ARCHITECTURAL DESIGN FOR CLIMATE CHANGE MITIGATION AND ADAPTATION STRATEGIES IN EXISTING BUILDINGS

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ABSTRACT

ARCHITECTURAL DESIGN FOR CLIMATE CHANGE MITIGATION AND ADAPTATION STRATEGIES IN EXISTING BUILDINGS

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Climate change has been proven largely to be a consequence of human activities and has a destructive impact on ecosystems. Societies and economies have become a growing global concern for the last few years and the building industry has a key role in this change due to its huge amount of environmental footprint. The energy consumption and greenhouse gases emissions of the built environment influence the climate in a negative way while the changing climate also influences the energy and thermal performance of the built environment and comfort and health of users. In this thesis, architectural design strategies for existing buildings that aim for climate change mitigation and adaptation are explored using research through design and a simulation-based quantitative approach is adopted. A design method is proposed in order to reduce the reciprocal influence of the built environment and climate change. The method is implemented in an educational building in Ankara by the aim of testing and verification. The aim is to evaluate the impacts of climate change predictions together with urban heat island effect on energy and thermal performance of existing buildings and to improve the performance of buildings through dynamic energy simulation software and passive architectural design techniques. The main contribution of the thesis is to understand the effects and interactions of different

design alternatives on the building performance and to develop the most effective and feasible design approach which can support the designers throughout the design processes for climate resilience in existing buildings.

Keywords: Climate change, Passive design, Existing buildings, Building performance, Building energy simulation

ÖZ

MEVCUT BİNALARDA İKLİM DEĞİŞİKLİĞİ HAFİFLETME VE ADAPTASYON STRATEJİLERİ İÇİN MİMARİ TASARIM

Akköse, Gİzem
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İklim değişikliğinin büyük ölçüde insan faaliyetlerinin bir sonucu olduğu ve ekosistemler üzerinde yıkıcı etkileri olduğu kanıtlanmıştır. Bu bağlamda, iklim değişikliğinin toplumlar ve ekonomiler üzerinde etkileri etkileri son birkaç yıldır büyüyen küresel bir endişe haline gelmiştir ve inşaat endüstrisi büyük miktardaki ekolojik ayak izi nedeniyle bu değişimde kilit bir rol oynamaktadır. Yapılı çevrenin enerji tüketimi ve sera gazı emisyonları iklimi olumsuz yönde etkilerken, değişen iklim de yapılı çevrenin enerji ve ısıl performansını aynı zamanda kullanıcılarının rahatlığını ve sağlığını etkilemektedir. İklim ve yapılı çevre arasında karşılıklı olarak bir etkileşim ve dinamik bir diyalog söz konusudur. Bu tezde, mevcut binalara yönelik olarak iklim değişikliğinin azaltılması ve adaptasyonunu hedefleyen mimari tasarım stratejileri tasarım araştırmaları kullanılarak incelenmiş ve simülasyon temelli nicel bir yaklaşım benimsenmiştir. Yapılı çevrenin ve iklim değişikliğinin karşılıklı etkilerini azaltmak için bir tasarım yöntemi önerilmektedir. Bu yöntem, Ankara'daki bir eğitim binasına test etme ve doğrulama amacı ile uygulanmaktadır. Tezin amacı, iklim değişikliğine ait tahminlerin kentsel ısı adası etkisi ile birlikte mevcut binaların enerji ve ısıl performansları üzerindeki etkilerini dinamik enerji simülasyonu yazılımı kullanılarak detaylı bir şekilde değerlendirmek ve binaların performanslarını pasif mimari tasarım teknikleri kullanarak iyileştirmektir. Tezin ana katkılarından biri, farklı tasarım alternatiflerinin bina performansına etkilerini ve birbirleri ile etkileşimlerini anlamaya yardımcı olmasıdır. Bir diğeri ise, mevcut binalarda iklim direnci için tasarım sürecinde tasarımcıları destekleyen en etkili ve uygulanabilir tasarım yaklaşımları geliştirmeye katkı sağlamasıdır.

Anahtar Kelimeler: İklim değişikliği, Pasif tasarım, Mevcut binalar, Bina performansı, Bina enerji simülasyonu

To my family…

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

3D: Three Dimensional

AAC: Autoclaved Aerated Concrete

AR5: 5th Assessment Report

CDD: Cooling Degree Days

CO_2: Carbon Dioxide

EP: EnergPlus

GHGs: Greenhouse Gases

HDD: Heating Degree Days

IPCC: International Panel on Climate Change

MCDA: Multi-Criteria Decision analysis

METU: Middle East Technical University

NASA: National Aeronautics and Space Administration

NURBS: Non-Uniform Rational B-Spline

OFAT: One Factor at a Time

RCP: Representative Concentration Pathway

SHGC: Solar Heat Gain Coefficient

UHIs: Urban Heat Islands

LIST OF SYMBOLS

SYMBOLS

A: function of the relative air speed

i: occupied hour

$N_{occ(z)}$: total occupied hours of z in a given calculation period

Q_C / ΔQ_C: monthly cooling requirement / annual cooling requirement

Q_H / ΔQ_H: monthly heating requirement / annual heating requirement

Q_{SG} / ΔQ_{SG}: monthly solar gain /annual solar gain

Q_T: monthly energy balance

t: time step (1 h)

T_a: mean air temperature

T_{ave}: Outdoor average dry-bulb temperature

$TL_{comf,i,z}$: comfort temperature limit at the time step i in the zone z

T_{mrt}: mean radiant temperature

T_n: Thermal neutrality temperature

T_o: operative temperature

$To_{i,z}$: operative temperature at the time step i in the zone z

z: zone

CHAPTER 1

INTRODUCTION

"The world will not be destroyed by those who do evil, but by those who watch them without doing anything." ~ Albert Einstein

1.1. Background

A global crisis - Climate Change

> “Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.” Fifth Assessment Report from the UN Intergovernmental Panel on Climate Change (IPCC), 2014.

Climate change is not a problem of the future, but rather it is a problem of the present. It has become a compelling, threatening, and devastating reality a long time ago. In other words, climate change has become a global crisis in every aspect. Many negative impacts of climate change on human health, earth ecosystems, economy, and society have begun to be experienced such as wildfires in California in 2018 or Hurricane Harvey in 2017. NASA reports that the average temperature of the Earth has already risen nearly 1°C since the late 19^{th} century and the global temperature has been recorded eighteen of the 19 warmest years since 2001. Besides, warming oceans, shrinking ice sheets, glacial retreat, a serious reduction in snow and ice covers, risen of sea levels, extreme events and ocean acidification has been recorded in last century (National Aeronautics and Space Administration [NASA], n.d.). These changes are driven mostly by increasing levels of carbon dioxide and other anthropogenic[1] emissions into the atmosphere (IPCC, 2014). The industrial, agricultural, and transportation activities, and human settlements on which the modern civilization depends upon produced greenhouse gases such as carbon dioxide, methane, and nitrous oxide. These activities have raised atmospheric carbon dioxide (CO_2) levels from 280 parts per million (ppm) to 412 ppm in the last 150 years (National Aeronautics and Space Administration [NASA], n.d.).

The human-induced impacts are expected to continue to increase with the growing population and increasing consumption. IPCC (2014) estimates that

- temperatures will continue to rise,
- precipitation patterns will change,
- extreme events such as hurricanes, storms, floods will become stronger and more intense,
- sea levels will rise and the Arctic will likely become ice-free (IPCC, 2014).

The climatic models point out that the global temperature will rise approximately plus 1.5°C by 2050 and 2-4°C by 2080 and the atmospheric concentration of CO_2 will have increased to 600ppm. Moreover, in IPCC AR5 report (2014), it is predicted that climate-related risks to human health, livelihoods, food security, human security, and water supply will all increase.

Buildings and Climate Change

Regarding the facts mentioned above, it is obvious that there is a strong relationship between climate change, greenhouse gases (GHG) emissions, and energy consumption in the fields of industry, agriculture, transportation, and human settlements. In this context, buildings are a significant contributor to GHG emissions. Smith (2005) indicates that building constructions, renovation works, and operations

[1]Anthropogenic: Relating to, or resulting from the influence of human beings on nature. https://www.merriam-webster.com/dictionary/anthropogenic. July 2019.

consume more neutral resources and more energy than any other human activities and they generate huge amounts of greenhouse gases, toxic air, CO_2 and water pollutants (Smith, 2005). In another study, the IPCC report (2014) states that the final energy use of buildings in 2010 generated 32% of total global energy use, 19% of energy-related GHG emissions and approximately one-third of black carbon emissions (IPCC, 2014). In line with these facts, buildings play a leading role in climate change crises.

There is a complex interaction between buildings and the changing climate. Just as the building-related emissions have impacts on climate change, the changing climate has an impact on building systems and performance. The shift in energy use and thermal comfort, HVAC capacity mismatch, problems caused by overloading, and inefficiency and malfunction in the building systems can be observed as a consequence of the climate change impacts on buildings (De Wilde and Coley, 2012). Furthermore, these impacts have potential consequences for building occupants such as discomfort, illness, morality, or reduction of productivity and performance. All these problems result in *a feedback loop where an increase in building emissions contributes to further anthropogenic climate change* (De Wilde and Coley, 2012, p.1).

