meteorological data station located in Yeşilköy/Istanbul, which measures a flatter area compared to other regions, is chosen to be used in the study. The map image of the selected region is shown in Figure 2.

On the other hand, the properties of the bottom surface of the domain can directly affect the velocity profile. For this reason, the right decision should be made in the Davenport class of the studied region in order to create a realistic velocity profile [114]. According to Stewart and Oke [114], the part of Istanbul around Atatürk Airport can be called very rough in the davenport class due to the number of floors (3-5 floors and dense) of the buildings.



Figure 3 : Example street from Yesilkoy/Istanbul

In the study, while creating the generic urban model, attention is paid to the building height values which are selected to be close to the existing structures in the region. When the location is examined, it has been observed that it does not consist of uniform buildings but generally buildings with floors between 3 and 5, as shown in Figure 3. In addition, the height of the building does not have a single parameter. Also, different colors are used on the surfaces of the buildings. In addition to the aspect ratio (change with the building height) and the albedo level (change with the surface), roof type and population are chosen as parameters for the analysis to be made on the generic urban area.

2.6 Meteorological Data

Hourly meteorological data, including wind speed, wind direction, temperature, and solar radiation, are obtained from the Turkish State Meteorological Service (TSMS) for these studies.

2.6.1 Extreme Meteorological Conditions

While determining the day to be analyzed, 29th July is chosen hottest day of 2020, accessible to all weather data between 2019 and 2021. Air temperature, wind velocity, and solar radiation values are shown in Figure 4. According to Figure 4 (a), while the maximum temperature reaches almost 34 °C at 2 pm, the minimum temperature value is recorded as 21 °C at 3 am. After examining the dataset, it is determined that the prevailing wind direction is from the north to the south.

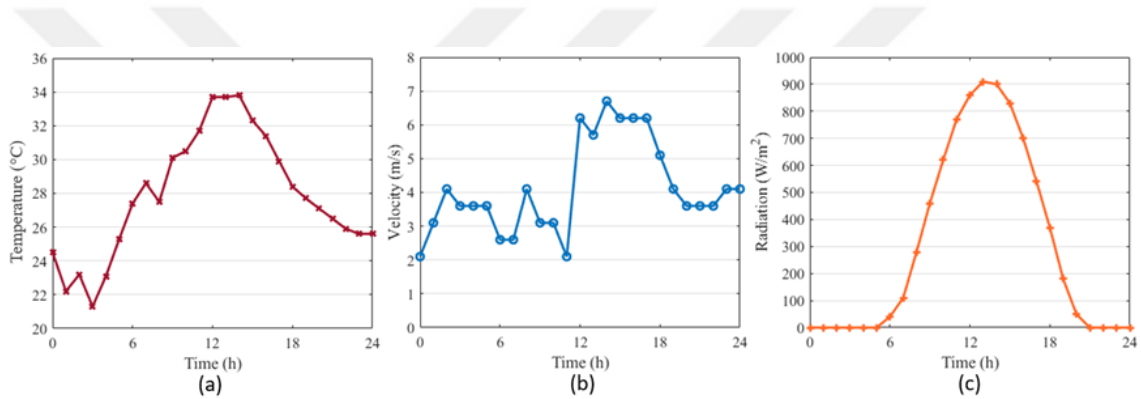


Figure 4 : Extreme meteorological data for (a) temperature (°C), (b) wind velocity (m/s), and (c) radiation data (W/m²) with hour

As per the information provided by the TSMS, wind measurements from meteorology stations are applied at a height of 10 meters. The recorded values obtained from stations at various heights are adjusted to the standard height. Upon examining the meteorological data, it is observed that the simulated wind speed at a 10-meter altitude fluctuates between 2.1 m/s and 6.7 m/s, as depicted in Figure 4 (b). Also, velocity differences between 11 am and 12 pm are found to be critical for heat transfer modeling. According to the wind velocity values, convective heat transfer coefficient values after 12 pm should be higher than before 12 pm. Increasing the wind velocity affects the convective heat transfer coefficient between the wall and air due to the direct relation

between wind speed and the convective heat transfer coefficient [115]. In addition, the global solar radiation values used in the analysis are given in Figure 4 (c). When the global radiation values are adopted in Ansys Fluent, values are separated into two parts direct and diffuse. Direct radiation from the sun reaches its target without any obstacles, whereas diffuse radiation, which is scattered by elements in the atmosphere like clouds and dust, follows a less direct path. According to Oke, the incident flux is diminished by approximately one-third due to atmospheric attenuation, which includes transmissivity, reflectivity, and absorptivity [6]. Around noon, about 25-30% of the radiation is categorized as "diffuse," while the remaining portion is classified as "direct." As the sun's altitude decreases, the ratio of diffuse radiation increases to 75% due to the longer path it travels through the atmosphere [6]. In this study, the given ratio between direct and diffuse radiation is incorporated to add radiation model.

2.6.2 Average Meteorological Conditions

In Figure 5, hourly average meteorological conditions data shows the average temperature, wind speed, and solar radiation values in July 2020. Average temperature and wind speed values are calculated separately for each hour of the day. According to Figure 5 (a), temperature values vary between 22.4 °C and 28.9 °C during the day. It is seen that the highest temperature in the average scenario is at 12 and 13 hours in the afternoon.

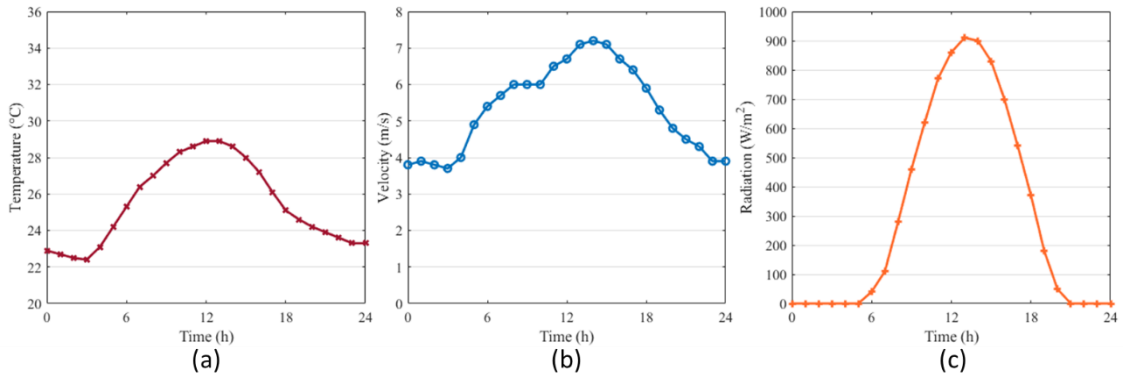


Figure 5 : Average meteorological data for (a) temperature (°C), (b) wind velocity (m/s), and (c) radiation data (W/m²) with hour

Figure 5 (b) shows that average wind speed values vary between 3.2 m/s and 7.2 m/s. When the data set is examined, it is seen that the wind directions mostly come from the northwest direction. Therefore, the average meteorological condition analysis uses the wind direction as a constant northwest. Since there is not enough radiation data in July 2020, radiation values are used in common with the extreme scenario.

2.7 Gap in the State of Art

Considering the dense population and rapid urbanization of Istanbul, it is a city that should be studied on the effects of urban heat island. As stated in Chapter 2.3, it is necessary to start taking measures for the negative conditions that may arise in urban areas as a result of the effects of urban heat island, in terms of economic and health issues. In the literature, there are microclimate modeling studies in mesoscale that examined the urban heat island in Istanbul [38][116][117], but these studies do not use CFD software to evaluate urban thermal performance and reduce the negative effects of the urban heat island. This study focuses on the strategy of reducing the urban heat island effect through different case studies and scenarios with the help of CFD software for the Yesilkoy/Istanbul region. In the analysis, the effects of design variables such as albedo level, aspect ratio, roof shape,

population and cool roof on the urban area are examined. In addition to comparing the configurations made, the analyzes examined the formation and development of a city by examining the changes that occurred due to the population growth from the establishment stage of the city.

Firstly, the initial urban area model is created depending on the albedo and aspect ratio variables. With these models, with monthly average and extreme weather data, the TS 825 standards used in the calculations for energy modeling in buildings and the results obtained from the CFD software are compared. Depending on the case studies and scenarios created, which calculation method would be more logical to use is evaluated.

In the continuation of the study, two ways are applied in the evaluation methods, different from the evaluations made in the literature. Firstly, in order to understand from which facade the heat fluxes coming out of the urban area come out more, the heat fluxes past the facades are evaluated by calculating in square meters. In this way, it is ensured that healthy comparisons are made between scenarios and control volume surfaces.

Another evaluation method that will contribute to the literature is considering the change in the wind character on canyons depending on the cool roof using the gradient Richardson Number.

CHAPTER III

METHODOLOGY

In this part of the study, the geometry details and formulation parts of CFD modeling are explained. Various studies are used as a guide for the model specifications. While studies from literature are used as a guideline for modeling the geometry of the urban area [18][118][119][120], studies by Franke et al. and Blocken et al. are used as guidelines on mesh design and details [50][51]. Study by Toparlar et al. is also followed for details on the boundary conditions and initial conditions [18]. In addition, the Ansys User's Guide and Ansys Theory Guideline are used as references for all adjustments, from mesh design in Ansys to mathematical and physical models [121][122].

3.1 Geometry Details

In the literature, domains with different geometric shapes such as quadrangular prism [123], hexagonal prism [18], and octagonal prism [119][120] are used for wind modeling. The biggest difference between the geometric shapes is the adjustment of the inlet and outlet surfaces and is chosen according to the wind direction angles to be used. The octagonal prism domain is the most useful as it allows to use four cardinal and four intermediate directions. Since two different real weather conditions are used in this study and dynamic wind direction is planned to be used in future studies, an octagonal prism is created for wind modeling in the studies. In this way, when the wind angle changes depending on the air condition, only the initial conditions are changed and the analyzes are taken again on the same model.

For the initial scenario, buildings' heights (H) and street widths (W) are taken as 10 meters, and there are a total of sixteen buildings. Additionally, computational dimensions are modified in accordance with studies by Abu Zidan et al. [118], such as incorporating upstream (l_u), downstream (l_d), lateral distance (b), and height (h), as shown in Figure 6. Based on this, the wind direction is taken as a constant from north to south, with three velocity inlets and three pressure outlets specified. The ground surface and building surfaces are modeled as walls, while other surfaces are modeled symmetrically due to the single wind direction.

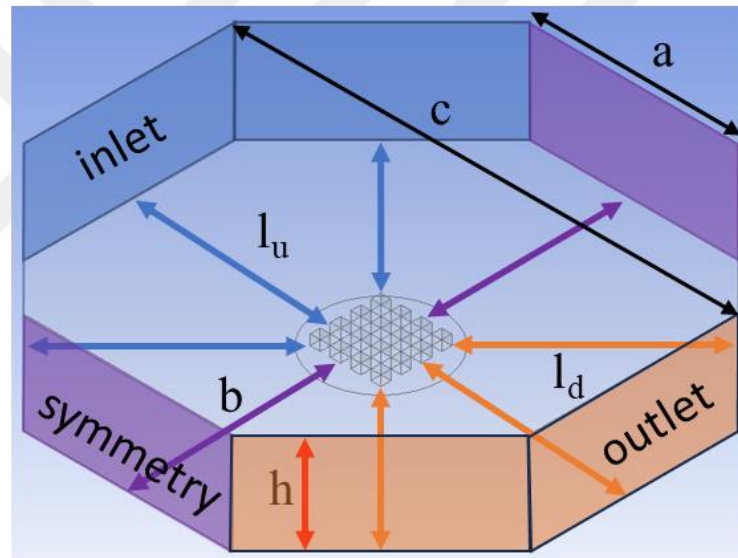


Figure 6 : Geometry of primary model

The length of the side (a), the height of the area (h), the shortest distance between the building-exit surface (l_d), and the distance between the two opposite sides (c) are drawn as 206.7 m, 100 m, 200 m, and 498.9 m, respectively. In addition, sixteen cubic buildings are located symmetrically in the center of the circular sub-domain, which has 120 meter diameter. The cross-sectional of the urban area has four buildings, and the

blockage ratio of the model is %1.4, which is less than the recommended value of %3 [50]. The dimensions used in the calculation of the blockage ratio are shown in Figure 7.

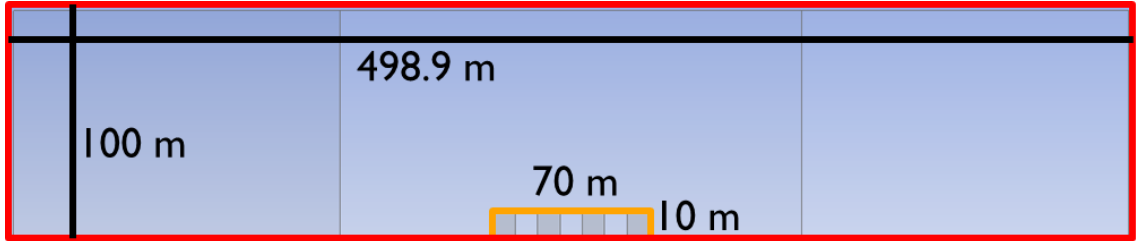


Figure 7 : Cross-sectional area of primary geometry

The created initial geometry model is used only for scenarios with sixteen buildings and H/W ratio equal to 1. The domains used in other scenarios have been re-updated according to 20H downstream (l_d) length, 10H total height of the domain (h), or less than 3% blockage rate, depending on the change in aspect ratio, roof shape, and number of buildings in the model. At the same time, the circular subdomain used around the buildings, which divides the ground surface into two parts and allows for modeling in different styles, has also been updated in other scenarios.

3.1.1 Geometry Details of Aspect Ratio Cases

In the model created for high aspect ratio (H/W), the heights of the buildings used are changed, and the buildings are designed as 15 m, but the distance between buildings is not changed. After this modification, the aspect ratio (H/W) value is increased to 1.5 for the high aspect ratio model. In addition, the height of the domain is changed at the same rate and increased to 150 meters. In this way, the total domain height of 10H and the blockage ratio are preserved in the new model.

In the low aspect ratio model, the heights of the buildings used in this model have been changed, and the buildings are designed as 7.5 m, and the dimensions of the street are not modified to decrease the aspect ratio to 0.75. In addition, the domain height is shortened at the same rate to preserve the total domain height ratio, and the blockage ratio is 1.4% which is below the recommended one. The dimensions are 206.7 m, 75 m, 200 m, and 498.9 m, the length of the sides, the height of the domain, the shortest distance between the building-outlet surface, and the distance between the two opposite sides, respectively.

3.1.2 Geometry Details of Roof Type Cases

As shown in the study by Yuan-Dong Huang et al. [78], roof shape and slope have an influence over the wind and the city. In the previous section, the slope value of the roof placed on cubic buildings has been increased. As mentioned in the previous sections, the buildings are cubic buildings with a width of 10 meters, a depth of 10 meters, and a height of 10 meters in the primary geometry.

While designing the roofs, the regulation created by the Istanbul Zoning Regulation is followed. According to the regulation, the slope of the roof can have a maximum value of 45%, and there is a 5 meter limit for the maximum height value of the roof ridge. On the other hand, in the regulation, there is no restriction on the shape of the roof if the ridge height and maximum slope limits are not exceeded. With this circumstance, to examine the roof effect, a total of three different models with flat roofs, roofs with maximum slope (45% slope), and roofs with average slope (22.5% slope) are used. With the roofs used, the height of the buildings and the cross-sectional area of the area to be analyzed have increased. Due to this situation, the domain has been adapted according to the new building heights.