1.2. Problem Statement

Climate change and architecture: Climate change is one of the main challenges facing humankind in the 21st century. At current rates of warming, it is estimated that many cities will become uninhabitable due to extreme events including floods, wildfires, drought and heatwaves and this is predicted to trigger mass migration (Murray, 2019). A research conducted in the Crowther Laboratory at the ETH University in Zurich, Switzerland examined how climate change will affect the world's top 520 cities by 2050. According to this research, 77% of the cities around the world will experience a striking change of climate conditions, and the other 22% will encounter conditions that currently don’t exist (Bastin et al., 2019). Throughout Europe, the temperature of cities will be 3.5°C warmer in summers, 4.5°C in winters. This implies that London can be as warm as today’s Barcelona, İstanbul today’s Rome, Ankara today’s

Tashkent (Bastin et al., 2019). These estimations make it clear that the built environment will be severely and intensely affected by climate change. In line with these facts, it is obvious that architecture is part of this crisis, both affecting and affected factor and architecture should respond to the changing climate. However, although the signs and predictions are so vital, the knowledge gap still exists corresponding with how emissions from built environments can be mitigated and, simultaneously, how buildings and their occupants can adapt to the changes in global and local climate. This gap is need to be filled with the development of a new form of architecture that can adapt to climate change, cope with extreme events and reduce damage to the environment. Moreover, this approach should be in dialogue with different disciplines that include urban design, engineering, physics, climatology, physiology, psychology, material science and biosciences, in order to address the complex requirements of climate change mitigation and adaptation processes. Consequently, buildings need to be designed and operated according to both dynamic environmental forces and comfort and health of their users with efficient use of energy and without harmful wastes and emissions all around the world.

Climate change and existing building performance: Newly designed buildings are not sufficient to deal with the climate crisis because they constitute only around 1.0-3.0% per annum compared to the existing buildings (Ma, Cooper, Daly, & Ledo, 2012). Buildings constructed in late 20^{th} century have already started to perform poorly in summer because they are characterized by lightweight, poorly insulated construction, large openings, unshaded glazing, and poor ventilation (Gething & Puckett, 2013). It is also an undeniable fact that existing buildings are an effective way to minimize the negative impacts of the warming climate, considering that buildings have a relatively long life-cycle. Therefore, it is essential to focus on the existing buildings stock for energy efficiency and thermal comfort interventions and to provide their mitigation and adaptation to climate change. In many instances, however, there is a general lack of relating to the variability of future climatic conditions to existing building performance. In consideration of some intergovernmental agreements on climate change such as the Paris Agreement, climate change adaptation policies have started to be implemented for existing buildings, but these projects show too slow progress.

Microclimate and existing building performance: In order to analyze the performance of existing buildings more accurately and reliably, microclimatic conditions need to be included in the design process. The built forms in cities create a unique, and site-specific climatic conditions and the climatic conditions in the cities differ from their surrounding rural areas. Generally, urban areas are in a tendency to be warmer than rural areas regarding to the thermal and optical qualities of finishing materials, geometry, spacing, orientation, and energy consumption of buildings and the use of green and blue infrastructures. This phenomenon is called the urban heat island (UHI) effect, one of the well-known forms of local anthropogenic climate change (Kleerekoper, Van Esch, & Salcedo 2012). As UHI effect causes a major increase in the outdoor temperature, it is directly associated with energy and thermal performance of existing buildings. However, the climatic data are generally collected at rural areas, *outside of the urban belt*, and UHI effect and its possible impacts on the temperature are neglected in general.

Energy consumption and thermal comfort in educational buildings: Educational buildings constitute a significant majority of the above-stated existing building stock. For instance, in Europe, they together with office buildings account for about 40% of the non-residential floor spaces (Ascione, Bianco, De Masi, de'Rossi, & Vanoli, 2017). In line with this, they are responsible for the high energy consumption of up to 18 percent within the non-industrial energy usage and a considerable amount of this energy is used to provide thermal comfort (Ascione et al., 2017 and Zomorodian, Tahsildoost, & Hafezi, 2016). Thermal comfort is one of the determinative indoor environment variables that affect physical and psychological health, productivity, and performance of users (Katafygiotou and Serghides, 2014). In this context, educational buildings with high occupant density in classrooms are unique and critical instances. . Their thermal conditions have the power to enhance and/or detract from the learning process and the performance and productivity of students and teachers (Sanoff, 2001).

Besides, thermal comfort perception varies according age, and students have a higher sensitivity towards hot temperatures relatively to their body weights and their tissues and differences in their metabolismic rates (Katafygiotou and Serghides, 2014). In other words, students are more vulnerable to poor thermal comfort conditions. Existing studies further show that in many instances, educational buildings are designed and constructed with disregard of the above-mentioned criteria (Katafygiotou and Serghides, 2014). That results in improper and poorly performed educational buildings in many countries.

As a result of above-mentioned considerations, architectural design requires a new approach that combines the built and natural environments, weather, climate, and human activity, behavior, and needs. The role of climate and climate change, microclimate or UHI effects and the preferences of building occupants need to be incorporated into the building design process. This thesis represents a comprehensive study of the interrelationship between the design variables associated with these metrics for the existing educational building.

1.3. Aims and Objectives

The main aim of this thesis is to evaluate and predict the impact of current and future variable climatic patterns on existing educational buildings energy and thermal performance and develop a framework of the design process in order to improve the energy demand and thermal comfort using simulation tools. In this regard, intervention scenarios are determined through passive design techniques as mitigation and adaptation strategies to achieve the development of the framework based on the selected representative school building. The scenarios need to be adapted to the context of Ankara, Turkey through the effective use of building materials and shading elements, the alteration of the façade configuration and the combination of various design parameters.

The proposed framework aims to support designers in the understanding of the different alternatives and proper selection among them.

In summary, the following specific focuses are to be succeeded in this research;

- An understanding of climatic conditions of Ankara corresponding with climate change and urban heat island effect;
- The evaluation of the combined effects of current and future variable climatic patterns with urban heat island effect on energy and thermal performance of the selected educational building through modeling and simulation;
- Identification of the intervention scenarios to improve the performance of the current design, based on passive design techniques and quantifying the effectiveness of these scenarios.
- Developing a guideline and recommendations for existing educational buildings towards mitigation and adaptation in/to climate change.

1.4. Research Questions

Considering the discussion in the previous sections, this thesis seeks to answer the following main question:

> *What is a viable design method that can support design activities for climate change adaptation and mitigation in existing buildings?*

To answer the main question, several sub-questions need to be examined thoroughly, as follows:

1) How can passive design techniques be employed in the existing educational buildings to provide the right balance between energy performance and thermal comfort under the future climatic conditions and further mitigate and adapt climate change?

2) How do the varying future climatic conditions and urban heat island (UHI) influence the outdoor temperature?
3) How do the varying future climatic conditions modified with UHI affect the energy and thermal performance of existing (educational) buildings?
4) How can passive design techniques be effective in improvement of the performance of educational buildings?
5) What are the most influential techniques for both energy efficiency and thermal comfort

1.5. Scope of the Thesis

Architectural design for climate change has a large research domain. To ensure the quality and clarity of the research, the thesis needs to be concentrated on its specific aims and objectives as described above. The scope of this thesis will be limited to and excluded some specific aspects as follows:

- Existing buildings particularly educational buildings are the main focus of this research. The other building types are not investigated.
- This research examines only the adaptation and improvement strategies on the building-scale. The urban-scale issues such as urban design, urban morphology and arrangement, and landscape design are out of the scope of this research.
- This thesis only focuses on passive design strategies. Active strategies such as photovoltaics, solar thermal collectors, mechanical systems, or efficient lighting and its impacts on the building performance are not included in the scope.
- One of the main subjects of this research is energy efficiency and thermal comfort. Indoor air quality, visual and acoustic comfort are not included in terms of comfort-related issue and it is assumed that thermal comfort is

independent of other issues. In terms of energy efficiency, requirements of heating and cooling and solar gain are focused on. The other issues such as lighting, equipment demand, and so on are excluded.

- Analyses of the climatic conditions were conducted only for Ankara, Turkey in this research.

1.6. Thesis Methodology

This research is based on a systematic methodology that is underpinned by building performance analysis through quantitative simulation. A design method is proposed that can help architects during the design processes of climate change adaptation and mitigation of existing buildings. The method seeks to incorporate the impact of the current and future climatic conditions modified with urban heat island effect on the performance of existing educational buildings and to provide guidance in the development and analysis of passive design scenarios. The research presented in this thesis consists of several steps, as indicated below:

a) An extensive literature review on climate and the built environment, urban heat island effect and its relationship with climate change, thermal comfort and comfort requirements in educational buildings, and architectural design approaches as mitigation and adaptation strategies to cope with the changing climate and warming temperature.

b) The assessment or analysis of current and future climate data with urban heat island effect and selection of climate scenarios to construct whole-building model simulations of the building.

c) The development of a simulation-based computational method to analyze the current performance of building and the impact of changing climate on the energy and thermal performances.

d) The identification and examination of mitigation and adaptation strategies on an individual basis to decrease the energy demand and to improve thermal comfort by material and design modification.

e) The determination of combinations consists of the most effective strategies among the energy efficiency and comfort, usable by designers.

1.7. Thesis Structure

This thesis constitutes of six chapters, shown as Figure 1.1. In the first chapter, a brief introduction, conceptual background, problem statement, aims and objectives, research questions, thesis methodology, and the main structure of the thesis are presented. The second chapter covers a comprehensive literature review of the main issues in accordance with the aims and objectives of the research included climate change impacts, urban heat island effect, thermal comfort, and architectural design solutions as mitigation and adaptation strategies in climate change. The third chapter represents the methodology of the thesis that considers the design of the research. The fourth chapter investigates the implementation of the proposed method to the selected case study. Chapter five discusses the results obtained from simulation model and it also presents a design guideline by using the proposed framework to provide an insight into the building performance. In final chapter, the conclusion, limitations, and the possible future extensions of the thesis are outlined.

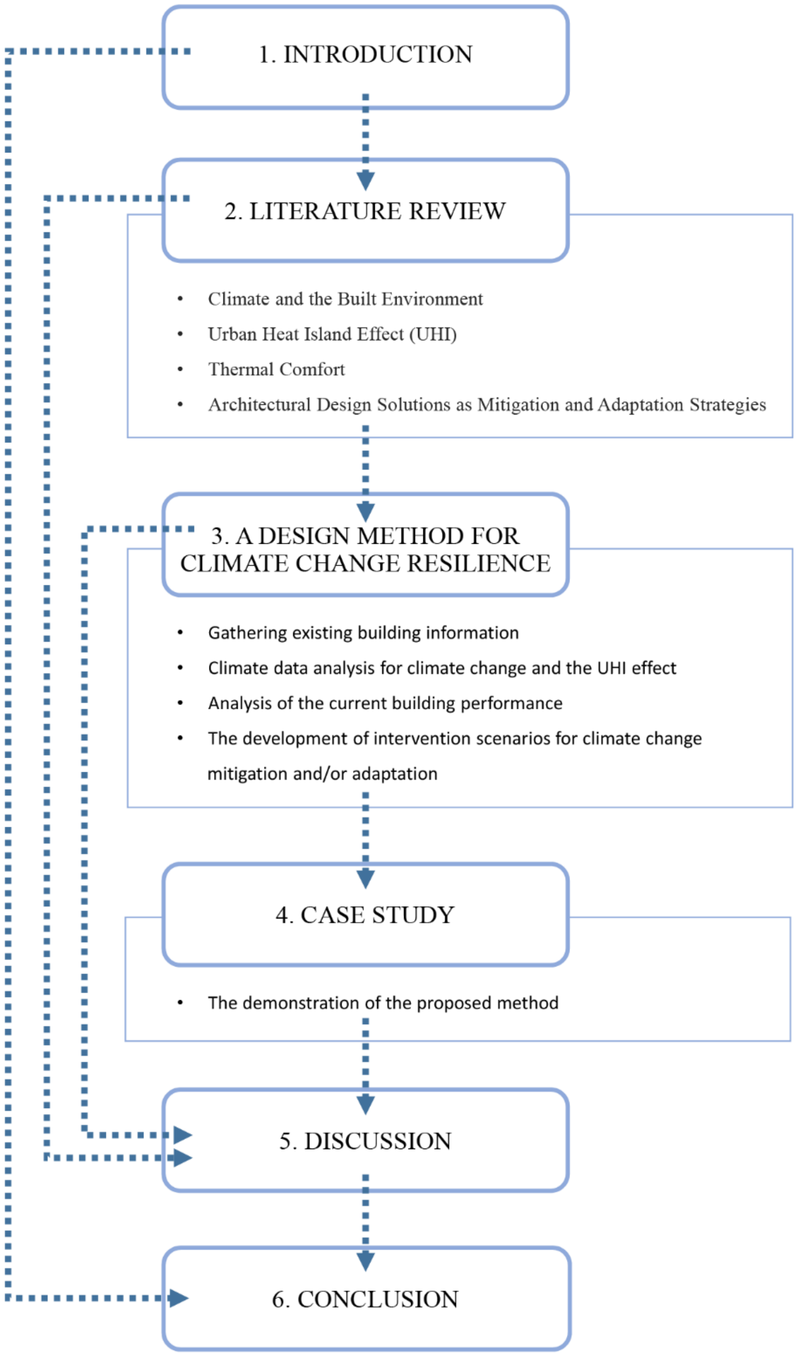

Figure 1.1. The structure of the thesis

CHAPTER 2

LITERATURE REVIEW

This chapter provides an extensive overview of research advancements related to climate change and its relation with the built environment, urban heat island effect and its relationship with climate change, thermal comfort and comfort requirements in educational buildings, and architectural design approaches as mitigation and adaptation strategies to cope with the changing climate and warming temperature. The aim of the chapter is to in detail identify the aspects and problems that have been successfully clarified by other authors.

2.1. Climate and the Built Environment

The climate and architecture are always in a complex interaction and in a dynamic dialogue. Architecture modifies the climate and creates unique and site-specific microclimatic conditions while the climate plays an important role while designing a building. David Pearlmutter state that ". In modern times, this cycle of influence has been obscured, because technology and cheap fuel have allowed architects the option of ignoring climatic cues."(Pearlmutter, 2007, p.752). However, with the changing climate, the necessity of re-establishing the dialogue of architecture with the climate has become a critical issue. The following sections present the climate and built environment relationship with respect to climate change.

2.1.1. The Earth's Climate System

Climate is defined as "the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years" by Fifth Assessment Report (AR5) of IPCC (IPCC, 2014, p.126). The Earth's climate system is a part of complex systems and in order to understand it and the climate change, it is essential to also understand the Earth system as encompassing the climate system. The Earth is made up of four independent but interconnected components called spheres that are the lithosphere, pedosphere, cryosphere, hydrosphere, and atmosphere. The lithosphere as the term given to the rock and minerals is uppermost part of the outer crust and it provides important minerals to the Earth. The pedosphere is the Earth's soil layer and also the foundation of terrestrial life. The cryosphere is the part of the Earth's surface where water exists as ice and there is a wide overlap with the hydrosphere. The hydrosphere is whole the waters on the earth's surface, such as lakes and seas, and sometimes including water over the earth's surface, such as clouds. The cryosphere and the hydrosphere are an integral part of the global climate system. Lastly, the atmosphere that is the most important parts of the global climate system consists of the thick layer of gaseous surrounding the Earth. It comprises: 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide and very small amounts of other gases. Moreover, atmosphere contains water vapour as a natural gas. These gases are often termed 'greenhouse gases' (GHG) as they balance to maintain the Earth's temperature at a level suitable to sustain life. In addition to sustaining life chemically, the atmosphere plays an essential role in storing moisture and solar energy while helping transport these energies in the form of heat and to create wind and weather systems (Skinner and Murck, 2011). These components of the Earth that constantly interact and adjust to both internal and external forces constitute the climate system and also, Skinner and Muck (2011) claim that the anthroposphere has also become a key constituent of the climate system since the Industrial Revolution. In substance, the climate system and its components are driven by solar energy that is also a component of the system. Clouds, atmospheric pollutants, gases, aerosols and surfaces of Earth reflect back 30% of the incoming solar energy into space and 20% of the solar energy is absorbed and remitted by the atmosphere, ocean and land (IPCC, 2013). All components relating to the global climate system is shown in Figure 1.1 schematically.

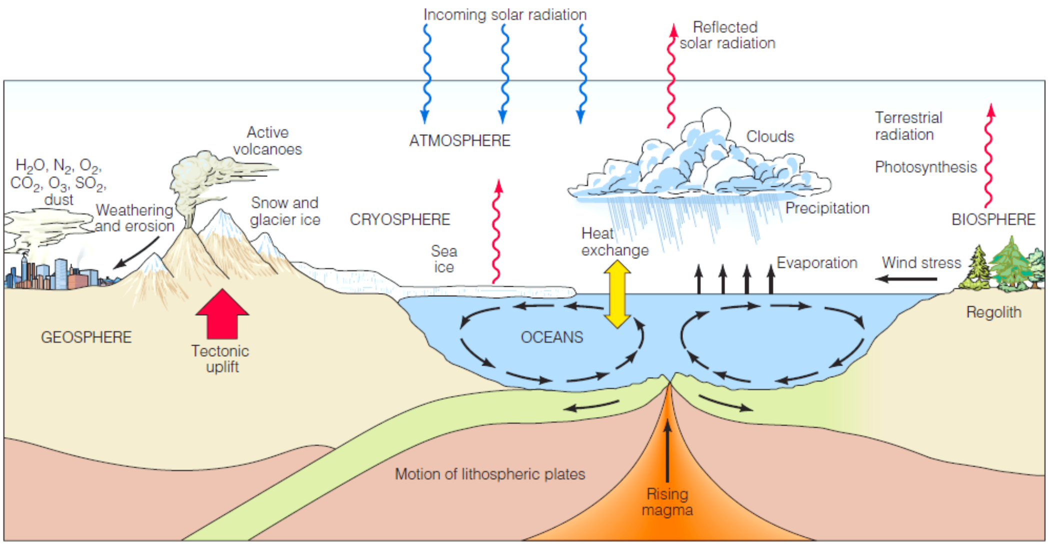

Figure 2.1. Schematic view of the components of the global climate system (Skinner et.al, 2011, p.380).

Natural or human-induced factors in components of this complex and interrelated system and their interactions could result in climate fluctuations. The following part introduces various aspects of natural and anthropogenic or man-made, climate fluctuations or changes.