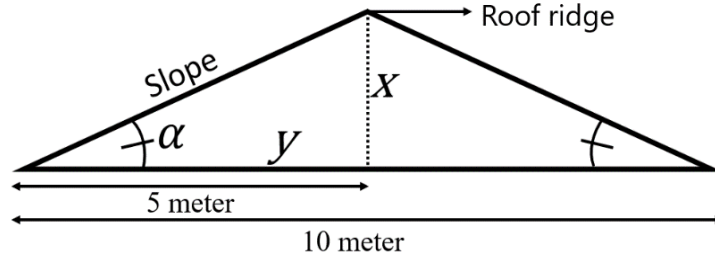


Figure 8 : Roof geometry

$$Slope (\%) = \tan (\alpha) * 100 = \frac{x}{y} * 100 \quad (1)$$

As shown in Figure 8, half of the base side length of the pyramid is equal to 5 meters. According to the Equation (1), the required roof ridge height to have a slope value of 22.5% is calculated as 1.125 meters and the required ridge height to have a slope of 45% is calculated as 2.25 meters. Due to these roofs with a ridge height of 1.125 and 2.25 meters, the height (H) of the buildings and the cross-sectional area of the region to be examined in detail in the analyzes has increased. The ratios in the physical characteristics of the urban area are also increased at the same rate, ensuring that the total area height ratio (10 H) and the blockage ratio remain 1.4% which is below recommended. The domain heights used for examining the roof effect are 112 and 123 meters, respectively.

3.1.3 Geometry Details of Population Cases

Three different models are used to examine the effect of population growth on urban area. At the same time, it is assumed that the number of buildings increases and the city expands horizontally to model population growth. For this purpose, 16, 36, and 64 buildings are located in the octagonal domain. Since the H/W ratio in the urban area does not change, there is no difference between the heights of the domains, the height of the domains is 100 meters in all population scenario designs. In these model designs, the blockage rate

value is less than the recommended value of %3. The downstream geometry ratio by recommended Abu-Zidan et al. [118] is followed, and downstream (l_d) is equal to 200 meters (20H). Domains expand horizontally with the populations, and the distances between the two opposite sides of the octagonal domains for low, average, and high populations are 498.9, 555.7, and 613 meters, respectively. In addition, circular sub-domains with three different diameters, 120, 180, and 240 meters, depending on the population, are made within the octagonal prism. Various boundary conditions are used on the ground layer area and sub-area surface, as mentioned in section 3.3.

3.2 Mesh Details

As mentioned at the beginning of the methodology section, Ansys Fluent meshing is utilized actively mesh design to prepare all of the scenarios. Particle sizes as small as 0.25 m are employed to generate fine mesh distribution across the building surfaces. However, this number rises with a growth rate of 1.1 as one moves away from the structures, which is less than the maximum value suggested by Franke et al. [50]. In areas with coarser meshes, cell size values rise to 8 meters. For all the simulations that vary based on the change in domain also employ the same physical characteristics and mesh construction techniques.

All the processes of Ansys Fluent Meshing are followed in the mesh design part. First of all, local sizing specifications are added with face sizing to building surface, and curvature and body sizing to the bottom surface of the earth. After the local sizing settings, surface mesh design is completed on the generate the surface mesh part as shown in Figure 9.

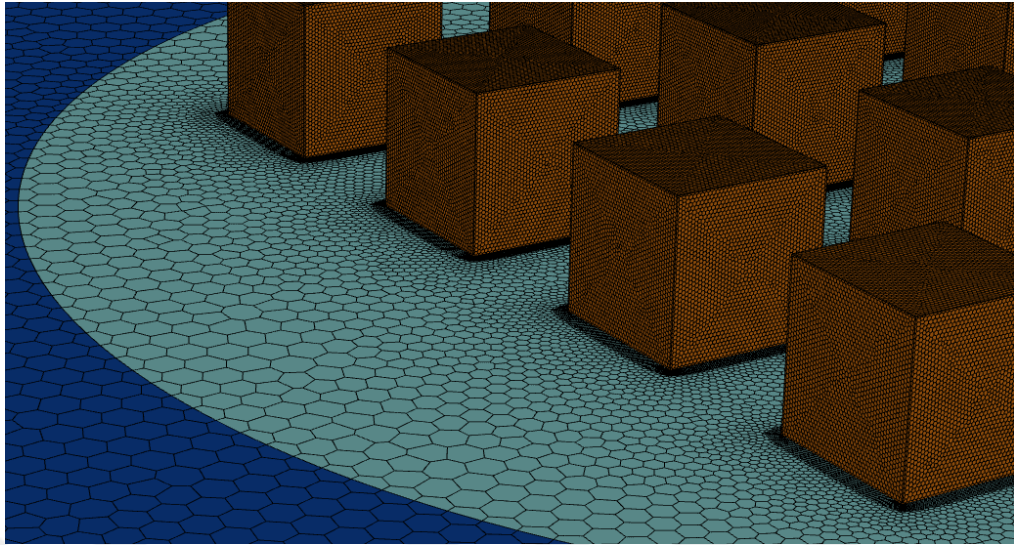


Figure 9 : Surface mesh details of primary model

When generate surface mesh is completed successfully, the application allows for checking the average and maximum skewness quality in the mesh design. Skewness quality is one of the important parameters, because it is seen that the accuracy of the result and computational time can be affected by the skewness quality metric. On the other hand, according to Ansys Fluent User Guide, the discrepancy between the form of the cell and the shape of an equilateral cell with an equivalent volume is known as skewness, and highly skewed cells might make the solution unstable and reduce accuracy [121].

Another important part of the mesh part is the generation the volume mesh. First of all, to prepare the volume mesh, the geometry should be described. In this study, only fluid region without void is used actively, and applying share topology to the domain is unnecessary. At the other step, boundaries on the domain are updated specifically as wall, velocity inlet, pressure outlet and symmetry. Information about details of boundary conditions is given in section 3.3 exhaustively.

As mentioned in the previous part, the base surface of the domain is separated into two different surfaces: the bottom surface and the interest zone (circular sub-domain).

These two surfaces are modeled with different formulations which are known as wall function. For using wall function method to solve fluid flow, specific first cell height should be regulated specifically due to local zone classification which is created by Stewart & Oke [114]. The boundary layer is created to add a specific height of the first cell with the last-ratio boundary layer method. Besides, the boundary layer is also used in wall surfaces of buildings with the uniform method and finely because airflow's effect on buildings' surfaces is wanted to be investigated exhaustively. The reason for using different boundary layers methods in the study is the opportunities of each technique. As it is seen in tries, while uniform boundary layer can not provide the exact first cell height on a huge surface such as all the base surfaces of the domain, the last-ratio boundary layer is suitable to use for constant first cell height on an extensive area.

After designing the first cell height with adding a boundary layer, the domain of the model is suitable for generating volume mesh. The point of attention is keeping the first cell height on the creating volume mesh part. As mentioned before, the minimum cell length is 0.25, and the maximum cell length is 8 meters. A value of 0 is used as the peel layer. The peel layer value is related to the hexahedra core ratio used in the transitions between the surfaces and domain. It is thought that when the hexahedra core usage rate between the two surfaces is high, it may adversely affect the first cell height. Due to this situation, this ratio has been used at the minimum level. After the volume mesh is created, the minimum and average orthogonal quality values are checked on the system. According to Ansys User Guide, the orthogonal quality of the worst cells will be closer to 0, while that of the best cells will be closer to 1 [121]. Moreover, for all cell types, the orthogonal quality should be at least more than 0.01, with an average value that is noticeably higher [121].

3.3 Boundary Conditions and Initial Conditions

For this study, hourly meteorological data such as wind speed and direction, temperature, and solar radiation are obtained and adopted from the Turkish State Meteorological Service, as explained in detail in section 2.6. The wind directions are constant, and they are determined from the dataset as north or northeast. Due to the single wind direction, there are three velocity inlets and three pressure outlets, the ground and buildings' surface are modeled as a wall, and other surfaces are modeled as symmetrical.

In inlet and outlet surfaces, UDF is used actively to create a logarithmic wind profile. The logarithmic wind speed profile, U (m/s), used in the simulation is given in Equation (2).

$$U(z) = \frac{u^*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \quad (2)$$

Davenport class	Roughness length, z_0 (m)	Landscape description
1. Sea	0.0002	Open water, snow-covered flat plain, featureless desert, tarmac, and concrete, with a free fetch of several kilometers.
2. Smooth	0.0005	Featureless landscape with no obstacles and little if any vegetation (e.g., marsh, snow-covered or fallow open country).
3. Open	0.03	Level country with low vegetation and isolated obstacles separated by 50 obstacle heights (e.g., grass, tundra, airport runway).
4. Roughly open	0.10	Low crops or plant covers; moderately open country with occasional obstacles (e.g., isolated trees, low buildings) separated by 20 obstacle heights.
5. Rough	0.25	High crops, or crops of varying height; scattered obstacles separated by 8 to 15 obstacle heights, depending on porosity (e.g., buildings, tree belts).
6. Very rough	0.5	Intensely cultivated landscape with large farms and forest clumps separated by 8 obstacle heights; bushland, orchards. Urban areas with low buildings interspaced by 3 to 7 building heights; no high trees.
7. Skimming	1.0	Landscape covered with large, similar-height obstacles, separated by 1 obstacle height (e.g., mature forests). Dense urban areas without significant building-height variation.
8. Chaotic	≥ 2	Landscape with irregularly distributed large obstacles (e.g., dense urban areas with mix of low and high-rise buildings, large forest with many clearings).

Figure 10: Davenport classification related to landscape description [114]

The roughness length is used as $z_0 = 0.5$ m due to the davenport class of the modeled area as shown in Figure 10. A reference wind speed is needed when using the logarithmic wind profile. According to TSMS, most stations take wind measurements at 10 m above ground level, and the observed values for meteorological stations measuring at other elevations are modified to 10 m altitude. Therefore, when the extreme meteorological data are checked, it seems that the simulation's wind speed changes depending on the hourly meteorological data between 2.1 m/s – 6.7 m/s at the 10 m altitude, as shown in Figure 4 (b). The formula is adapted according to the reference point, and then the wind speed based on each height is formulated. Atmospheric wind flows require turbulent modeling during the simulation. Therefore, at the inlet boundary conditions near the logarithmic mean wind speed profile, turbulent kinetic energy (k)(m²/s²) and turbulence dissipation rate (ε)(m²/s³) are determined using Eq. (3) and Eq. (4) [18];

$$k = \frac{u^{*2}}{\sqrt{C_\mu}} \quad (3)$$

$$\varepsilon(z) = \frac{u^{*3}}{\kappa(z + z_0)} \quad (4)$$

In these equations (Eq. (2)(3)(4)), u^* (m/s) is the atmospheric boundary layer friction velocity, and it is calculated depending on the reference wind speed taken from meteorology, as shown in Equation (5). z_0 (m) is aerodynamic roughness length due to local climate classification, z (m) corresponds to the height coordinate of equations, κ is the von Karman constant, equal to 0.41, and C_μ is a constant, which equals 0.09 value.

$$u^* = \frac{\kappa * U_{ref}}{\ln \left(\frac{z + z_0}{z_0} \right)} \quad (5)$$

As part of Computational Domain and Mesh Details mentioned, any structures outside the sub-domain are not modeled explicitly. For this part of the domain, the standard wall function depends on the roughness height (k_s) parameter calculated from the roughness constants (C_s) and z_0 value as shown in Equation (6) [18].

$$k_s = \frac{9.793 * z_0}{C_s} \quad (6)$$

The roughness height (k_s) parameter is essential to creating the first cell mesh design on the bottom surface of the domain. In determining the roughness height parameter, the z_0 value is accepted as 0.5 m due to the davenport classification created by Stewart & Oke [114]. On the other hand, the roughness constant (C_s) value of urban areas is calculated as 7. According to the given detail about aerodynamic roughness length and roughness constant, the roughness height (k_s) parameter is calculated by Eq. (6) as 0.7. Nevertheless, in the center of the domain, which is called the sub-domain, the ground plane is modeled as $z_0 = 0$ m. In addition, according to a study by Franke et al. [50], it is discussed that wall function can adversely affect the accuracy of surface heat and mass transfer calculations of complex 3D flows since it does not resolve the viscous sublayer and buffer layer. Correspondingly, smooth wall modeling is preferred on the building's wall and the surface of the circular sub-domain in this study. As a result of this choice, adequately fine cell particulars are used instead of wall function parameters.

While the thermal information of the surfaces is added, the internal air at the building is assumed to be 24 °C. The convection heat transfer coefficient value is chosen as 20 W/m²K since windows and any openness are not modeled in the study [124]. Because of not modeling any openness in the building, the convection type is assumed to be natural convection. Brick material is used as a construction material on the surface

with a 0.4 m thickness value. Also, as seen in Table 1, the absorptivity values used for wall materials are 0.4 - 0.6 - 0.75. As in the study by Toparlar et al. [18], windows on building surfaces are not modeled and permeability is ignored. In this case, it can be said that the absorptivity value is equal to the value of 1 – albedo level. The earth's material is created with the same specific thermal properties for all ground surfaces for the ground layer in ANSYS software. The thermophysical properties of materials used in primary model are provided in Table 1.

Table 1 : Thermophysical material properties

Materials	Density (kg/m ³)	Specific Heat (J/kgK)	Thermal Conductivity (W/mK)	Albedo			Emissivity
Earth Materials	1150	650	1.5	0.4			0.9
Wall Materials	1400	900	1.7	0.25	0.4	0.6	0.88
Roof Materials	1400	900	1.7	0.25	0.4	0.6	0.88

In addition, the ground layer of the domain is modeled with a 10 m thickness and 10 °C constant temperature is added at 10 meters below ground. Earth material is created according to values represented in Table 1. The top surface of the computational domain is formed as a symmetry because this surface type includes zero normal gradients for all variables. At the earth's surface, heat flux values are used actively to add the evapotranspiration effect, which is generated by the impact of the green area. These heat flux values are changed according to time and radiation; for instance, it increases to 246 W/m² at the time from the first light of the day until the sun's rays are perpendicular, then it starts to decrease again. When the values for the evaporation effect are evaluated in the

investigation, the evapotranspiration values are adopted project's scenarios and location according to literature studies [18][125].

It is mentioned in section 2.7 that while evaluating the analysis results, heat flux values on the control volume surfaces are used to understand the direction of the wind exiting the urban area. Q_{conv} and Q_{turb} are determined to calculate the heat flux on surfaces of control volume that is built around the buildings [56][126]:

$$Q_{conv} = \int u(T - T_{\infty})c_p\rho dA \quad (7)$$

$$Q_{turb} = \int k_{eff} \frac{\Delta T}{\Delta n} dA \quad (8)$$

In Equations (7) and (8), u is the velocity component normal to the investigated plane, T is the temperature, which is obtained from control volume, T_{∞} is the reference temperature for flow, c_p is the specific heat capacity, ρ is the density of air, k_{eff} is the effective thermal conductivity, and n is the direction normal to the plane.

Also, another evaluation approach mentioned in section 2.7 is the gradient Richardson Number (Ri). It is used as the evaluation parameter in the last scenario of analysis. Richardson Number is used to assess the relative importance of convection and the turbulence caused by mechanical wind shear [127]. Many studies in literature have used the Richardson number in various ways, such as the bulk Richardson Number, the flux Richardson Number, and the thermal Richardson number. In the literature, the Richardson Number value used to interpret the convection type in urban areas is calculated by the relationship between the temperature of a heated surface and the reference temperature value. According to the result, it is understood which type of convection (natural or forced convection) the heat transfer in the model has. As in

atmospheric studies, the relationship between points and planes created with certain distances is examined in this study. That's why this article uses the gradient Richardson number as an evaluation parameter and calculated as Equation (9) [128];

$$Ri = \frac{-\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \quad (9)$$

In Equation (9), g presents gravitational acceleration ($9.81 \text{ (m}^2/\text{s}^2)$), the density value of the air is shown as $\rho \text{ (kg/m}^3)$, and $\rho_0 \text{ (kg/m}^3)$ is the specific density of air. Also, $u \text{ (m/s)}$ and $v \text{ (m/s)}$ represent horizontal wind speed values for the x and y directions. The part that depends on the density change is interpreted as the buoyancy term, while the denominator part is considered as the mechanical wind shear term. According to a study from the literature, small positive Richardson numbers point out a stably stratified environment with significant wind shear and mechanical turbulence, while negative Richardson number values suggest an unstable stratification that creates thermal turbulence [128]. Thermal stability eliminates mechanical turbulence and produces a stable boundary layer at high positive Richardson numbers. Firstly, in this evaluation method, a line is placed at the midpoints of the corridors from 1.5 m to 10.5 m. The aim here is to evaluate the wind character in the corridor shortly. However, the density, velocity u , and velocity v values taken from a point represent an area of 100 m^2 in this method. Therefore, the Richardson Number values calculated together with the line do not give logical information about a certain height in the corridor. It has been seen that the density and velocity values of all cells on the plane should be added to the calculation in order to understand the general character of the selected area. That's why square planes with 100 m^2 are used as a control mechanism to have information about the wind character

at a certain height. Also, these planes are positioned between 1.5 meters and 10.5 meters in the corridors between the buildings, with a total of 19 planes with a difference of 0.5 meters between them. Average density, velocity u , and velocity v values taken from planes give more successful and consistent results to understand the general character at a certain height. However, while calculating the average density, velocity u , and velocity v values in square planes, the sum of the values in each cell is not divided by the total number of cells. If the areas of cells are not considered, a realistic value will not be obtained because the areas are different. That's why the values are multiplied by the ratio of the cell area to the total plane area, and the values from each cell are added to get the average value.