2.1.2. Natural and Anthropogenic Causes and Effects of Climate Change

Climate change can be defined as the variability of its properties that occur in different time scales, ranging from decades to many millions of years (IPCC, 2013). It is difficult to determine the responsibility of these variables, as several different mechanisms are responsible for them in a complex way. As stated previously, natural and anthropogenic factors that result in changes in the climate are observed. Natural factors can be listed as follows;

- Alteration of the Earth’s orbit and movements
- The variation in the intensity of solar radiation (the so-called ‘solar constant’)
- Shift in the geological equilibrium of the planet (such as shape or position of the continents)
- Variation in the equilibrium of oceanic currents, modification of the Earth’s albedo (i.e. the reflectivity of the planet’s surface and atmosphere) (Altomonte, 2008).

Best known examples that arise from natural factors are the Ice Age of 20.000 years ago and the Little Ice Age in the early Middle age and researchers have connected them to some possibilities and theories such as variations in Earth's orbit, cyclical lows in solar radiation, heightened volcanic activity, changes in the ocean circulation or variations in Earth's orbit. In addition to these theories, as stated in the IPCC reports (2014), the climate has changed both locally and globally in time and it is believed that carbon dioxide concentration has a role in triggering these changes. Carbon dioxide (CO_2) that is a natural greenhouse gases and carbon cycle have a key role to sustain life and to stabilize the climate. CO_2 absorbs less heat per molecule than the greenhouse gases methane or nitrous oxide, but it has more longevity in the atmosphere and it absorbs wavelengths of thermal energy. That is to say, it has a great impact on the greenhouse effect and the total energy imbalance that are responsible for the increase in temperature of the Earth. Compared with the natural causes, the pace of the increase in carbon concentration is higher in anthropogenic causes. Atmospheric CO_2 levels from 280 parts per million (ppm) have been raised by human activities in the last 150 years and the current levels in the air that has reached 411 ppm are the highest levels in 650,000 years and quite threatening (National Aeronautics and Space Administration [NASA], n.d.) (Figure 2.2).

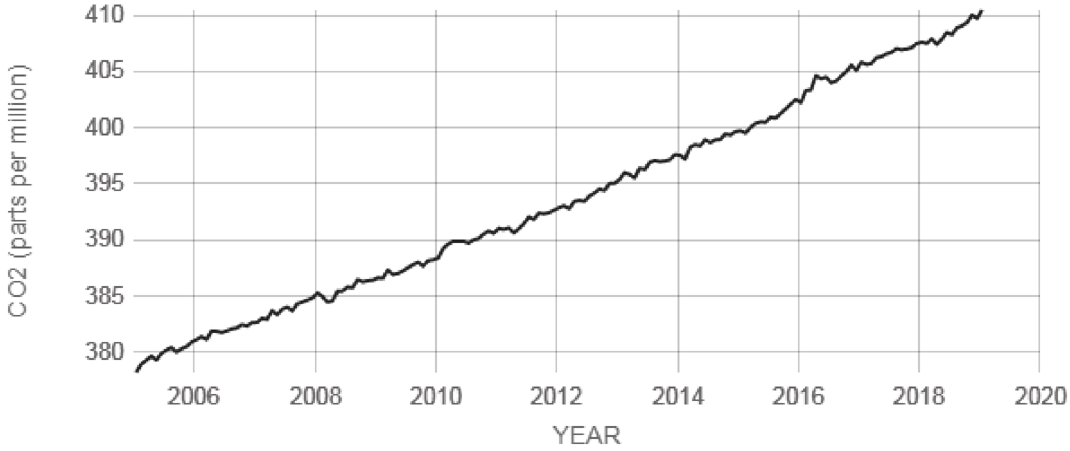

Figure 2.2. CO2 Measurement: 2005-Present. Reprinted from Global Climate Change in NASA. Retrieved March 20, 2019, from https://climate.nasa.gov/vital-signs/carbon-dioxide/.

Anthropogenic factors, the reason for this rapid increase, are mainly rapid population growth, economic, industrial and agricultural activity, urban lifestyle, energy use, land use patterns with huge environmental impacts, urbanization, building operations, technology and climate policy (IPCC, 2014).

Human influence on the climate is explicit and the current climate change has had widespread and vital impacts on human and natural systems. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, lakes have broken up earlier, plant and animal ranges have shifted and trees are flowering sooner (Figure 2.3). Moreover, changes in much extreme weathers and climate events such as heat waves, droughts, floods, cyclones and wildfires, reveal significant vulnerability and exposure of some ecosystems have been observed as the results of anthropogenic climate change (IPCC, Synthesis report, 2014).

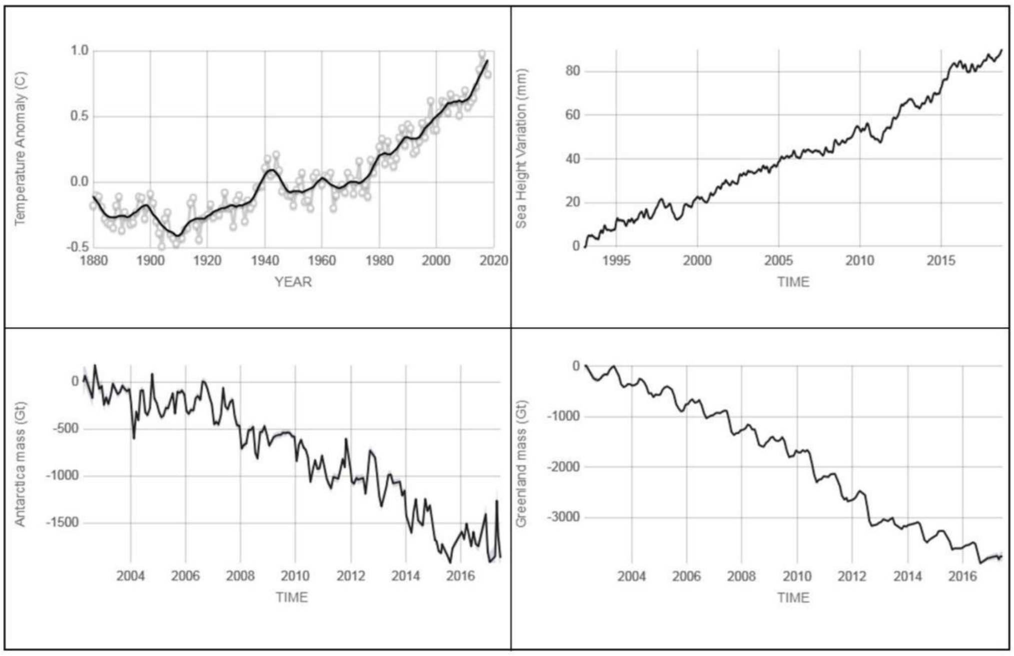

Figure 2.3. Data of climate change impacts. Reprinted from Global Climate Change in NASA. Retrieved March 20, 2019, from https://climate.nasa.gov/vital-signs

2.1.3. Future Scenarios

Effects that scientists had predicted in the past would result from global climate change are now occurring and they are predicting in the present that the change will continue through the extended period of time. The future emissions of greenhouse gases, aerosols and other natural and man-made factors designate the future of the climate and future climate depends on how the Earth reacts these factors together with its internal variability (IPCC, 2014). There are four different scenarios depending on different emission scenarios that are called Representative Concentration Pathways (RCPs). The four RCPs, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, represent possible changes in future anthropogenic GHG emissions and aim to represent their atmospheric concentrations (IPCC, 2014). These are a stringent mitigation scenario, two intermediate scenarios and a very high gas emissions scenario (IPCC, 2014). According to the best estimate scenario for the stringent mitigation (RCP2.6), it is expected to increase the temperature 1.5°C-2°C while the estimation of the higher emission that is called high emission scenario RCP8.5 is that the global mean surface temperature would rise 2.6°C-4.8°C in 2081-2100 (Figure 2.4).

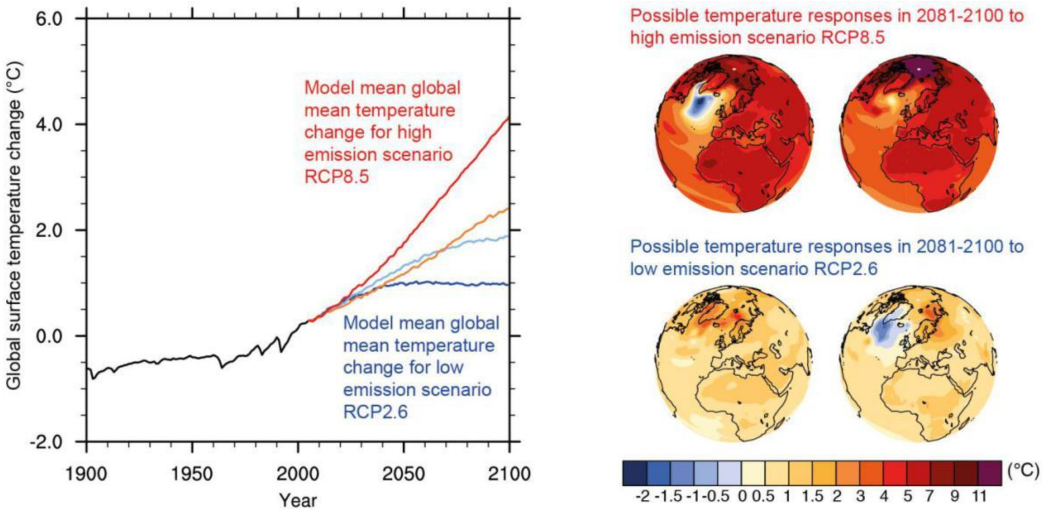

Figure 2.4. Possible temperature responses to emission scenarios (IPCC AR5 p.1037)

Additionally, according to IPCC (IPCC, Synthetic Report, 2014, p.10),

> "It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is very likely that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur."

Moreover, it is predicted that the precipitation patterns will change in an uneven manner, the ocean will continue to warm and rise, extreme events will become stronger and more intense during the 21st century and the glacier volume will continue to shrink.

In addition to natural hazards, there will be the impacts on the physical and psychological health of humans. Luber and Prudent (2009) point out that excessive heat-related illnesses, and waterborne diseases, increased exposure to environmental toxins, exacerbation of cardiovascular, respiratory diseases will appear due to consequences of climate change. Moreover, mental and social health are also affected through flood and drought impacts on housing, food security, and livelihoods.

2.1.4. Climate Change and Built Environment

As stated previously, human development and the Earth system have an intricate relationship that dramatically influences each other. In this context, the built environment and infrastructure, man-made structures, features, and facilities that provide the settings for activities of humans, is one of the key drivers of the greenhouse gases (GHGs) especially CO_2 emissions, energy consumption, and current and further anthropogenic climate change.

First of all, the contribution of urban areas to climate change will be discussed. According to information from UN Habitat, although urban areas cover 0.5% of the Earth’s surface, 71 to 76% of the world’s carbon dioxide from global final energy use and a significant portion of total greenhouse gas emissions are derived from urban areas (UN Habitat, n.d.). As cited in AR5 report of IPCC, it is reported that

> “Urban energy related CO2 emissions at 19.8 Gt or 71% of the global total for the year 2006. This corresponds to 330 EJ of primary energy, of which urban final energy use is estimated to be at 222 EJ. The Global Energy Assessment provides a range of final urban energy use between 180 and 250 EJ with a central estimate of 240 EJ for the year 2005. This is equivalent to an urban share between 56% and 78% (central estimate, 76%) of global final energy use” (IPCC, 2014, p.935).

Moreover, urbanization has multiple dimensions, including population size, land use, and density that are the main factors of anthropogenic climate change and rapid urbanization especially in developing countries has resulted in acceleration of the global change. As a result of rapid urbanization, it is estimated that in 2030, urban land cover will increase by 1.2 million km^2 and the world will have 43 mega-cities with more than 10 million inhabitants (UN Habitat, n.d.). As consequence of these, the most cities are expected to become uninhabitable.

Secondly, the role of buildings in climate change will be addressed. It is indicated that buildings including construction, renovation works, and operations consume more neutral resources and more energy than any other human activity. They generate approximately 33% of annual global GHG emissions that means higher emissions than emissions from industry and transportation, shown as Figure 2.5 (Smith, 2005 and La Roche, 2012).

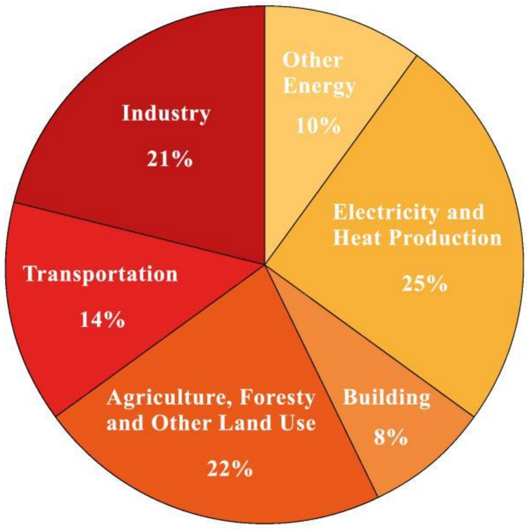

Figure 2.5. Annual global emissions according to the sectors.

Generally, this number only involves emissions from a demand for energy use in buildings, not the other building related emissions, but in fact, the specified percentage may reach larger numbers. Electricity use in the buildings and the key trends for instance space and water heating, cooling and lighting represent a majority of global final energy consumption and CO_2 emissions related to this consumption have shown dynamic growth. The AR5 of IPCC reported that "in 2010, the building sector accounted for approximately 117 Exajoules (EJ) or 32 % of global final energy consumption and 19 % of energy-related CO_2 emissions; and 51 % of global electricity consumption" (IPCC, 2014, p.677). It is foreseen that energy used by buildings double or triple at the mid-century due to the key trends (IPCC, 2014). In summary, built environment have a long life cycle during which they consume the excessive amount of energy and emit a major CO_2 and it is one of the main responsible of the anthropogenic climate change.

As buildings have an influence on the changing climate, climate change has some degree of impact on building behavior and performance. For instance, rising temperatures have an impact on external surfaces and thermal performance of buildings. Another example of this situation is that flooding and sea level rising lead to coastal and inland flooding, contamination from sewage, soil and mud, water damage to buildings, and undermining of foundations. Besides, the consequences of climate change on buildings have an extremely complicated interaction with the occupants of the buildings and major processes inside the buildings. Figure 2.6 represents this complex relationship between climate change, buildings, occupants, and processes.

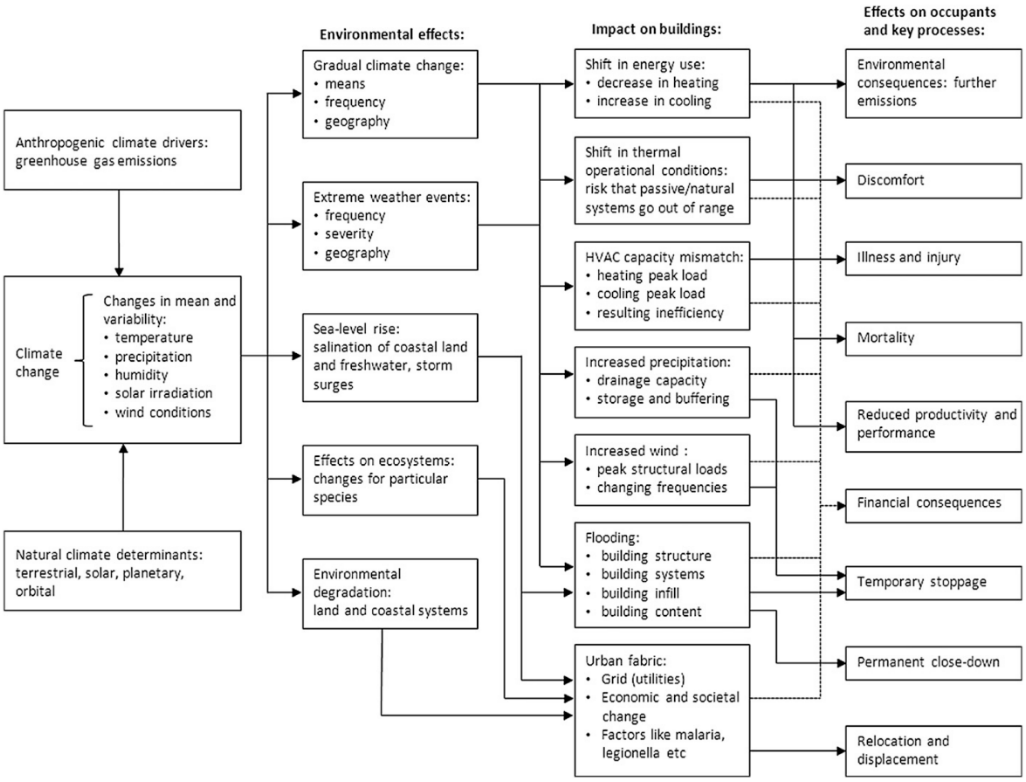

Figure 2.6. Representation of complex relationship between climate change, buildings, occupants and processes (De Wilde and Coley, 2012, p.2)

2.1.5. Climate conditions and climatic change in Turkey

Turkey is located in the Mediterranean geographical region that has quite temperate climatic conditions, however, there are significant differences in climatic conditions from one region to the other in there. In compliance with the Köppen system of climate classification, the climate of Turkey is divided into three different climate zones.

The coastal areas of the Mediterranean Sea and the Black Sea have a Csa Climate, a warm temperate Mediterranean climate with dry, warm summers and moderate, wet winters and the warmest month above 22°C over average. The mountainous regions of Anatolia have a Dsa Climate, with snowy winters and dry summers and the warmest month above 22°C and the coldest month below -3°C. The climate of the central

Anatolian plateau can be classified as Csb Climate, a cold, dry climate with a dry summer and annual average temperatures under 18°C.

As compared to the global change in temperature, the impacts of climate change in Turkey reflect global patterns but Turkey is projected to be one of the regions that is most vulnerable to climate change in the Mediterranean basin (IPCC, 2014). The impacts are projected to continue and can be summarized as follows:

- Temperature increases causing warmer winters with less snow
- Heat waves and greater droughts frequency
- Reduction in surfaces and freshwater resources
- Greater frequency of floods due to sudden and heavy rainfall
- The gradual shifting of the seasons.