3.4 Setup Specifications

The first part of the setup allows for the specification of general settings about the unit, solver type, velocity formulation, solver time, and gravity. All the cases have the same general setting with the pressure-based solver type, absolute velocity formulation, time-dependent analysis type (transient), and gravitational force active in the negative z -direction. The formulations related to heat transfer and flows, which are the main purposes of using CFD analyzes, are shared in more detail in sections 3.4.1 and 3.4.2.

3.4.1 Heat Transfer

It is possible to make many general settings in the Models task section. First, it allows the calculation of energy or heat transfer equations of the model using the energy model. Heat transfer refers to the movement of thermal energy from one area of space, where matter is present, to another area of space that contains different matter. ANSYS Fluent uses different versions of the energy equation, depending on the issue addressed, and considers the specific heat transfer techniques designated. In this study, energy equations are

actively used since the effects of heat and wind on the building surfaces on the temperature of the building surfaces are the parameters to be examined [122]. The equation used to activate the energy equation in Ansys Fluent is shown in Equation (10).

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\bar{v}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \bar{J}_j + (\bar{\tau}_{eff} \bar{v}) \right) + S_h \quad (10)$$

Where E is the total energy, k_{eff} is the effective thermal conductivity value, J_j is the diffusion flux of species j . In Equation 10, initial three terms on the right side indicate the transfer of energy that arises from conduction, diffusion of species, and the dissipation of viscous forces, in that order. In addition to that, According to Ansys Tutorial Guide, Equation (10) accounts for pressure work and kinetic energy, but in incompressible flows, these terms are typically insignificant. Therefore, the pressure-based solver does not consider pressure work or kinetic energy by default when solving for incompressible flow. E represents energy and is calculated as;

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \quad (11)$$

And sensible enthalpy is shown with h and defined for incompressible flow as;

$$h = \sum_j Y_j h_j + \frac{p}{\rho} \quad (12)$$

In equation 10, Y_j is the mass fraction of species j and h_j is defined as;

$$h_j = \int_{T_{ref}}^T c_{p,j} dT \quad (13)$$

There are solid surfaces in the domain such as buildings' wall or earth surface. Ansys Fluent uses Equation (14) to calculate energy transport equation in the solid regions;

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\bar{v}\rho h) = \nabla \cdot (k\nabla T) + S_h \quad (14)$$

The components listed on the left-hand side of Equation (14) describe the energy transferred due to the rotational or translational movement of the solid, while the components on the right-hand side of the equation refer to the heat flow arising from the conduction process and the volumetric heat sources within the solid, respectively.

In addition, radiation model is used for modeling sun effect. The P-1 radiation model is a radiation simulation method in Ansys Fluent that heat transfer via radiation in a system. It's based on the P-1 approximation, a simplified version of the discrete transfer radiation model. Despite its simplification, the P-1 model is computationally efficient and requires less time than other radiation models. This makes it ideal for simulations with extensive geometries and complicated boundary conditions. In this study, non-gray P-1 Radiation Model Theory is used actively and the radiation equation is written as;

$$\nabla \cdot (\Gamma_\lambda \nabla G_\lambda) - a_\lambda G_\lambda + 4a_\lambda n^2 \sigma T^4 = S_{G\lambda} \quad (15)$$

In Equation (15), a_λ is a spectral absorption coefficient, n is the refractive index of the medium, G_λ is the spectral incident radiation, σ is defined as Stefan-Boltzmann constant, and $S_{G\lambda}$ is the result of the equation and can be defined as a user-defined source term. Also, Γ_λ is defined as;

$$\Gamma_\lambda = \frac{1}{(3(a_\lambda + \sigma_{s\lambda}) - C\sigma_{s\lambda})} \quad (16)$$

Besides, depending on the global position; the sun direction vector is computed from the solar calculator available in ANSYS Fluent user interface. The latitude, longitude and time zone of the Yesilkoy/Istanbul region are used, and the parameters defining the position of the global position and the solar radiation are entered into the ANSYS. The start date of the analysis is changed to 29 July, whose data are taken from

meteorology for analysis, and the start time is set to 0 hour and 0 minute. In addition, the directions of the domain created from the mesh orientation part on the model are defined to the system. In this way, the sun's movement is customized according to the desired location and time interval. Since the direct and diffuse irradiation values will be entered with UDF, the solar irradiation model has been set as fair theoretical and general values have been preferred. The Sunlight Factor is used at the default settings and the operations is continued.

3.4.2 Viscous Model

In this study, 3D URANS (Unsteady Reynolds-Averaged Navier–Stokes) equations are solved with the realizable $k-\varepsilon$ turbulence model. The solution variables in the instantaneous (exact) Navier-Stokes equations are separated into mean and fluctuating components in Reynolds averaging. Regarding the velocity components:

$$u_i = \bar{u}_i + u_i' \quad (17)$$

In Equation (17), $\bar{u}_i$ and u_i' parameters show the mean and fluctuating velocity components. In similar way, other scalar quantities such as pressure can be formulated with Equation (18);

$$\varphi = \bar{\varphi} + \varphi' \quad (18)$$

In the Equation (18), φ can denotes scalar quantities like pressure, energy and etc. The ensemble-averaged momentum equations are obtained by taking a temporal average over the instantaneous continuity and momentum equations and substituting expressions of this kind for the flow variables. They may be expressed as follows in a Cartesian tensor form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (19)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = & -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] \\ & + \frac{\partial}{\partial x_j}(-\rho \overline{u'_i u'_j}) \end{aligned} \quad (20)$$

Navier-averaged Navier Stokes (RANS) equation is calculated with Equation (19) and Equation (20). The Reynolds stresses in Equation (20) must be accurately approximated in order to use the Reynolds-averaged approach to turbulence modeling.

As mentioned beginning of this section, the realizable k - ε model is used in the study as the turbulence model because of contains an alternative formulation for turbulent viscosity and a modified transport equation for the dissipation rate, ε [TH Shih et al. 1995]. When a model is said to be "realizable," it indicates that it complies with specific mathematical restrictions on the Reynolds stresses that are in line with the physics of turbulent flows, but this indication both the normal model and the RNG model cannot be realized [122].

In the realizable k - ε model, modeled transport equations for k and ε are shown in Equation (21) and (22).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (21)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = & \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] \\ & + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \end{aligned} \quad (22)$$

Also, eddy viscosity, μ_t , is modeled from;

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (23)$$

Also, generation of turbulence kinetic energy due to the mean velocity gradients, G_k , is modeled from the exact transport equation of k , the term defined as;

$$G_k = -\rho \overline{u'_i u'_j} \frac{\partial u_j}{\partial x_i} \quad (24)$$

Effect of buoyancy on turbulence in the k - ε models for ideal gas is used and defined as;

$$G_b = -g_i \frac{\mu_t}{\rho Pr_t} \frac{\partial \rho}{\partial x_i} \quad (25)$$

where Pr_t is the Prandtl number, g_i is the gravitational vector depends on direction. According to Ansys Tutorial Guide, default turbulent Prandtl number is 0.85 for the realizable k - ε model. To model turbulent heat transport, ANSYS Fluent utilizes the concept of Reynolds' analogy for turbulent momentum transfer. The energy equation which is modeled defined by;

$$\frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_i} [u_i (\rho E + p)] = \frac{\partial}{\partial x_j} \left(k_{eff} \frac{\partial T}{\partial x_j} + u_i (\tau_{ij})_{eff} \right) + S_h \quad (26)$$

In the equation (26), E is the total energy, k_{eff} is the effective thermal conductivity, and $(\tau_{ij})_{eff}$ is the deviatoric stress tensor. The terms $((\tau_{ij})_{eff}$ and k_{eff}) is defined as respectively equation (27) and (28);

$$(\tau_{ij})_{eff} = \mu_{eff} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \frac{2}{3} \mu_{eff} \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (27)$$

$$k_{eff} = k + \frac{c_p \mu_t}{Pr_t} \quad (28)$$

3.5 Solution Parameters

There are two different solver types which are called pressure-based and density-based in ANSYS Fluent. Differences between these two types are that the pressure-based solver is typically used for incompressible, while the density-based approach is originally designed for high-speed compressible flows. Both solvers can be used for various types of flows, but one may perform better than the other in certain situations [121]. Because of this calculation differences and using incompressible flow on analysis, pressure-based approach is used as a solver technology on the analysis.

ANSYS Fluent utilizes four types of algorithms that are separated from each other for pressure-based solver type. These algorithms are known as SIMPLE, SIMPLEC, PISO, and Fractional Step (FSM). The SIMPLE algorithm is utilized in solving pressure-velocity coupling, and gradient discretization is carried out through The Least Squares Cell Based method, which assumes a linear variation of the solution and calculates changes between adjacent cells based on their center. Additionally, pressure interpolation is adjusted to the second order which leads to better results, especially for complex flows, and spatial discretization of momentum, turbulent parameters, and energy are performed using second-order upwind. The time integration method is second-order implicit. In the analysis, transient simulations are used actively instead of steady-state simulations for illustrating and evaluating all hours of the day. Transient simulations are carried out for fifteen-minute periods, and a total of 96 time steps are used for a day (24 hours). The simulation is run until all residual criteria drop to the minimum value and converge. The minimum values for different scaled residuals obtained are as follows: 10^{-3} for continuity, 10^{-4} for $u - v - w$ velocities, 10^{-4} for k and ϵ , and 10^{-7} for energy and radiation.

CHAPTER IV

RESULTS AND DISCUSSIONS

In this chapter of the study, the parts from the initial formation of the city to its horizontal expansion are examined with four different case studies and the specifications, results and discussions, and conclusions related to the studies are given below.

4.1 Case Study I - Scenario of Designing an Urban Area

In the first case study, the best configuration is created for albedo level and aspect ratio parameters by using extreme weather conditions (29 July 2020) for the chosen location. In total, the thermal performance of five different urban designs is evaluated with parameters such as the average temperature on the buildings' surfaces, the temperature on the surface of the urban area, and the air temperature and wind speed at the height of 1.5 meters.

The albedo level values for different cases are determined based on literature (0.25 is taken from Toparlar et al. [18], 0.4 is taken from Saneinejad et al. [74], 0.6 is taken from Taha [73] and Allegrini & Carmeliet, [129]), with wall surface albedo values of 0.25, 0.4, and 0.6 used for Case I, Case II, and Case III, respectively. The aspect ratio is also examined for three different cases (Case III, IV, and V) with different building heights (10m, 15m, and 7.5m). The study looked at the average temperature values on the building surfaces and considered wind velocity as an additional evaluation parameter for

the given cases. Changes on the albedo level and aspect ratio are clearly shown in Table 2.

Table 2 : Summary of the studied parameters for Case Study I

Number of Case	Scenarios	Albedo Value of Wall & Roof	Aspect Ratio (H/W)
Case I	Low Albedo	0.25	1
Case II	Average Albedo	0.4	1
Case III	High Albedo	0.6	1
Case IV	High H/W	0.6	1.5
Case V	Low H/W	0.6	0.75

4.1.1 Results and Discussions

As seen in Figure 11, the warmest value of the building's average surface temperature is seen at 11 am. Because of this, all the figures are prepared for the maximum temperature value at 11 am. The reason for the warmest value of the building's average surface temperature seems before noon time is related to wind velocity (Figure 4 (b)). Normally, it is expected to see warmer values at noon or afternoon due to the angle of the sun. However, the wind speed value at noon is almost three times more than the speed value at 11 am. With increased speed, the convection heat transfer effect changes, and this changing effect prevents the rising of average temperatures.

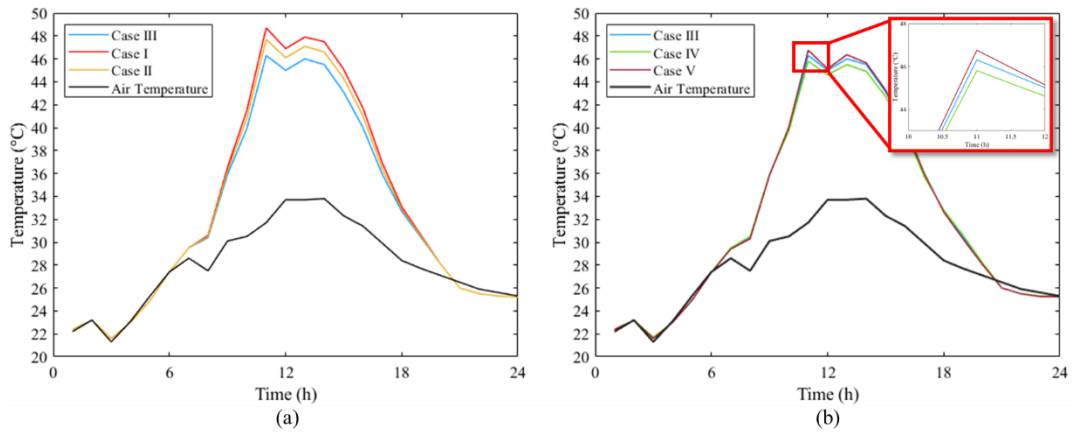


Figure 11 : Hourly average temperature on building surface (a) albedo level effect and (b) aspect ratio effect

Differences in the average temperature on buildings' (with $H/W=1$) surfaces are clearly seen in Figure 11 (a), the change depending on the albedo level of the surface material. Albedo level or shortwave reflectivity value can be calculated basically depending on absorptivity value, and the two values change inversely. The critical difference of the scenario, which has high albedo (Case III) buildings, is more heat energy reflection coming from outside compared to the other scenarios, which are called Case I and II. According to the result acquired from the analysis, temperature differences between Case III-I and Case III-II are respectively 2.4°C and 1.4°C . Therefore, Case III, with a high albedo value, can be demonstrated as the best option for chosen location due to the extreme meteorological conditions in the study.

On the other hand, the effects of the different aspect ratio values are demonstrated in Figure 11 (b). According to the results obtained from the analysis, the buildings' surface average temperature value is respectively warmest in case V, warm in case III, and less warm in case IV. According to the comparison of Figure 11 (a) and Figure 11 (b), Case IV has a remarkable average temperature value in the scenarios because the buildings' surface average temperature value in this case (with a 1.5 aspect ratio) is less warm than

in Case III (high albedo). The only difference between these two scenarios is the aspect ratio values. In addition, all the surface average temperature values are illustrated in Figure 12. The temperature distribution on the buildings' surfaces also shows that Case IV has the lowest temperature value.