The major causes of these impacts are incorrect agricultural activities and implementations, fast-growing population and rapidly and wrongly increasing urbanization. In the UNDP project report (2010), it is stated that *Turkey's urbanization rate increased from 52.9% in 1990 to 74.9% in 2008 and the number of residential and commercial buildings in large cities has risen rapidly*. In the same time frame, 1,524 million m^2 of total area have been covered with residential, commercial, and public buildings. These numbers constantly continue to increase and in direct proportion to this expansion, energy consumption and CO^2 emission originated from the building sector constitute the majority of Turkey's final energy consumption and emissions. In 2009, in consideration of information from UNDP report (2010), building sector in Turkey generated 53.4 Mt of CO2 emissions and energy consumption in the same year was 29.5 million TOE (tonne of oil equivalent) and it is estimated to reach 47.5 million TOE in 2020, meaning that the CO2 emission figures will double in 2020.

2.2. Urban Heat Island Effect

Although cities cover up to 2% of the world, they are changing the land use with their construction and construction activities and the expansion of transportation networks, resulting in a tremendous amount of energy consumption and loss of natural resources. These processes with the built forms in cities create unique and site-specific climatic conditions and the climatic conditions in the cities differ from their surrounding rural areas. At the urban or local scale, differences in cloud cover, precipitation, solar irradiation, air temperature, and wind speed are observed (Kleerekoper et al., 2012). At the smaller scale or micro-scale, the thermal and optical qualities of its finish materials, the geometry, spacing, and orientation of buildings and the use of landscape vegetation modify the climate. The phenomenon that air or surface temperatures of urban areas tend to be higher than its surrounding is called urban heat island effect (UHI effect). According to Erell, Pearlmutter, & Williamson (2011),

> "Under certain weather conditions a substantial difference in temperature may be observed between a city and its surrounding rural areas. When isotherms are drawn for the area in question, the city is apparent as a series of concentric, closed lines of higher temperature, with maximum values recorded at or near the densest part of the urban area (Figure 2.7). This condition is known as the urban heat island" (Erell et al., 2011, p.67).

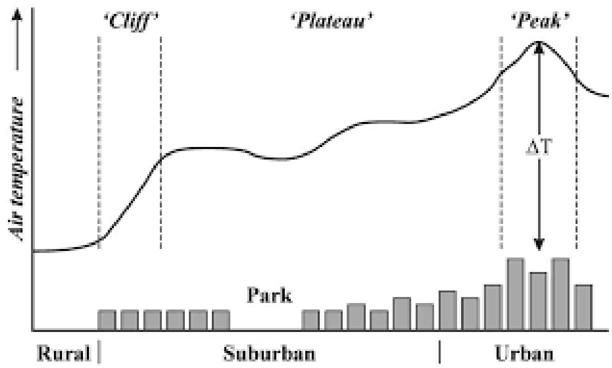

Figure 2.7. Generalized cross section of a typical UHI

2.2.1. Types of UHIs

Urban heat islands can be categorized into two types: the surface and atmospheric heat islands. These two heat island types are different in terms of their formation, intensity, impacts, temporal behavior and degree of homogeneity (Erell et al., 2011).

- **The surface urban heat islands:** The surface heat islands refer to that the temperature of surfaces is greater than surrounding natural surfaces that can remain close to air temperature. They occur day and night but tend to be more intense during the day depending on the intensity of the sun and weather conditions.
- **Atmospheric urban heat islands:** Atmospheric urban heat islands refer to warmer air temperatures and they can be defined as warmer air in urban areas compared to the cooler air in nearby rural surroundings. There are two sub-categories of them, the canopy-layer heat islands and the boundary-layer heat islands. The canopy-layer heat islands exist in the layer of air where is the closest to the surface in urban areas and they can be observed generally at night. They have a direct effect on the occupants of buildings. The boundary-layer heat islands form from the rooftop to downwind of the cities and they can be observed one kilometer or more in thickness in the day time.

2.2.2. Cause of UHIs

The formation of UHIs is one of the most effective evidence of the anthropogenic changes to the natural environment and Erell et al. (2011) state that even a single building may create a measurable disturbance to the land in its natural state (Erel et al., 2011, p.70). There are variables that can be categorized as controllable and uncontrollable, as shown in Figure 2.8 (Rizwan, Dennis, & Chunho, 2008). Wind speed, cloud cover, anticyclone conditions, diurnal conditions, and season that are derived from nature are uncontrollable variables and they have temporary effects (Rizwan et al., 2008 and Lee, Din, Ponraj, Noor, & Chelliapan, 2017). The main factors affecting the intensity of UHIs are urban form, building density, sky view factors, impervious surfaces, vegetation, properties of urban materials, and anthropogenic heat sources including the cooling and heating of buildings and they are controllable and permanent variables related to the built environment. Population density also plays an important role in UHI intensity.

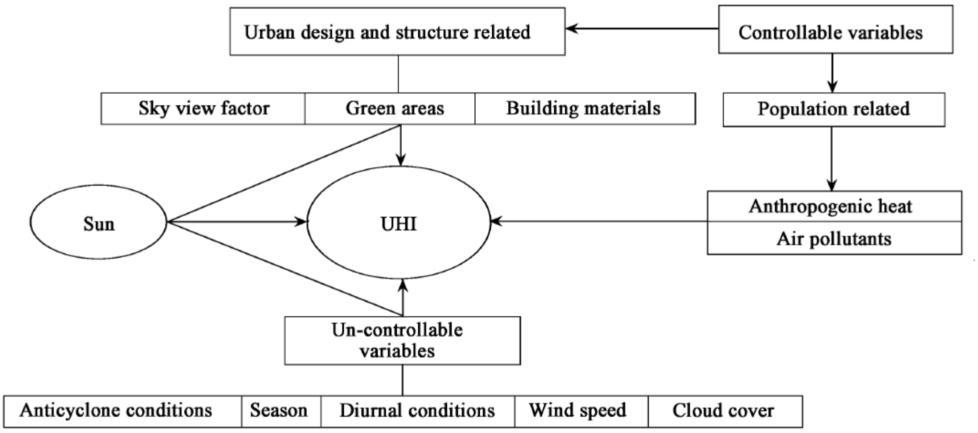

Figure 2.8. Controllable and Uncontrollable Factors (Rizwan et al., 2008).

The variables affecting UHIs intensity by built environment are (Kleerekoper et al., 2012, p.30).

1. Absorption of short-wave radiation from the sun in low albedo (reflection) materials and trapping by multiple reflections between buildings and street surface.

2. Air pollution in the urban atmosphere absorbs and re-emits longwave radiation to the urban environment.

3. Obstruction of the sky by buildings results in a decreased long-wave radiative heat loss from street canyons. The heat is intercepted by the obstructing surfaces, and absorbed or radiated back to the urban tissue.

4. Anthropogenic heat is released by combustion processes, such as traffic, space heating and industries.

5. Increased heat storage by building materials with large thermal admittance. Furthermore, cities have a larger surface area compared to rural areas and therefore more heat can be stored.

6. The evaporation from urban areas is decreased because of 'waterproofed surfaces' – less permeable materials, and less vegetation compared to rural areas. As a consequence, more energy is put into sensible heat and less into latent heat.

7. The turbulent heat transport from within streets is decreased by a reduction of wind speed (Figure 2.9).

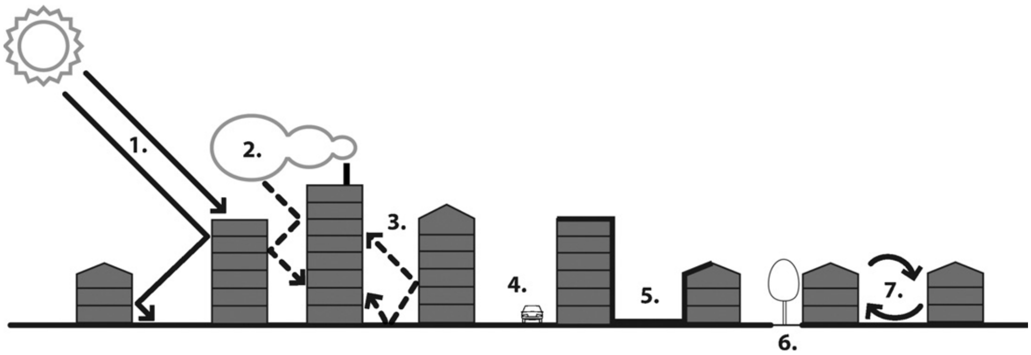

Figure 2.9. Causes of UHIs (Kleerekoper et al., 2012, p.30).

In addition to these variables, manufacturing, transportation, and lighting also have a contribution to UHIs effect in an instant and direct ways. UHI intensities show different trends in different seasons and hours and especially in the summertime; they tend to be largest in the early morning hours. The built environment continuously absorb radiation from the Sun in the daytime, from sunrise to late afternoon and they store this radiation as the heat energy. After sunset, the temperature of the air becomes colder than the daytime and then the heat energy is released to the environment (Rizwan et al., 2008). As a result, UHIs reach the highest point in the early morning hours. Bohnenstengel et al. (as cited in Sailor, 2014) determined that the temperature in the city center is 4-5 °C higher than rural areas in early morning hours in London, UK. Another study in Hong Kong found similar results which in the summertime, the temperature difference between the urban areas and the rural areas is 2-3 °C in early hours but it is not more than 0.5-1 °C during the day (Sailor, 2014). According to Çiçek and Doğan (2005), in Ankara, Turkey, the UHI magnitude in the city center also showed 3-4 °C temperature differences with respect to rural areas in the mornings. As a consequence, temperature differences may reach 2-5 °C generally at night or early in the mornings and UHIs are more affective in these hours.

2.2.3. Impacts of UHIs

The concept of urban heat island is one of the well-known forms of local anthropogenic climate change but it plays a role in much broader in a global sense. In point of fact, urban heat islands and climate change affect each other consistently. Temperature increases resulting from climate change are expected to impact the urban heat island (UHI) effect exacerbatingly while UHIs have a high potential to trigger the interaction between climate change-related risks and vulnerability especially in terms of excessive heating and GHG emissions (Corburn, 2009 and Evyatar, 2011).

As was mentioned in the previous section, heating and cooling energy demands, especially in urban areas, intensify the impact of climate change and UHI (Santamouris, 2014). According to the analysis of the impact studies, the average cooling load of typical buildings in urban areas is 13% higher compared to similar buildings in rural areas due to UHIs (Santamouris, 2014). In Melbourne, Australia, it was found that the UHI has an increasing effect on cooling uses by 10% and 17% while it affects the space heating in 5% and 7% decline for existing and new residential buildings in the one-year analysis (Zinzi, Carnielo, & Mattoni, 2018). Another study on residential buildings was carried out in Milan, Italy with urban and rural data for seven years and it indicated similar results to other studies which the heating loads decrease by 12–16%, while the cooling loads increase by 39–41%.

These studies show that the energy demand for cooling contributing to urban and global warming is increasing. The ongoing rapid urbanization and land use, which leads to warming, will continue to show an upward trend. In parallel to these, UHIs are directly associated with energy and thermal performance of buildings. In addition to this, they enhance the problems of indoor quality, health, and mortality. Therefore, UHIs should be taken into consideration for taking proper action on climate change, the accurate predictions performance of the built environment, and the improvement of human thermal comfort.

2.3. Thermal Comfort

Environmental conditions are directly associated with people's physical and mental state. It is pointed out that people are more active, more productive and healthier under good and satisfactory environmental conditions, while they feel more depressed and physical and mental energy decrease in an unsatisfactory environment (Olgyay, 1963). From this point of view, indoor environments become crucial because people spend an average of 80–90% of their time in indoor environments. Mendell and Heath (2005) state that starting with the 1970s, health problems associated with buildings that were common complaints in the eye and upper respiratory tract irritation, headache, fatigue, and lethargy, and breathing difficulties or asthma have been reported. In conjunction with these reports, concerns have increased that indoor environments influence not only health but also performance, productivity and emotional health of the occupants.

All of these taking into account, there is always a dynamic dialogue between buildings and their occupants and thus, providing a healthy indoor environment that depends on thermal, visual, and air quality parameters is one of the important parts of this dialogue. Among these parameters, thermal comfort is a key issue, not only because of the comfort of occupants but also because it makes a contribution to control energy consumption of buildings (Nicol & Humphreys, 2002). That is to say, it is significant to understand thermal comfort in terms of:

- *providing a satisfactory condition for people*
- *controlling energy consumption*
- *suggesting and setting standards* (Taleghani, Tenpierik, Kurvers, & Van Den Dobbelsteen 2013).

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2004) defines thermal comfort as "condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". In other words, thermal comfort may be expressed as a feeling of well being in relation to heat (Goulding, Lewis, & Steemers, 1992). On the basis of these definitions, thermal comfort may be considered as a cognitive concept influenced by physical, physiological, psychological and other factors. In a built environment, factors affecting thermal comfort are related to the individual and the surrounding environment. The individual factors are metabolism, clothing and skin temperature and the surrounding environmental factors are air temperature, radiation, air motion, and relative humidity (Goulding et al., 1992). Besides, thermal perception can be influenced by the differences in sex, age, adaptation, seasonal, and many other factors with regards to subjective manners. In order to understand clearly the thermal comfort, it is necessary to understand the factors that affect it.

Metabolism and the activity of the body: Metabolism is the sum of life-sustaining biochemical reactions in the body to generate required energy which results in heat production. The human body uses and regulates metabolic heat production to maintain constant body temperature. For this reason, when the air temperature is different from the body, metabolic reactions occur in the form of heat production or heat loss in order to equalize the temperature. Besides, the amount of metabolic heat production that can be measured in joules, calories or kilocalories per unit time depends on the activity level of the body influences.

Clothing: Clothing is a layer that acts as insulation around the body. It can be a quick and immediate solution to thermal discomfort with the decrease of heat emission by conduction, radiation or convection (Kristensen et al., 2010). In order to simplify, a new unit called the clo has been created. One clo is equal to a resistance of 0.155m^2K/W and the thermal resistance of summer clothes is 0.5 clo while the thermal resistance of indoor winter clothes is 1 clo (La Roche, 2012 and Goulding et al., 1992).

Air temperature: Air temperature is the average temperature of the air that surrounds the living being. It is measured by dry bulb temperature (DBT) and for this reason, it is generally known as dry-bulb temperature. The air temperature is the most important factor to thermal comfort because it affects the other thermal comfort factors such as the rate of evaporation, relative humidity, wind speed and its direction and it also affects *the rate of convective heat dissipation* (La Roche, 2012, p.82).

Radiation: The radiant exchanges between the body and the surrounding surfaces and that affects thermal comfort. This change depends on the temperatures and the qualities of the surrounding surfaces and the view angle between these surfaces and our bodies (La Roche, 2012). A larger angle or higher temperature differences between two surfaces enhance the radiant exchange and the radiation always tend to move from a higher to a lower temperature (La Roche, 2012).

Air movement: The body is always exposed to air and air movement helps the body to evaporate the moisture that is one of the reasons for thermal discomfort. Air velocity has an increasing effect on the evaporative cooling and also a reducing effect on the body's surface resistance (La Roche, 2012). Thus, air movement has a greater potential to provide thermal comfort than the other factors.

Relative humidity: Relative humidity is "the ratio of the vapor pressure in a sample of air to the saturation vapor pressure at the same temperature, expressed as a percentage" (Skinner and Muck, 2011, p.336) and it has an effect on the evaporation rate from skin or sweating that is one of the heat loss mechanism. Both very low relative humidity that is below 30% and higher relative humidity that is above 70% causes an uncomfortable environment. Hence, as La Roche (2012) state, humidity between 30 and 60% is an acceptable percentage for thermal comfort criteria.

2.3.1. Thermal Comfort Studies

The interaction between the abovementioned factors that affect thermal comfort depends on the cultural, personal, location and time parameters and therefore it is very difficult to determine precise comfort parameters for everyone (Goulding et al., 1992). In order to understand the interactions between the parameters and identify environmental and comfort indices, many studies have been carried out over the years and these studies that showed both deterministic and empirical results have a background dating back to the 1900s. Initial studies on thermal comfort generally based on measuring the energy exchange between the body and its surroundings and also obtaining verbal reaction from subject to the physical conditions at the same time in the laboratory environment (Erell et al., 2011).

In 1923, Houghten and Yaglou developed the Effective Temperature scale in which the notion of comfort zone was proposed on a psychrometric chart. As cited in "Urban Microclimate: Designing the Spaces Between Buildings", it was defined as "an index of the degree of warmth which a person will experience for all combinations of temperature and humidity" by Houghten and Yaglou (Erell et al., 2011, p.126).

Bedford considered the thermal comfort from a different angle compared with previous studies and he developed Bedford scale based on field studies to find out the thermal sensation of factory workers in the UK (Erell et al., 2011). It was aimed to figure out the temperature and combination of thermal variables and to relate impressions of his subjects on a seven-point of comfort, as shown in Tablo 2.1.

Table 2.1. *ASHRAE and Bedford thermal sensation scales*

ASHRAE scale		Bedford scale	
+3	Hot	7	Too much warm
+2	Warm	6	Too warm
+1	Slightly warm	5	Comfortably warm
0	Neutral	4	Comfortably - neither cool nor warm
-1	Slightly cool	3	Comfortably cool
-2	Cool	2	Too cool
-3	Cold	1	Too much cool

Another different approach, namely the bioclimatic approach as a tool for designers was developed by Victor Olgyay. Olgyay (1963) aimed an environmentally conscious building design depending upon the climatic environment and human needs. Olgyay used the term 'comfort zone' that means the range of environmental conditions within which the average person would feel comfortable. Olgyay (1963) claimed that "*the approach should be rephrased in terms of comfort; the presentation should be in graphic form; and, to be easily applicable, the data should derive from the empirical findings available to the practicing architect"* (Olgyay, 1963, p.17) and he developed a bioclimatic chart applicable to the temperate climates of the United States, as shown as Figure 2.10.