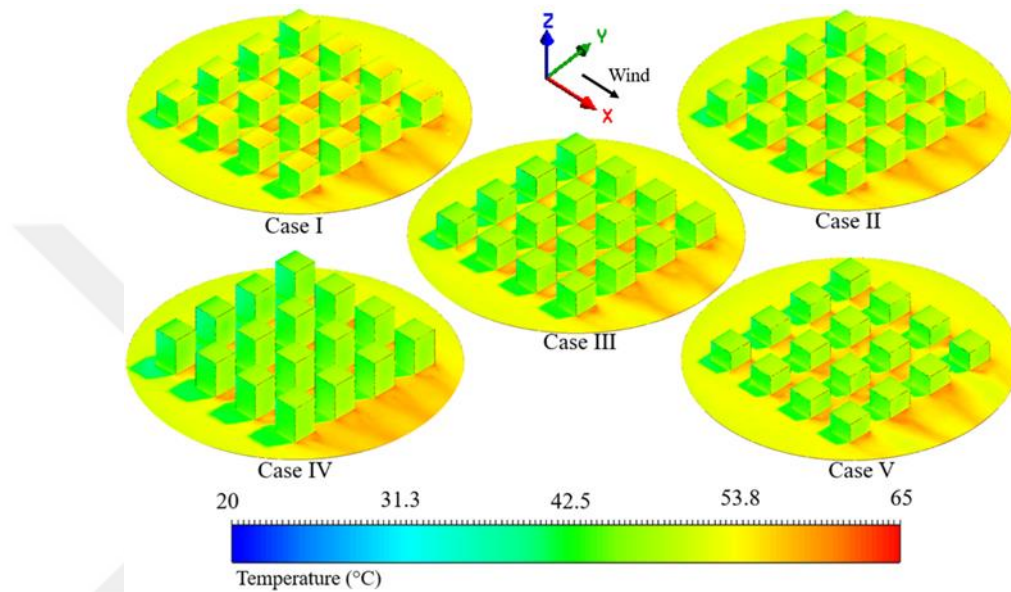


Figure 12 : Surface temperature value for 11 am

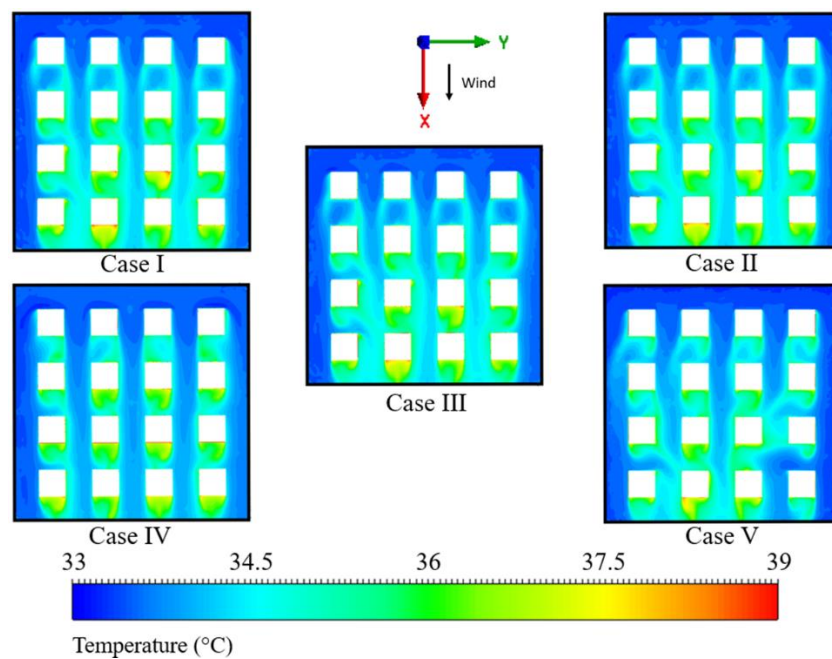


Figure 13 : Air temperature at 1.5 m height for 11 am

However, when the total height of the building increases and the distance to other buildings does not change, it affects the wind flow. As a result, the wind speed that passes through the streets, which are parallel to the wind direction, starts to increase, and with this increase, convection heat transfer also increases. Besides, in Figure 13, temperature values 1.5 meters above the ground surface are seen. Since the air temperature is lower in regions with high wind speed, the surfaces of the buildings are positively affected by this change. In addition, the wind speed maps 1.5 meters above the ground on the designed models are given in Figure 14.

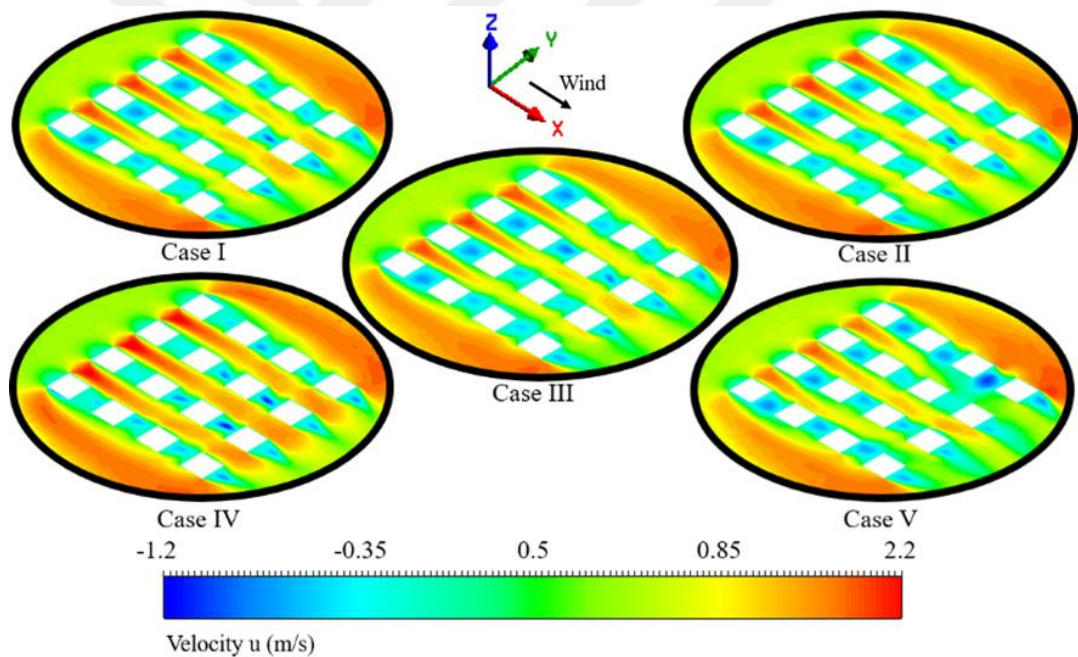


Figure 14 : Wind velocity u at 1.5 m height for 11 am

As a result of five cases, when the average temperature values on the surfaces of the buildings are examined, it is seen that the most efficient design is Case IV, which consists of buildings with a high albedo value (0.6) and a height of 15 m. However, this project aims not only to find a configuration with the lowest temperature on building or urban area modeling, even if it is on mitigation strategies. Because of that, only the

average temperature value cannot be adequate to choose the best configuration. In addition, checking the other parameters help the choice, and wind pattern comfort can also be a remarkable parameter for evaluation. The wind speed value is demonstrated in Figure 14 for all cases. According to the contour maps, the range of wind speed in the x-direction is between -1.2 and 2.2 m/s at a 1.5-meter height.

When the contour map created for Case IV is examined, the maximum and minimum wind speed difference is more significant than in other cases. In the contour map, the wind speed increases from 0.9 m/s to an average of 2.07 m/s in the models in Case I-II-III, while the wind speed increases to 2.27 m/s from 0.9 m/s in Case IV, also the speed is between 0.9 and 1.94 m/s in Case V. In a study on wind pattern comfort by Adamek et al., (2017), pedestrian wind pattern comfort criteria are separated into six groups depending on wind speed. When the obtained values are compared with these criteria, it is seen that they remain at an acceptable speed. However, looking at Figure 4 (b), it is seen that the reference wind speed used at 10 m altitude at 11 am. is 2.1 m/s. Since this value rises above 6 m/s after 12 pm, there is an increase in wind speed on the streets. Figure 15, created to control extreme wind velocities, displays wind speed 1.5 meters above the ground at 2 pm.

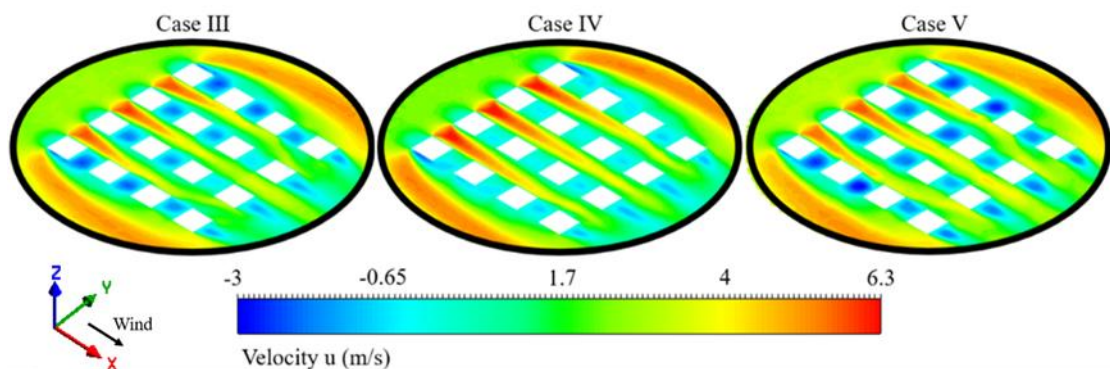


Figure 15 : Wind velocity u at 1.5 m height for 2 pm

As a result of the examination, the maximum wind speed values in the x-direction are 5.9 m/s and 6.3 m/s for Case III and Case IV, respectively. In addition, the mean wind speed in the x-direction for the middle street is found to be 3.4 m/s and 3.9 m/s for Case III and Case IV, respectively. When these average wind speed values in the x-direction in the middle street are checked according to the wind pattern comfort criteria in the literature, it is seen that Case III is suitable for people waiting in open-air restaurants, sitting areas, and waiting for bus stops, while Case IV cannot provide a suitable environment for these situations [130]. In this case, Case IV is the best configuration when comparing surface temperatures only. However, Case III seems to be a more successful configuration in projects where the wind pattern comfort parameter is important according to the intended use of the urban area to be created.

4.1.2 Conclusion of Case Study I

As a result of the evaluations, it has been determined that Case IV, which consists of buildings with a high albedo level of 15 meters, has the lowest average temperature. However, considering that the comparison of the models within the scope of the average temperature value would not be sufficient for urban modeling, the wind speed values are also checked. According to the findings of the controls, the best configuration is chosen depending on the average building surface temperature and the wind model comfort parameters. According to the 3D Transient analysis performed on Ansys Fluent, the best configuration for the specific time and space used is the city model with a high albedo level and a height of 10 meters (Case III). Thanks to the analyzes made, the positive and negative effects of the models, as well as the best configurations, have been obtained and can be used as a guide for urban areas in other projects to be made.

4.2 Case Study II - Effect of Meteorological Conditions

The main aim of this case study is to compare the extreme and monthly average weather conditions in five urban area models, designed in the first case study, and examine the effect of evaluation approaches. These configurations are analyzed using Computational Fluid Dynamics software (ANSYS) along with two different meteorological data. Models are simulated using data of July 29 of 2020 for the hottest day, and monthly average of July 2020 data. Details about the weather conditions are given in section 2.6. Table 3 presents all the specific information about the studied parameters in the cases.

Table 3 : Summary of the studied parameters for Case Study II

Number of Case	Albedo Value of Wall & Roof	H/W	Weather Condition	Number of Case	Albedo Value of Wall & Roof	H/W	Weather Condition
Case I	0.25	1	Extreme	Case VI	0.25	1	Average
Case II	0.4	1	Extreme	Case VII	0.4	1	Average
Case III	0.6	1	Extreme	Case VIII	0.6	1	Average
Case IV	0.6	1.5	Extreme	Case IX	0.6	1.5	Average
Case V	0.6	0.75	Extreme	Case X	0.6	0.75	Average

Also, in the study, TS 825 standards are used for a basic model as an evaluation approach to check the effect of the solution way. The outputs aim to enlighten the effect of weather data on the most suitable geometric configuration and best thermal

performance design for the given climate projections. The advantages and disadvantages of extreme and average weather data are presented.

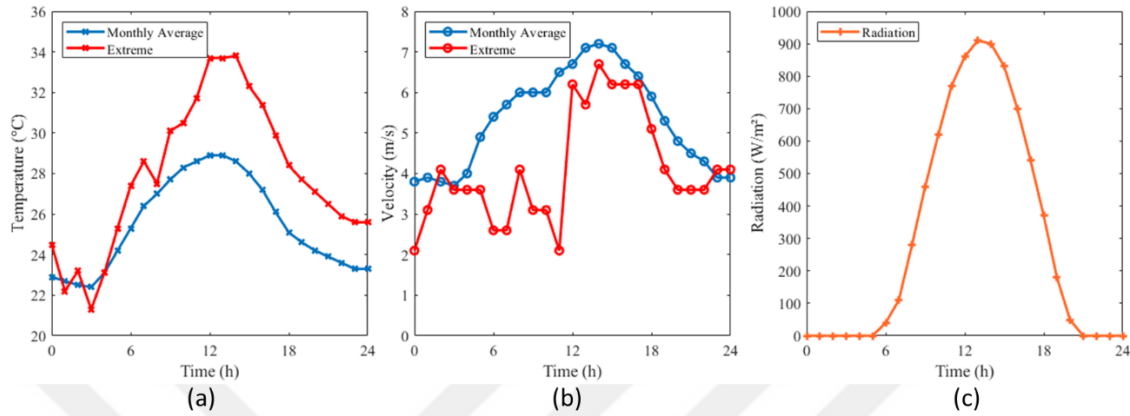


Figure 16 : Data of extreme and average meteorological conditions, (a) temperature (°C), (b) wind velocity (m/s), and (c) radiation data (W/m²)

Hourly meteorological data are adjusted to a user-defined function (UDF) for extreme (29th July 2020) and average (July 2020) climate modeling. Wind speeds, wind directions and air temperature values are modified based on scenarios. While wind which is obtained for the extreme scenario comes from the north direction, otherwise in the average scenario, the wind comes from the north-east direction and generally has a higher speed than the extreme scenario. Furthermore, wind speed differences between hours are critical because the change in wind speed is clearly smoother in average scenario data.

When the temperature value is examined, air temperature values of extreme scenarios are found to be higher than the average scenario from 4 am to end of day as shown in Figure 16. Also, the temperature differences between the two cases are increased to almost 5 °C at 2 pm. Direct and diffuse radiation values are used the same in both scenarios since amounts of radiation data are not adequate to modify to the average

scenario. In this circumstance, only wind speed, wind direction, and air temperature are specified as weather parameters.

4.2.1 Results and Discussions

In Figure 17, the highest average temperature value on the extreme and average scenarios are found to be 48.7 °C and 42.12 °C respectively. The peak hours of the highest temperatures differ between the two scenarios, with the extreme scenario showing the critical hour at 11 am, whereas in the average scenario, the warmest time of the day is 2 pm. Moreover, by examining the minimum average temperature values during the critical hours of 11 am and 2 pm in both scenarios, the results showed respective values of 45.8 °C and 40.02 °C. In light of these result, temperature differences between two scenarios are found to be 6.5 °C and 5.8 °C in maximum and minimum average building surfaces' values.

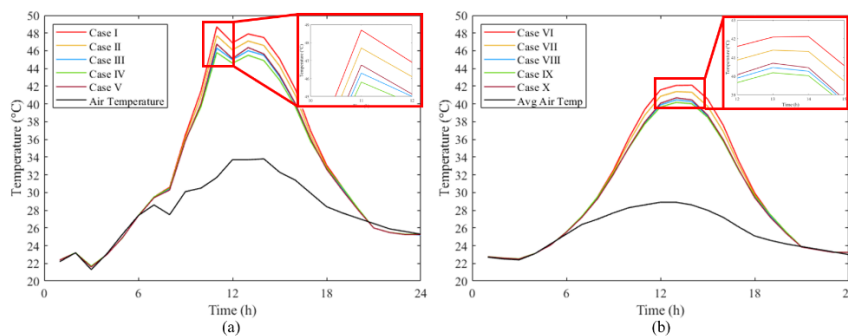


Figure 17 : Average temperature on buildings' wall in (a) extreme and (b) average data

In addition to that, when the temperature values are compared between two scenarios, for extreme weather conditions, the average surface temperatures remained higher than the maximum average temperature value of monthly average conditions for up to 5 hours. With these evaluations, the effect of the weather boundary conditions can be observed clearly. Maximum and minimum average surface temperature values are

shown in the same cases with high albedo level and 1.5 H/W ratio (IV and IX) and low albedo and 1.0 H/W ratio (I and VI) in both scenarios are depicted in Figure 18.

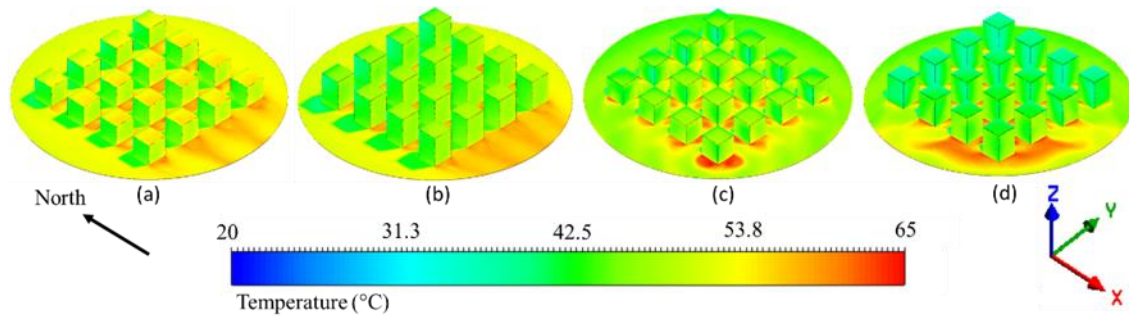


Figure 18 : Average surface temperature on cases (a) I and (b) IV at 11 am, (c) VI and (d) IX at 2 pm

Another comparison parameter to evaluate the effect of the meteorological data is the TS 825 Thermal Insulation Requirements in Buildings (the obligatory standard). Using this approach, the cases with the highest average surface temperature values (I and VI) in both weather conditions are selected, and their cooling costs are calculated. Cooling cost ratios related to five calculations are illustrated in Figure 19.

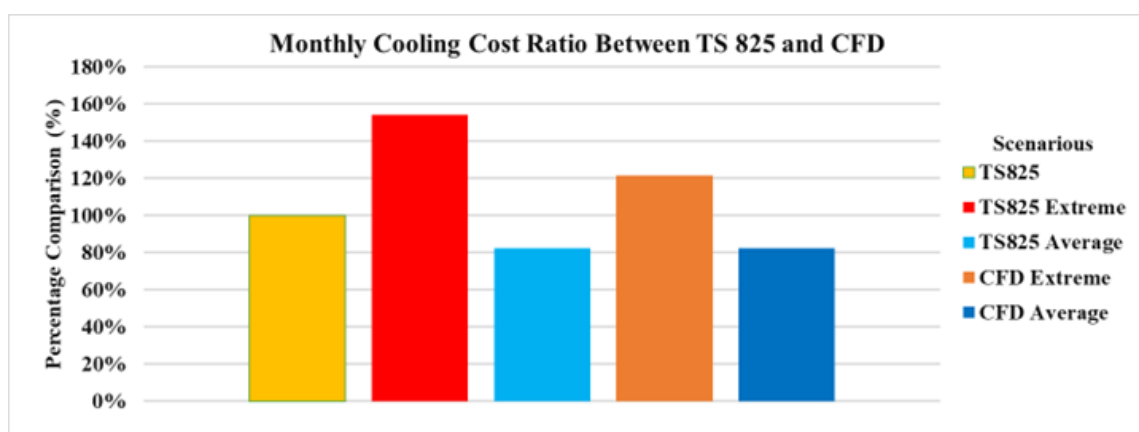


Figure 19 : Cooling cost ratios

Firstly, with the tables and data given in the standard, the cooling cost of the 10-meter-high building is calculated according to the reference values given in TS 825

formulations. The thermophysical properties of the wall given in Table 1 are used in the calculation of the reference scenario, “TS 825 Case”. In addition, 19°C, which is given as the reference monthly average indoor temperature in TS 825, is used as the indoor temperature of the building, while the outdoor temperature values are determined as 24.9°C in accordance with the second zone value reached in the guide. Similarly, other parameters such as solar radiation intensity, shading factor, and solar energy transmission factor are selected in accordance with the guide and the building. In the second and third scenarios which are called TS 825 Extreme and Average, monthly average outdoor temperatures are increased to 33.8 and 28.65 °C respectively. Also, the monthly average inside temperature is increased to 24 °C as used in ANSYS simulations. According to the results, while the cooling cost ratio increases by almost 54% in the extreme scenario, the cooling cost is decreased by 18% in the average scenario. In further analysis, the monthly costs of CFD Extreme and CFD Average are computed by determining the wall heat flux values per cell on the building surfaces using simulation results. As seen in the results of extreme and average analysis, cooling costs increased by 21% and decreased by 18%.

As a result, the monthly cooling cost value is found to be almost equal in the average scenarios, however, there is a huge difference between the monthly cooling cost value of extreme scenarios in TS 825 and CFD calculations. The cost value obtained from TS 825 guide is computed to be 27% higher than value acquired from CFD. The reason for these differences in the investigations of cost analysis is the solution details of CFD Analysis and TS 825 Guide. While TS 825 guide uses average weather conditions and locations, without actual modeling of the wind flow, CFD simulations can use specific weather conditions, boundary conditions, and locations.

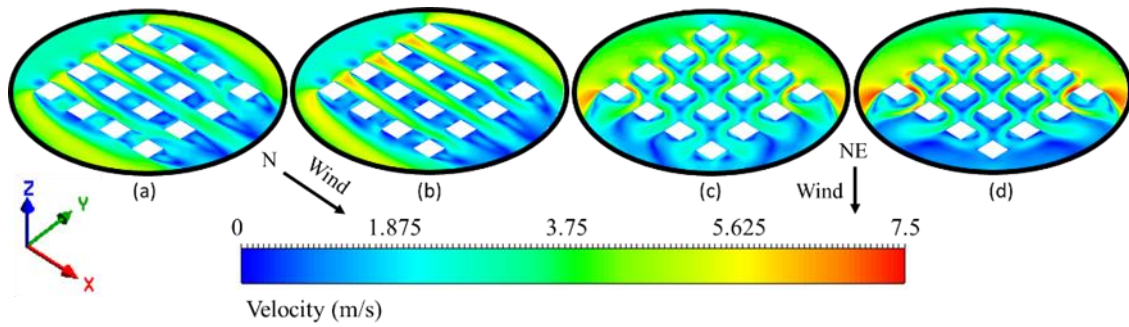


Figure 20 : Wind velocity values at 2 pm on cases (a) I, (b) IV, (c) VI and (d) IX at 1.5 m height

The wind speed values obtained at 2 pm as a result of this wind modeling are shown in Figure 20. Wind direction has a critical role in wind speeds that occur in an urban configuration. In the extreme scenario, while the wind can enter the corridors in the x direction without being blocked, this does not occur in the average scenario. In the average scenario, the wind slows down as it enters the corridors and is ineffective in heating the building surfaces. Since convective heat transfer is directly related to the temperature difference and velocity of the liquid, convection heat transfer values in the urban area are also affected by these changes in wind speed and temperature. These analyzes of the wind models of the two situations allow for a more detailed interpretation of external effects in CFD simulations. Together with the external weathers examined, more detailed solutions can be developed for the urban heat island problem in the region. At the same time, as seen in Figure 16 (b), the wind speed values of the extreme scenario are slower than the wind speed values of the average scenario according to the weather conditions. However, as seen in Figure 20, unlike the TSMS data (Figure 16 (b)), the wind speed is generally lower in corridors in the average scenario.

4.2.2 Conclusion of Case Study II

This article presents the results of five scenarios calculated using unsteady CFD simulations and TS 825 regulation for comparing the cooling costs of buildings. In the models created for the TS 825 calculation, the standards given in the TS 825 regulation are used without wind and heat modeling. Positive and negative advantages scenarios are interpreted by calculating the cooling cost as a percentage with two different examination approaches.

It has been observed that results obtained from buildings with a height of 10 meters and low albedo levels, the order made for monthly cooling expenses can be listed as “CFD Average”, “TS 825 Average”, “TS 825”, “CFD Extreme”, and “TS 825 Extreme” from lowest to highest. The results show that using CFD simulations to model the urban area with average weather conditions is not more efficient than the results from the TS 825 cases due to computational power. The TS 825 cases are more advantageous for the average scenario because of the high computation cost and simulation time of CFD methods. For instance, when the value obtained in the original TS 825 scenario is considered 100 units, the cost in the average TS 825 and CFD models is the same. However, in extreme cases, wind and heat transfer modeling in 3D configurations of CFD simulations has critical differences. Accordingly, CFD simulations created with guidelines provide low cooling costs for urban areas in extreme weather events. Considering the value obtained in the original TS 825 scenario as 100 units, the cost calculated in the TS 825 extreme scenario is approximately 33 units more than in the CFD extreme scenario. As a result, it is deemed appropriate to continue the studies with CFD software, as it is aimed to see the maximum effect in cities with extreme weather conditions.

4.3 Case Study III - Thermal Performance Analysis with Control Volume

The aim of this scenario is to determine the urban model effect on the first few meters of the earth's surface with the generic urban area which is created in the first case study and increase the thermal performance of the urban area with extreme thermal conditions. For this purpose, by adding two different roof designs to the best configuration of the first scenario, the effect of roof design on the performance of the urban area is examined and a total of seven different models are evaluated. The effects of parameters on thermal performance are evaluated using average surface temperature and heat fluxes. Similar to the study of Allegrini et al. [56], Q_{conv} and Q_{turb} are examined with the control volume created around the urban area. Unlike previous studies, the heat fluxes on the control volume surfaces are evaluated per square meter to prevent the difference due to the surface area variation. Table 4 summarizes all the case studies and the control volume around the buildings is shown in Figure 21.

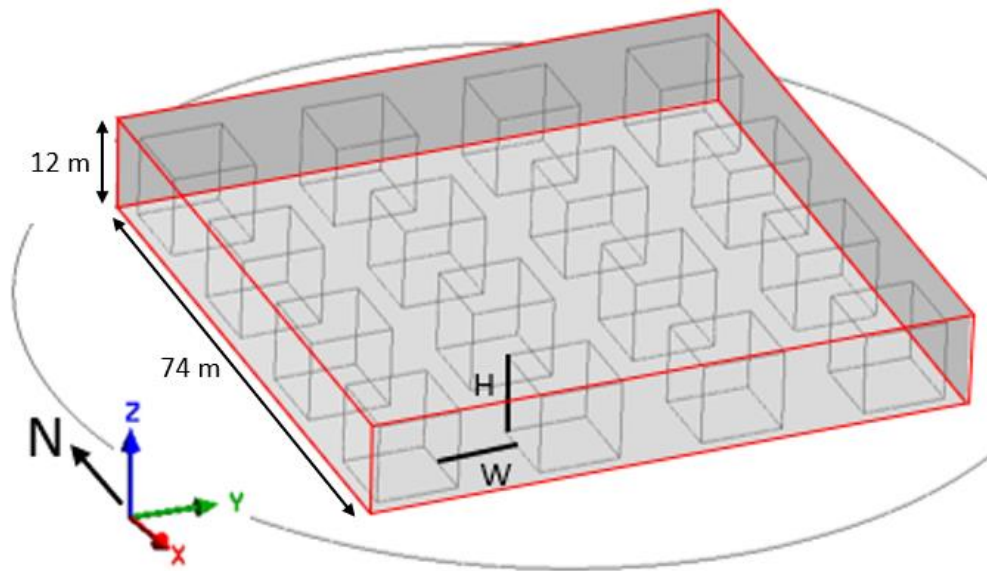


Figure 21 : Control volume of primary urban model

Table 4 : Summary of the studied parameters for Case Study III

Number of Case	Scenarios	Albedo Value of Wall & Roof	Aspect Ratio (H/W)	Roof Type
Case I	Low Albedo	0.25	1	Flat Roof
Case II	Average Albedo	0.4	1	Flat Roof
Case III	High Albedo	0.6	1	Flat Roof
Case IV	High H/W	0.6	1.5	Flat Roof
Case V	Low H/W	0.6	0.75	Flat Roof
Case VI	Average Roof	0.6	1	22.5% Slope
Case VII	High Roof	0.6	1	45% Slope

4.3.1 Results and Discussions

Two different control mechanisms, average surface temperature on building surfaces, and heat fluxes on control volume are used for evaluation. First, the average surface temperature is compared to decide on the best configuration. The hottest average surface temperature is seen at 11 am; therefore, it is chosen as the primary time for the upcoming investigations. At 11 am, the reference velocity is 2.1 m/s at 10 m above the earth's surface.

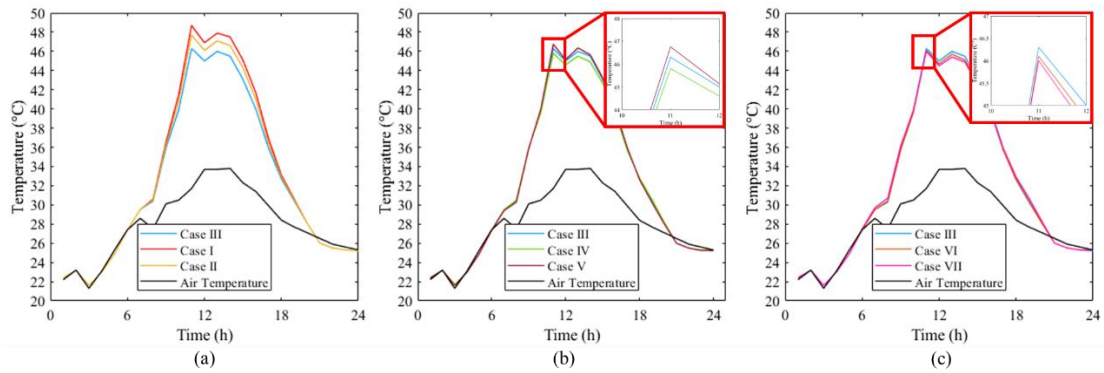


Figure 22 : Hourly average temperature on building surface (a) albedo level effect, (b) aspect ratio effect and (c) roof shape effect

As mentioned with details in the results and discussions part of the first case study, Figure 22 (a) shows that Case III has the lowest surface temperature due to the low absorptivity of the building's surface. Figure 22 (b) represents the aspect ratio effect on the average surface temperature, and Case IV has performed the best ratio in terms of surface temperature. Moreover, Figure 22 (c) compares the results of three different roof designs. According to Figure 22 (c), the roof type with a 45% slope has a higher performance in terms of the average temperature values. In general, when all cases are compared according to the average surface temperature, the cases can be listed as Case I, Case II, Case V, Case III, Case VI, Case VII and Case IV, from hottest to coldest. In scenarios where different roof designs are used, there are two reasons for the average building surface temperature to decrease. The first reason is that with the slope given to the roofs, the angle of incidence of the sun rays on the roofs has been changed. This change has reduced the absorption on the roofs, especially at noon when the sun's rays are steep. The second reason is that natural ventilation is increased by affecting the direction of the wind passing over the buildings. In this way, more air entering between the buildings made the building surfaces less warm.

Another control parameter is the heat flux through the surface of the control volume. It is created with different dimensions for all models to cover urban areas 2 m far away from buildings. Q_{conv} and Q_{turb} are calculated per cell, and the sum of the heat fluxes of the cells gives the total heat flux for each surface. In Figure 23 (a), the Q_{conv} and Q_{turb} ratio for each surface is plotted, and it shows almost 50% of heat fluxes are emitted from the upper surface of the control volume. Notably, this ratio is affected by area differences between the four surfaces. When values are compared according to the surface areas, the upper surface area can be up to 6 to 7.8 times larger than other (east, west, and south) surface areas, depending on the building height. Due to fact that, as the building height increases, the lateral surface areas grow, whereas the upper surface area of the control volume remains constant. On the other hand, Figure 23 (b) is created with heat flux per unit, and the surface area effects are eliminated. With this evaluation approach, the ratio of heat fluxes from the upper surface decreased to 15-18.5% from 50-60% on average.

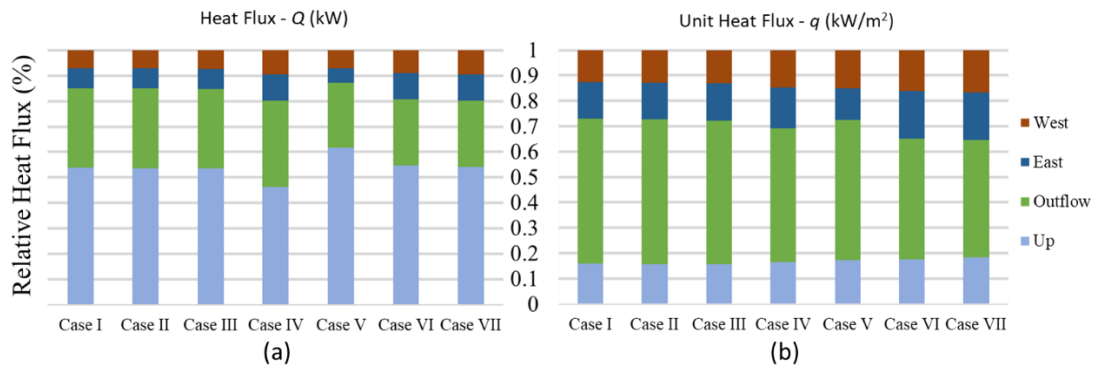


Figure 23 : Relative heat fluxes with four surfaces for urban configurations, (a) Q (kW), and (b) q (kW/m²)

While Case V has the highest percentage of heat flux leaves from the upper surface in Figure 23 (a), this ratio is decreasing, and Case VII provides the highest amount of heat

flux on the upper surface in Figure 23 (b). Furthermore, Figure 23 shows that even if the aspect ratio has the most impact on the heat flux ratio in Figure 23 (a), when heat flux per unit is determined, changes in albedo level and aspect ratio could not affect the heat flux ratio as effectively as roof design.

4.3.2 Conclusion of Case Study III

This scenario investigated the effects of various urban areas on average surface temperature and control volume and heat fluxes. Average surface temperature and heat flux distributions are used as evaluation criteria.

The reason for looking specifically at the heat flux distributions is to examine the effect of the urban area model that can be built around it. In case the heat fluxes emanating from the urban area come out of the west, east and south facades, it will increase the density of the surrounding urban heat island. In order to avoid this situation, an urban area has been created where the heat fluxes spreading around move vertically instead of the urban areas where they move horizontally. In addition, it has been observed that natural ventilation is also increased, since the increase in the heat flux from the upper surface of the control volume proves the vertical wind flow.

In the studies carried out on the control surface, the effect of the unit used is shown while examining the distribution directions of the heat fluxes to the environment. In comparisons made for the heat flux (Q) value, the increase in the slope of the roof seems to have a negative effect, while the comparison with the unit heat flux (q) shows that the increase in the roof slope has a positive effect on the urban area. Considering these observations, it is seen that examining the heat flux on the basis of m^2 gives more

successful results than the total heat flux. Also, Case VII is found to be the best configuration for average surface temperature and heat flow distribution.

4.4 Case Study IV - Cool Roof Effect on Urban Area

The fourth case study is divided into three scenarios and extreme weather conditions are used in simulations. In the first case study, two different mitigation strategies (aspect ratio and albedo level) are considered as parameters on the building surfaces in the analyzes that started on 16 buildings. As a result of the examinations made in the first case study, it is decided that the best design is Case III. More details about the first case study are presented in section 4.1.2.

In this study, it is aimed to expand an existing urban area depending on the number of buildings and to solve the problems that will arise. As it is known, population is the parameter that has a negative impact on urban areas. As a result of migration from rural areas to cities, the use of construction materials is increasing in the regions. This causes more heat absorption. Also, if the design of the urban area is not efficient, it may result in less natural ventilation and evapotranspiration. The number of buildings in the Case III ($H/W = 1$ and Albedo Level = 0.6) model which is chosen as the best design to examine the impact of the population, is increased to 36 and 64, respectively and changes in temperature values are examined. Model specifications are given in Table 5.

As a solution to the negative effects of population increase, strategies such as green roofs or aspect ratios which requires physical reinforcement or reconstruction will not be realistic due to the replacement cost incurred, in an urban area used by people. Due to this situation, it is aimed to prevent the increase in temperature caused by the population effect by using cool roofs. It is aimed to examine the wind character in the

canyons and understand the effect of the use of cool roofs on the canyons. Also, this approach will give the chance to interpret the general mechanism.

Table 5 : Summary of the studied parameters for Case Study IV

Number of Case	Considered Parameter	Albedo Value of Wall & Roof	Aspect Ratio (H/W)	Population
Case I	Low Albedo	0.25 & 0.25	1	16 buildings
Case II	Average Albedo	0.4 & 0.4	1	16 buildings
Case III	High Albedo	0.6 & 0.6	1	16 buildings
Case IV	High H/W	0.6 & 0.6	1.5	16 buildings
Case V	Low H/W	0.6 & 0.6	0.75	16 buildings
<i>Case VI</i>	<i>Average Population</i>	<i>0.6 & 0.6</i>	<i>1</i>	<i>36 buildings</i>
<i>Case VII</i>	<i>High Population</i>	<i>0.6 & 0.6</i>	<i>1</i>	<i>64 buildings</i>
<i>Case VIII</i>	<i>Cool Roof</i>	<i>0.6 & 0.9</i>	<i>1</i>	<i>64 buildings</i>

4.4.1 Results and Discussions

As a result of the measurements made both in the average temperature values on the building surfaces and in the corridors, it is observed that the temperature values increased as the number of buildings increased. Figure 24 and Figure 25 show the temperature values at 1.5 meters height and the average temperature values on the building surfaces. Figure 24 shows that in the model with 64 buildings, especially in the center and

downstream parts, the temperature increased by almost 4 °C compared to the upstream.

All three models analyzed used the same H/W ratio (1) and albedo level (0.6).

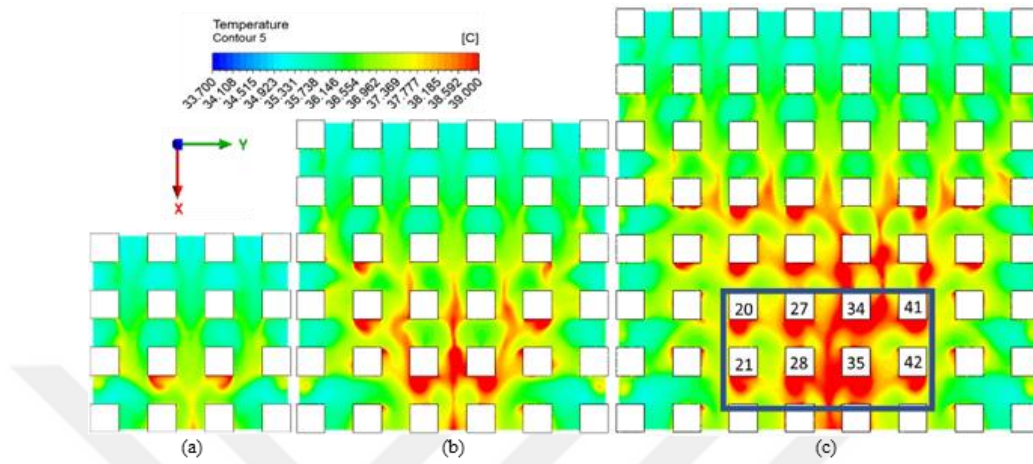


Figure 24 : Air temperature contour map at 1 pm and 1.5 m height on (a) 16 buildings, (b) 36 buildings, and (c) 64 buildings

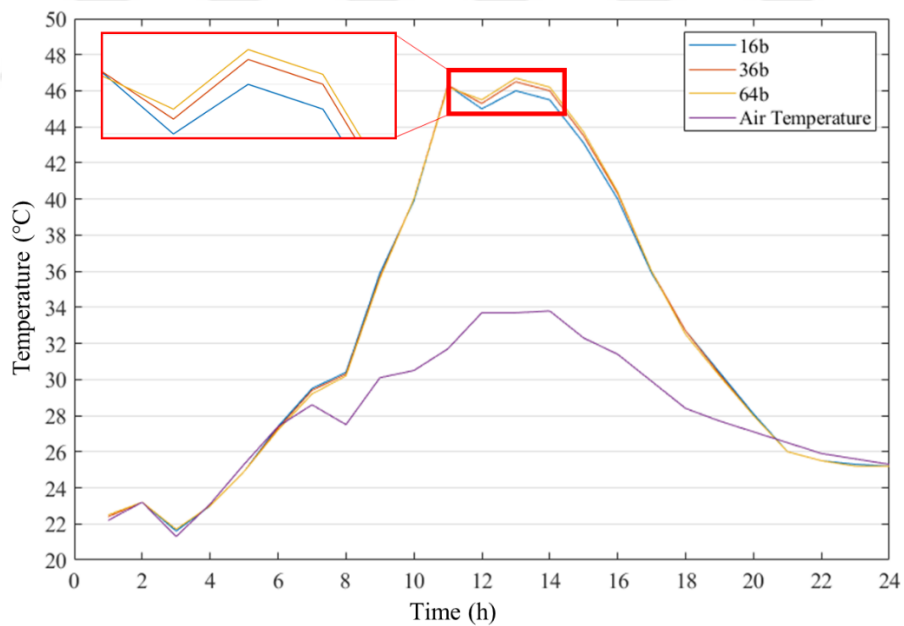


Figure 25 : Average surface temperature on buildings' surface for population scenarios

Due to this situation, the reason for the remarkable temperature increases in the configuration consisting of 64 buildings is the decrease in the wind speeds in the x and y

directions downstream. These increases in the air temperature of the street have a negative impact on the building surfaces because cooling energy demand is increased related to surface temperature. This population study shows that the H/W ratio and albedo values used do not work adequately for large urban areas. Cool roof mitigation strategy is used to eliminate the temperature increase observed in the model with the highest population.

The advantages and disadvantages that arise with the cool roof effect have been examined in three different ways. First, the average temperature values on the surfaces of the buildings are compared. The average buildings' surface temperature values obtained are shown hourly in Figure 26.

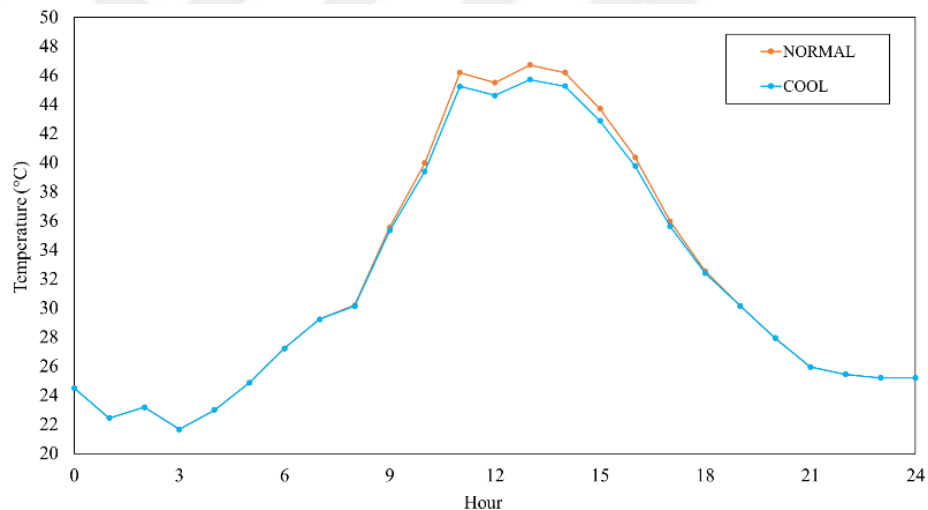


Figure 26 : Average buildings' surface temperature

As can be seen in Figure 26, the average temperature value on the building surfaces decreased with the cool roof effect, especially during the hours when the sun effect is high, that is, from 9 am to 6 pm. While the most striking differences are between 11 am and 2 pm, the maximum difference occurred at 1 pm with 1 °C. Also maximum average surface temperature value is seen at 1 pm. The point that should not be ignored here is that when the temperature value on the roofs decreases, the temperature of the

wind entering the corridors decreases. For this reason, cooling is provided on the northern facades of the buildings as well as the roof.

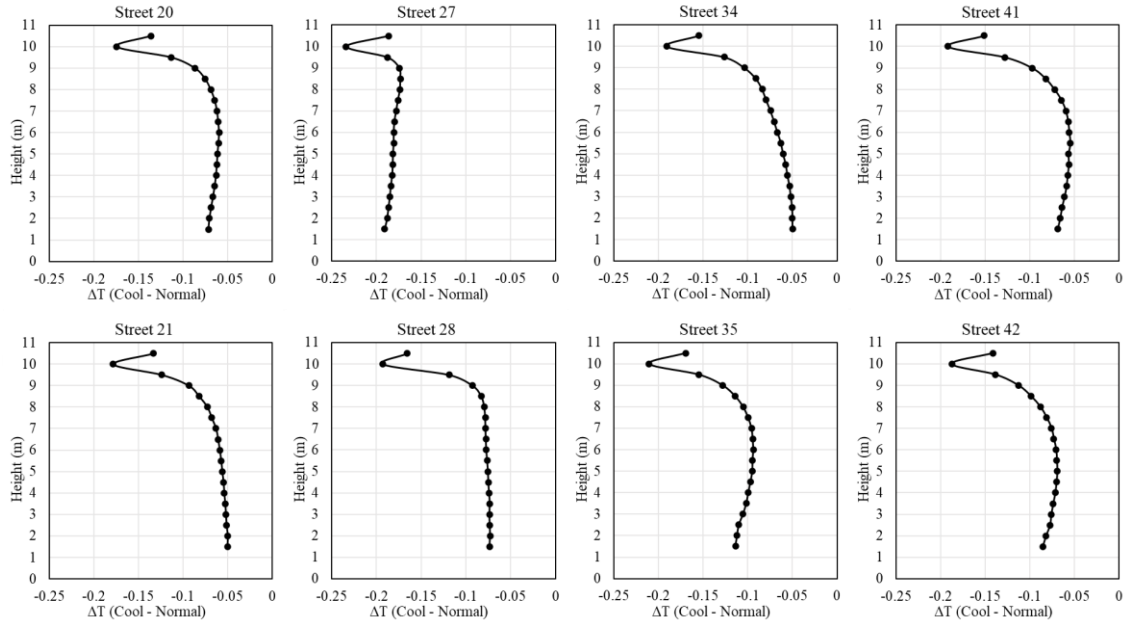


Figure 27 : Decreases on average street temperature (Cool – Normal) for 64 buildings between 1.5 and 10.5 meters heights at 1 pm

The second evaluation approach is the differences in the air temperature between the buildings. According to the given temperature contour map at 1.5 meter height, since there is not much heating in the upstream and side areas, the study focused on the corridors, which are heating more. The corridors (20 – 21 – 27 – 28 – 34 – 35 – 41 – 42) are shown in Figure 24 (c). The differences in the average street air temperature values between normal and cool roof scenarios obtained as a result of the change are shown in Figure 27. The differences in values on the planes with a height of 10.5 meters from 1.5 meter that the heating in the corridors. According to the calculated temperature difference (cool-normal) values, the most striking value between the two scenarios is seen in Corridor 27. Corridor 27 has the most difference both in the lower levels of the corridor and in the upper parts where the wind enters the corridor. In addition, when the values are

examined in general, the effect of the cool roof in the graphs created for corridors 20, 27, 35, 41, and 42 has a more significant cooling effect in the near-to-ground parts than in the middle height. On the other hand, the difference increases as the rise from the ground in corridors 21, 28, and 34, for this reason, it can be said that the cool roof effect is less visible in the lower parts of these streets. In order to understand the different behavior in corridors 21, 28 and 34 compared to other corridors, the character of wind due to buoyancy and mechanical shear terms need to be examined with the gradient Richardson Number as a third evaluation way in the study.

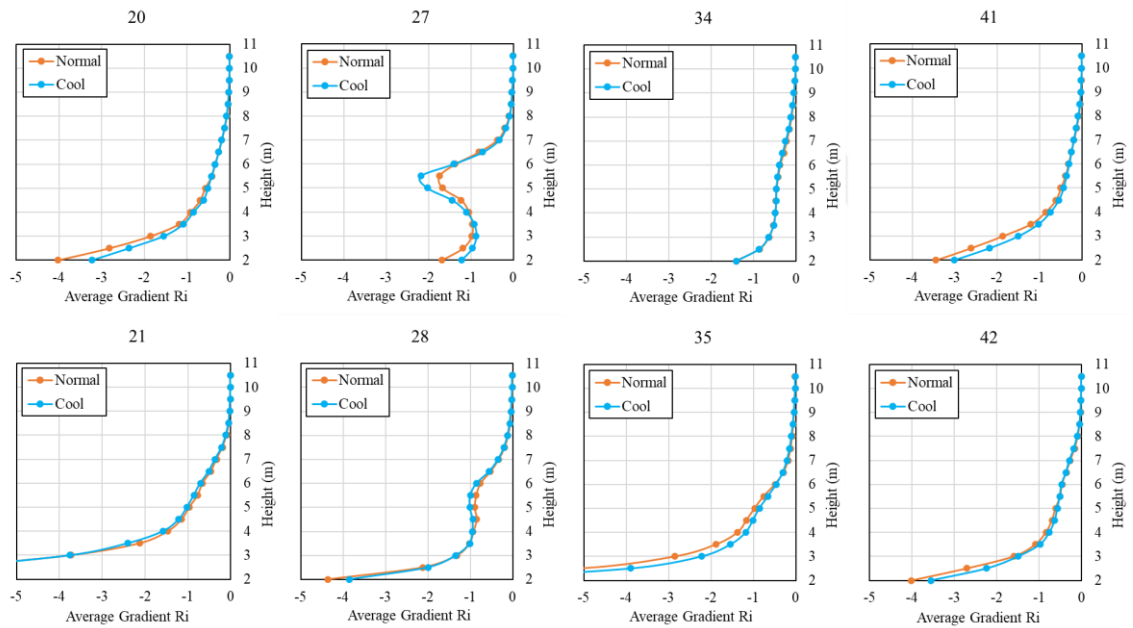


Figure 28 : Gradient Richardson Number values on planes of 64 buildings at 1 pm

The orange values show the gradient Richardson Number values in the 64-building model with a standard roof, while the blue values show the gradient Richardson Number values in the 64-building model with a cool roof in Figure 28. When the values are examined, gradient Richardson Number values at 2 meters show that there is unstable stratification that creates thermal turbulence, while gradient Richardson Number values

at 10.5 meters show that a stable layered environment is formed by approaching zero. The corridors considered for evaluation can be divided into three groups. Groups can be formed as positively affected (streets 20, 35, 41, 42), fluctuating (streets 27, 28, 34), and negatively affected (21) until six-meter height. In general, after a height of 6 meters, the gradient Richardson Number goes to negative in all corridors. It is seen that gradient Richardson Number of the cool roof scenario is closer to neutral than the normal roof scenario between 2 meters and 6 meters in corridors 20, 35, 41, and 42. On the other hand, in Corridor 21, the wind character has moved away from neutral to unstable with the cool roof effect. At the same time, there are fluctuations in the gradient Richardson Number in corridors 27, 28, and 34. This movement is due to the difference in density between the two planes being greater than the difference in wind speed at corridors having fluctuations. However, these two changes must be checked to see if the gradient Richardson Number variation between the lower and upper planes the main cause of the differences in density or wind speeds.

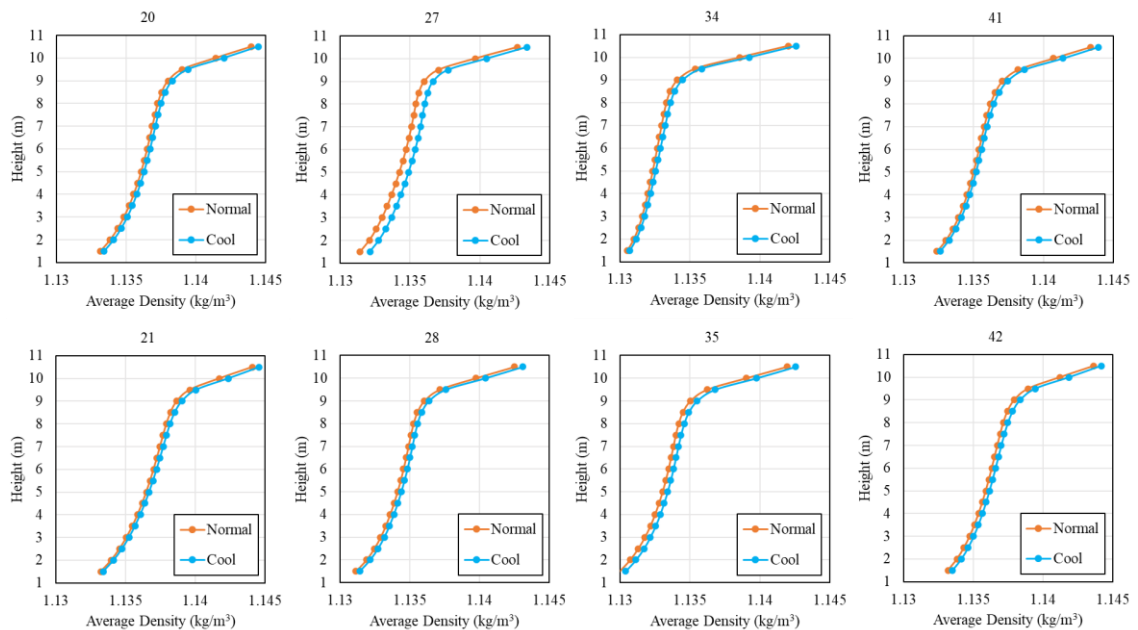


Figure 29 : Average density of planes at 1 pm

In Figure 29, where the average density values are shown, the blue points in all corridors have higher average density values. Especially in corridor 27, the difference in density at 2 meters in height is at a remarkable level. However, the point to be noted here is the density change between the individual planes for the two scenarios. Therefore, when looking at the corridors, the difference between the average density change of the orange and blue points in the two scenarios must be calculated, and its effect on the buoyancy term should be considered. In Figure 29, it is seen that the density values increase very much after 8 meters of height in the corridors in the urban area where there are buildings with a height of 10 meters. This increase is because the ambient temperature is lower than the temperature in the corridors.

Also, another point to be considered is the difference between the wind speed near the ground and the reference wind speed. When the wind speeds in the x direction, which is the flow direction of the analysis, are examined, it is seen that the wind speed variation in the upper parts of the street is much greater than in the lower parts, as given in Figure 30. Also, other average horizontal wind speed values in y directions in the planes are shown in Figure 31. Depending on the formulation of the gradient Richardson Number value, the decrease in the difference of the density values and the increase in the differences of horizontal velocity values bring the air closer to the neutral state.

Under ordinary circumstances, these differences in density values are expected to affect the gradient Richardson Number and result in an unstable character. As shown in Figure 30, the increase in velocity u values is higher than the density values. Therefore, the gradient Richardson Number values calculated are close to the neutral character after 8 meters of height according to the average density and average velocity figures.

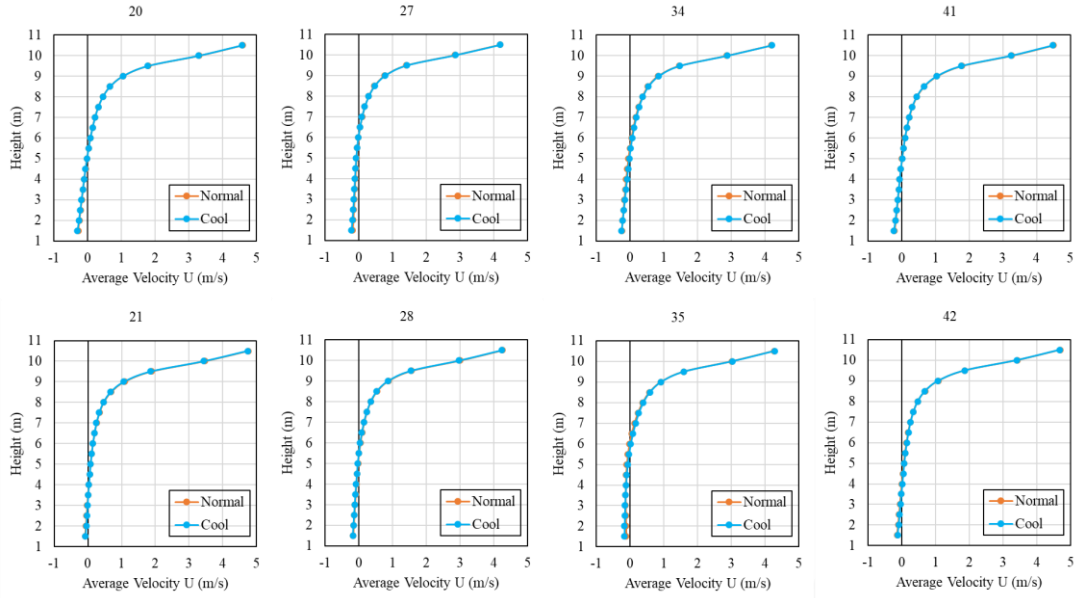


Figure 30 : Average velocity u values of planes at 1 pm

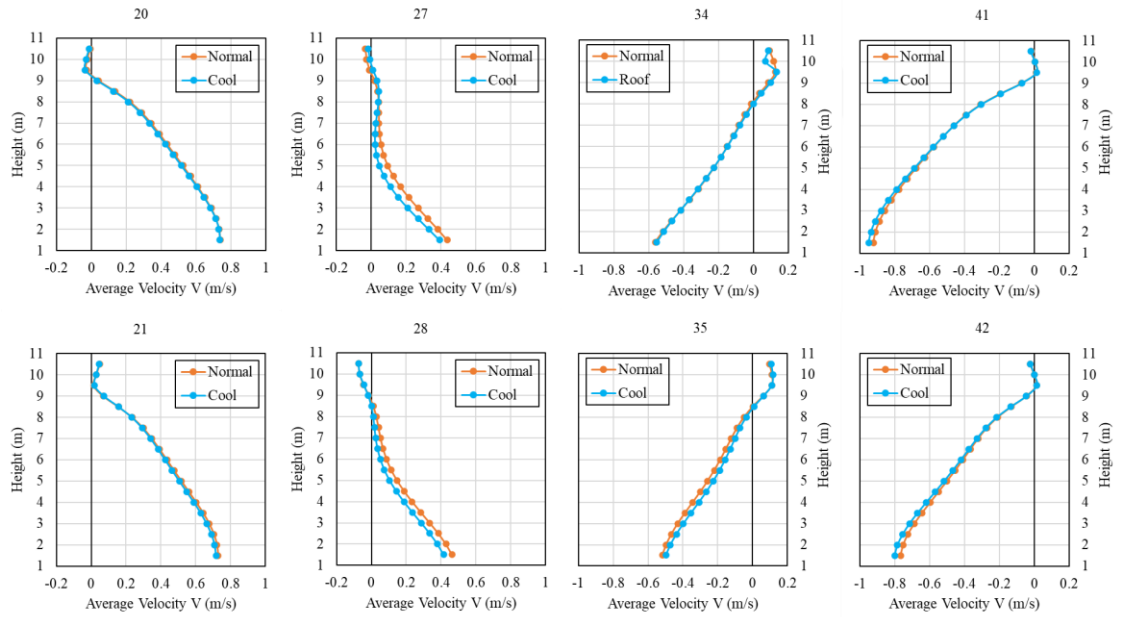


Figure 31 : Average velocity v values of planes at 1 pm

While the wind speeds in the x direction exceed 4 m/s after 8 meters of height, the average value of the wind speeds in the y direction decreases as the height increases. Depending on the average velocity value range, the difference in velocity u values between the two scenarios is not clearly visible. However, since the range in velocity v

value is less, the difference between the two scenarios is more obvious. In summary, when the effect of horizontal velocities on the gradient Richardson Number is examined, the character of the wind in the region automatically moves towards neutral since the average velocity u value reaches very high speeds at positions higher than 8 meters. For this reason, it will be more useful to examine the buoyancy and mechanical shear thermal change rates between 2 meters and 8 meters to examine the effect of the cool roof on the corridors.

Also, the other difference between the two wind speed parameters is the change in wind direction. As mentioned in the Methodology section, the wind direction of the analysis is from negative x to positive x direction. Although no velocity is entered in the y direction as the initial condition, the y direction velocities are formed in the corridors with the effect of the buildings. Since the building effect in the higher parts of the urban area is less than in the lower parts, the average velocity v value also decreases depending on the height. Velocity v values show that there is flow from the sides of the urban area towards the center of the urban area. When these velocities in the y direction are examined, it is seen that the velocity values in the outer corridors (20-21-41-42) are higher than in the inner corridors (27-28-34-35). This variation in wind speeds shows how the increasing number of buildings, depending on the population, reduces the natural ventilation in the center of the urban area. In order to understand the character inside the corridor, the air character between 2 meters and 8 meters is examined with the buoyancy term and mechanical shear in Figure 32 and Figure 33. Buoyancy term values are adapted with the maximization ratio and maximum value (in Street 41 and at 8-meter height ($\Delta_{\text{buoyancy}}=0,000232$)) on between 2 and 8 meters is shown as a unit.

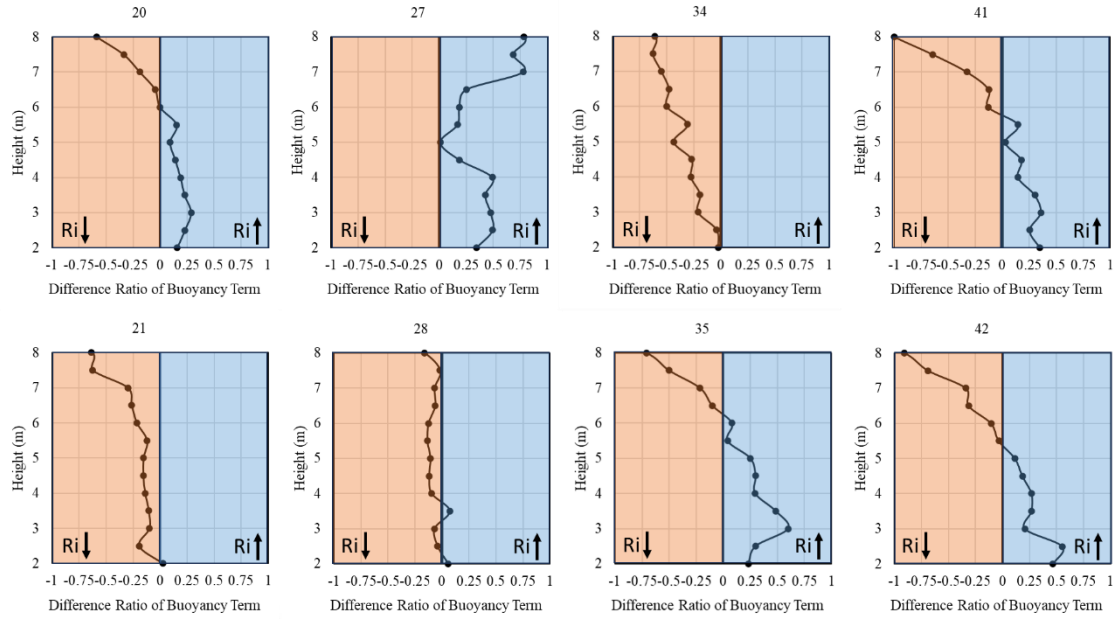


Figure 32 : Buoyancy term with global maximization between 2-8 m heights at 1 pm

When looking at the buoyancy term for interior and exterior corridors in Figure 32, it is seen that the cool roof decreases the buoyancy term ratio between 2 meters and 5.5 meters in corridors 20-27-35-41-42. However, the changes in the buoyancy term affects negatively the gradient Richardson Number between 5.5 meters and 8 meters. In corridor 27, it is seen that the density difference ratio between the planes in the cool roof scenario is less than in the normal scenario and positively affects the gradient Richardson Number. In summary, according to the results obtained from the five corridors that have a positive effect, the temperature and density variation between the planes is less in the cool roof scenario than in the standard scenario. This situation can be interpreted as a decrease in the temperature values observed on the floor surface as well as the average air temperature in the corridors. The other corridors numbered 21-28-34, on the other hand, affect the gradient Richardson Number negatively, as mentioned before. It is seen that the buoyancy effect, which is basically dependent on the temperature change, does not give a symmetrical result in the corridors. The reason for this situation is that the

analyses are taken transient, although the created urban area is a symmetrical urban area. In the analysis, the sun rises on the right (+y) side of the model and sets on the left side (-y) and gradient Richardson number calculations are based on values at 1 pm, the hottest hour.

The difference ratio of mechanical turbulence values between normal and cool roof is another parameter to be considered in order to fully understand the effect of the cool roof reduction strategy on corridors. Horizontal wind speed differences between planes are investigated in terms of mechanical effects. The results obtained are shown in Figure 33. Also, mechanical shear differences between normal and cool roof values are adapted with the maximization ratio for comparing the street each other and maximum value (Street 35 and 8 meter height ($\max \Delta_{\text{wind shear}}=0,00238$)) on between 2 and 8 meters is shown as a unit.

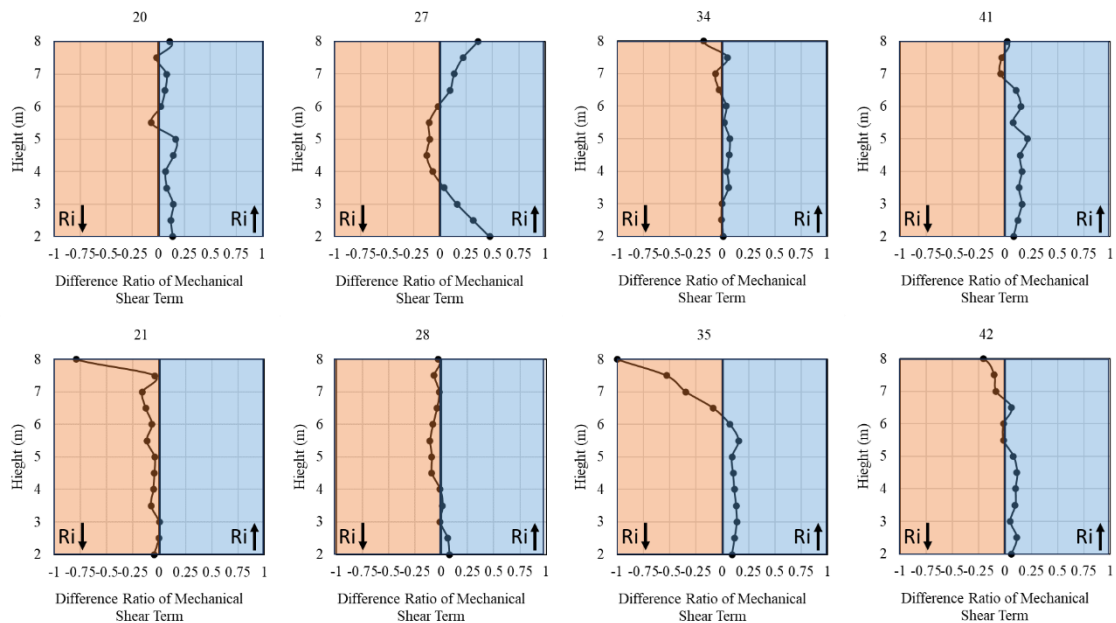


Figure 33 : Mechanical shear term between 2-8 m with global maximization at 1 pm

The differences between the difference of wind speeds in the horizontal direction (x and y) with respect to height and the calculated mechanical effects are shown in Figure 33. Corridors can be divided into three groups, as in the gradient Richardson Number (Figure 28). Fluctuations appear in the ratio of mechanical effects on corridors 27-28-34, as shown in Figure 33. In the corridors numbered 20-35-41-42, where the gradient Richardson Number is positively affected, the cool roof has a negative effect on the mechanical shear effect in the evaluations above 5.5 meters. On the other hand, in corridor number 21, the cool roof mechanical shear change has a negative effect on the gradient Richardson Number. The corridor where the wind speed difference between the planes is most evident is corridor 35. However, when the rate of change between 2 meters and 4 meters is considered, there is a high rate of acceleration in corridor 27 with the cool roof effect. In addition, this range is the range where the most temperature and density changes are seen with the effect of positive change in wind speeds. Also, the maximum difference used in the maximization process for the buoyancy term is 0.000232, while the maximum difference between the two scenarios used in the maximization process for the mechanical shear term is 0.00238. In other words, the ratio values seen in Figure 33 are almost ten times higher than the values seen in Figure 32.

Because of the difference, when the rates in buoyancy thermal change are compared with the rates of mechanical shear thermal change, it turns out that the differences between wind speeds affect the gradient Richardson Number values more. For example, according to Figure 33, the horizontal velocity difference between the planes in corridor 27 has a negative effect between 4 meters and 6 meters in height. Although there is no negative effect on buoyancy rates at any height in the same corridor, it is seen that the gradient Richardson Number values in corridor 28 become more unstable with the

cool roof effect between 4 meters and 6 meters. As previously indicated in Figure 32, the highest density variation between corridors is in the first few meters in corridor 27. It should not be thought that the only reason for the temperature and density difference here is due to the change in horizontal velocities. Although it is not directly one of the gradient Richardson Number parameters, it is a parameter that should be examined in order to fully understand the effects of the cool roof on the urban area at vertical speeds.

By examining the buoyancy and mechanical terms that affect the gradient Richardson Number value, the character of the air in the corridors is understood, and the effects of the cool roof on the character of the air in the corridor are explained. The only physical difference between the standard scenario and the cool scenario is the temperature difference between the roofs of the buildings. To better understand the effect of this temperature change on corridors, it is necessary to control their velocities in the vertical direction. Velocity w values will contribute to our interpretation of the cool roof effects as it is a component of the wind velocity value. Velocity values will be affected by the vertical airflows caused by the density difference.

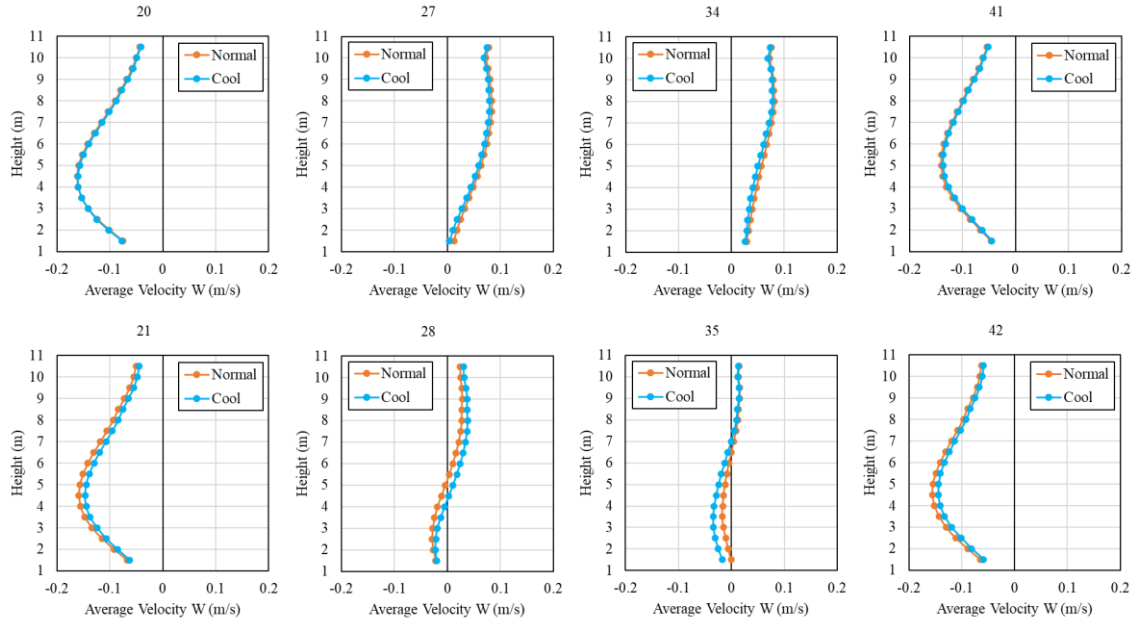


Figure 34 : Average velocity w of planes at 1 pm

According to the velocity w values shown in Figure 34, corridors can be divided into three groups as corridors 20-21-41-42, corridors 27-34 and corridors 28-35. In corridors numbered 20-21-41-42, the average velocity w values of all planes are negative both in the normal scenario and in the cool roof scenario. Also, with the cool roof effect, the negative average velocity values approached zero with a small percentage. This means that the flow in the negative z direction is reduced. On the contrary, in corridors 27-34, it is seen that there is a decrease in positive average wind speeds in the normal scenario together with the cool roof effect. Because of this situation, it can be said that the flow in the positive z direction decreases. In the corridors numbered 28-35, while the wind speeds on the planes below half of the building heights are in the negative direction, the vertical average wind speeds in the planes above have a positive value. Vertical wind speeds change upwards in corridor 28 and downwards in corridor 35.

It is observed that the velocity w values also had an effect on the decrease in temperature values in the interior corridors in the cool roof scenario. In the normal scenario, the roofs increase the wind temperature and decrease the density value, and the downward flow of the air with the low density from the corridors will be less. However, since the air flowing over the roof is not heated in the cold roof scenario, it has a low temperature and high density.

Depending on this situation, the downward flow of wind currents passing over the roof in the urban area is increasing. The use of cool roofs in the urban area also affects the walls of the building, apart from lowering the temperature value in the corridors and bringing the Richardson value closer to neutral. In the cool scenario, the temperature of the wind acting on the surfaces of the north and south facades of the buildings decreases and its speed increases. Due to this situation, the convection heat transfer between the air and the wall increases and further prevents the heating on the building surface. Therefore, it can be said that one of the reasons for the decrease in the average temperature values of the building walls in Figure 26 is the vertical winds.

4.4.2 Conclusion of Case Study IV

Urban areas with 36 and 64 buildings are created and analyzed in order to examine the problems that may arise by increasing the population in the selected configuration. The remarkable problem that arises with the increase in population is the formation of high temperatures, especially in the middle of the downstream region, due to the decrease in the level of natural ventilation. This problem is planned to be solved economically without any new construction or reinforcement work, and as a solution, cool material with an albedo level of 0.9 is used on the roofs of the buildings.

In comparisons made for an urban area with 64 buildings, the highest average temperature values on the building surface in the scenario with a cool roof decrease by 1 °C at 13:00 compared to the scenario with a normal roof. In addition, the effect of the cool roof application on the wind temperature and character in the corridors is examined. In particular, Cool Roof brought the Richardson Number values continuously closer to neutral in 4 (20-35-41-42) of the 8 corridors examined in the first six meter height and partially closer to neutral in 3 (27-28-34) of other corridors. In the corridor 21, more unstable stratifications are created regardless of height. Studies on the Richardson Number give the opportunity to examine the relationship between two different parameters. By examining the buoyancy term and mechanical wind shear term effects in detail, it is observed that the changes in the mechanical wind shear term are almost ten times higher than the buoyancy term in the differences caused by the cool roof effect.

CHAPTER V

SUMMARY AND CONCLUSIONS

This study uses CFD methods on generic models to conduct thermal performance and adverse temperature effect reduction strategies analyses. The location is selected as Yesilkoy/Istanbul, and the weather conditions are used as extreme conditions (29th July 2020) and average conditions (July 2020) related to the aim of the case study. The CFD analysis is simulated using the 3D URANS approach and the realizable k- ϵ turbulence model performed on a high-resolution grid, taking into account wind flow and heat transfer (conductivity, convection, and radiation). The simulations used factors affecting the urban climate, such as short and long-wave radiation, wind speed, evaporation-transpiration, and heat storage, excluding the effect of anthropogenic heat sources. During the whole study, 4 different case studies are examined. The objectives of the cases are, respectively;

- the first formation of an urban area in a selected location,
- the effect of weather conditions on thermal performance studies and the comparison of numerical calculations with TS 825,
- the examination of the direction of distribution of heat generated in the urban area to the environment,
- the strategy to reduce the warming that will occur due to the increase in population in the created urban area.

A total of 15 different scenarios with 9 different geometries are used in the CFD simulations and 3 urban model are used with TS 825 standard to examine energy modeling. The parameters taken into account while creating the models are, respectively, albedo level, aspect ratio, weather condition, roof design, population and cool roof. Firstly, five urban designs are used in the establishment of the urban area using different albedo level and aspect ratio values. The most successful design is selected according to the average temperature on the building surfaces, air temperature at 1.5 meter height, and the wind speeds at 1.5 meter height in the canyons, with an albedo level of 0.6 and a H/W ratio value of 1.

The second case study examined the effects of the air conditions used in CFD analysis on the urban areas created and the differences between the results. The results obtained are compared with the TS 825 standards, and it is observed which solution approach is more efficient depending on the weather condition. In light of the results obtained, cost ratios in extreme scenarios are seen as variable values due to the wind and temperature modeling ability, while the average monthly cooling fee obtained in the scenario using average air condition is similar. The calculations are continued with CFD software to evaluate wind and thermal differences in configurations and the studies will be continued over extreme scenarios.

Within the scope of the third case study, two more models with different roof designs are added to the five urban models created in the first case study. Heat flux (Q) and unit heat flux (q) values are calculated to examine the heat fluxes leave from the urban area. It is seen that the results vary according to the evaluation parameter used in the studies. While the difference due to aspect ratio is remarkable compared to heat flux

ratio, the most significant effect according to unit heat flux ratio is the roof design with a slope of 45%.

In the last case study, the results of the population increase are examined and the warming in the canyons of the model with 64 buildings is found to be remarkable. It is observed that the difference between the air temperature difference at a height of 1.5 meters in the rear and middle parts of the urban area and the temperature of the air entering the urban area is almost 4 °C. In order to prevent this problem, the cool roof strategy is used. With this method, the temperature values in the canyons and building surfaces are reduced. In addition, the effect of the cool roof strategy on the corridors is examined with the gradient Richardson Number. As a result of the examination, it is seen that the cool roof had a positive effect on the wind character in the canyons in general.

To sum up, in this study, the formation of a city, its expansion with population growth, and the improvement of design quality are modeled. As a result of the analysis, the lowest value for the average temperature on the building surfaces in the 16-building models is the scenario with an albedo level of 0.6 and a H/W ratio of 1.5. However, due to its negative effect on pedestrian wind pattern comfort, the best scenario model with an albedo of 0.6 and a H/W ratio of 1 is selected. With the addition of a 45% inclined roof to this model, the leave heat flux rate from the up surface of the urban area has been increased, and the average temperature on the building surfaces has been reduced. The cool roof strategy, which is used to minimize the effect of the increasing population, reduced the average temperature on the building surfaces from 46.7 °C to 45.7 °C. In addition, the wind character in the canyons is mainly changed from negative to neutral. Together with the gradient Richardson Number, it has been proven that a cool roof reduces the temperature change due to height in canyons and increases natural ventilation.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORK

The urban climate model can be more inclusive and efficient by diversifying the urban areas used in the simulations and developing new evaluation approaches.

Firstly, a more expansive time period can be modeled by extending the period examined in CFD analysis. The study over an extended period of time contributes to better modeling the heat accumulated by urban areas and a more realistic calculation of financial impacts.

The calculation of the gradient Richardson number, which is calculated to allow us to comment on the general mechanism in the urban area by classifying the wind character, can be developed. The method used in this study gives a chance to comment on the wind in the canyons in general. However, the character of the wind can be examined in more detail by increasing the number of planes taken into account in the corridor.

In examining the effect of population growth, the use of the shape of the normal distribution as geometry or the production of model geometry by artificial intelligence while modeling urban areas with more population in studies that do not have the opportunity to work on real urban areas can increase the quality of the studies.

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VITA

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