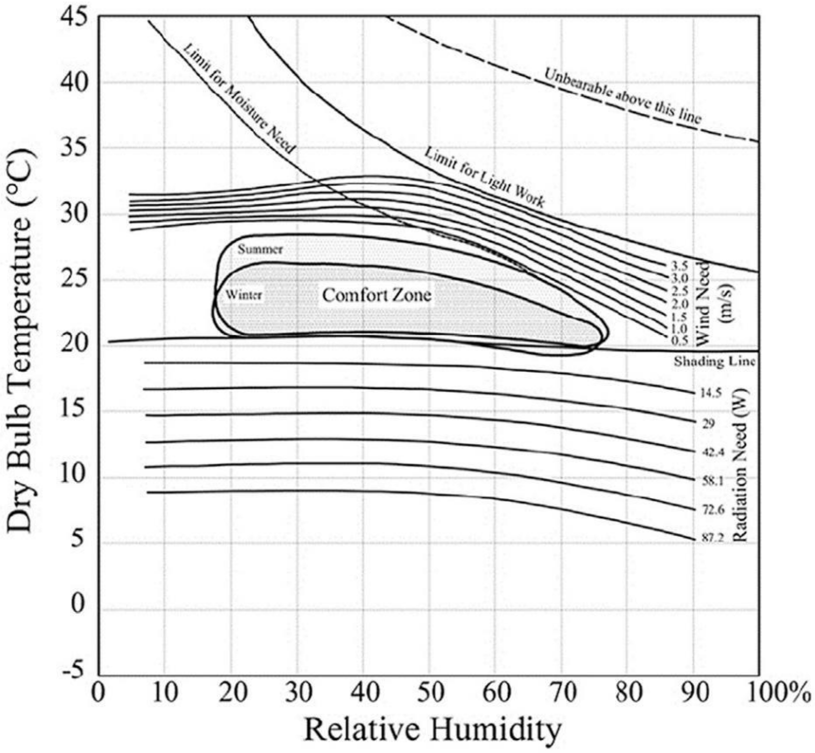

Figure 2.10. An example of the Olgyay Bioclimatic Chart. (Olgyay, 1963, p.22).

2.3.1.1. The Steady-State Model

The well-known and commonly cited and empirical research is Fanger's theory and his equation. His analysis indicated that the sensation of thermal comfort was determined by using heat-balance equations and laboratory-based studies for/about skin temperature and his equations are used to calculate predicted mean vote (PMV) and predicted the percentage of dissatisfied (PPD). Roche (2012) explains that

> "The PMV is the average comfort vote predicted by a theoretical index for a group of subjects when subjected to a particular set of environmental conditions. The PMV uses a seven-point thermal scale that runs from cold (-3) to hot (+3) with zero as ideal. Lower or higher values are possible. From the PMV, the PPD can be determined. As PMV moves away from zero in either the positive or negative direction, PPD increases. The maximum number of people that could be

dissatisfied with their comfort conditions is 100%. However, as you can never please everybody even under optimum conditions, the minimum PPD number even under optimum comfort conditions is 5%" (Figure 2.11) (Roche, 2012, p.90).

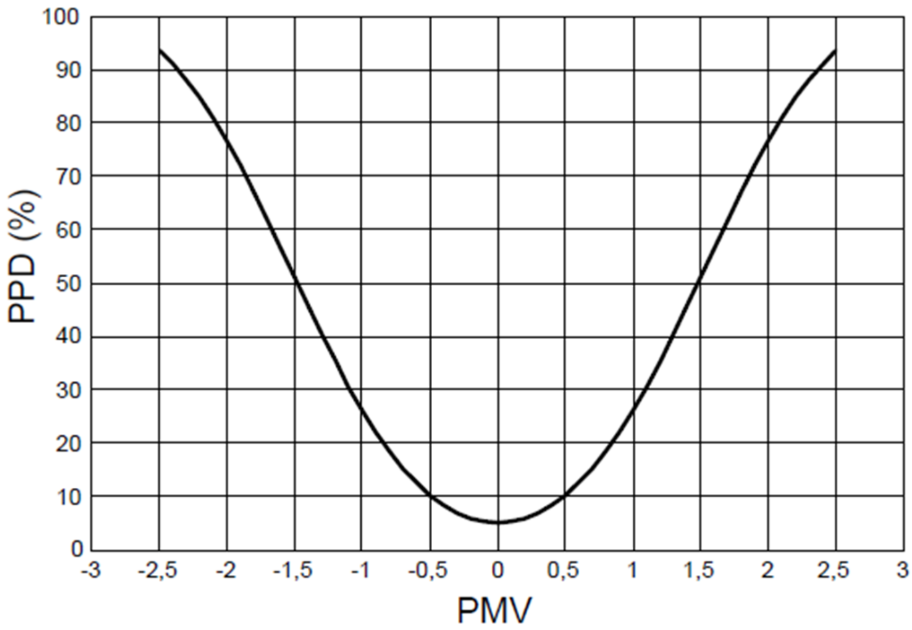

Figure 2.11. The relationship between PPD and PMV

This equation, afterward, becomes the basis for steady-state or physiological comfort model. The model only approaches thermal comfort in terms of *physics and physiology of heat transfer* and evaluates it independently of all other factors affecting thermal comfort such as location, adaptation, and so on. International standards ISO 7730-1984 and ASHRAE 55-1992 are developed based on this approach. ISO 7730 aims to provide a method for estimating the degree of dissatisfaction (PPD) and thermal sensation (PMV) for people exposed to an average thermal environment and to determine acceptable thermal environment conditions for comfort. On the other hand, ASHRAE standard aims to determine the comfort range by using operative temperature and humidity ratio and plots them into a psychrometric chart with the comfort zone, shown as Figure 2.12 (La Roche, 2012). The operative temperature is a temperature that represents both the air temperature and the average radiation temperature.

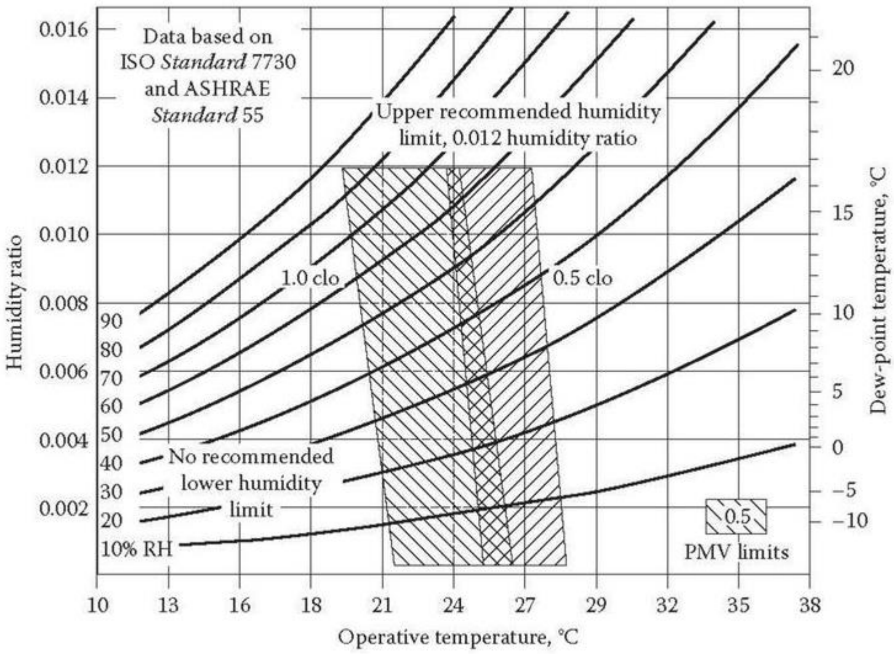

Figure 2.12. Acceptable range of operative temperature and humidity for 80% of occupants acceptability (From ASHRAE Standard 55-2004).

2.3.1.2. Adaptive Comfort Model

The adaptive model relies on the idea that environmental conditions or outdoor climate has an effect on the thermal comfort of indoor zones, and thus occupant behavior. The adaptive approach was proposed by Michael Humphreys and Fergus Nicol, who state that the experiments in laboratory conditions might not reflect the complex situations in real-life as thermal comfort responses of the people that might be affected by their psychological, physiological and behavioral external environment conditions and they might show different behavior patterns from laboratory conditions by adapting themselves to these conditions. Humphreys and Nicol (1998) found a statistical relationship between mean outdoor temperature and mean comfort or neutral temperature. Andris Auliciems in Australia also examined the similar interrelationship between the neutral temperature in free-running buildings and the outdoor mean temperature and this relation was expressed in the following equation by Auliciems:

$$T_n = 17.6 + 0.31T_{ave} \quad (18°C \leq T_{ave} \leq 28°C) \qquad (1)$$

where

T_n : thermal neutrality temperature

T_{ave}: outdoor average dry-bulb temperature (as cited in La Roche, 2012).

In 1998, deDear and Brager (as cited in La Roche, 2012) studied the same relationship between indoor, outdoor temperature and thermal comfort and their findings showed that in buildings that are not fully mechanically controlled, the thermal comfort temperature range expectations are broader than the range obtained by Fanger's theory. Although, as stated previously, ASHRAE standard 55 was originally based on the PMV model, the results of deDear and Brager's research contributed to reshaping the standard (La Roche, 2012). This can be only applied in naturally ventilated buildings where the occupants have access to operable windows and other adaptive opportunities. That is to say, this provides the occupants of the building more control over their thermal comfort and a wider range of comfort zone. In this standard, the monthly outdoor temperature varies from 10°C to 33.5°C and Figure 2.13 shows this range together with thermal acceptability rate.

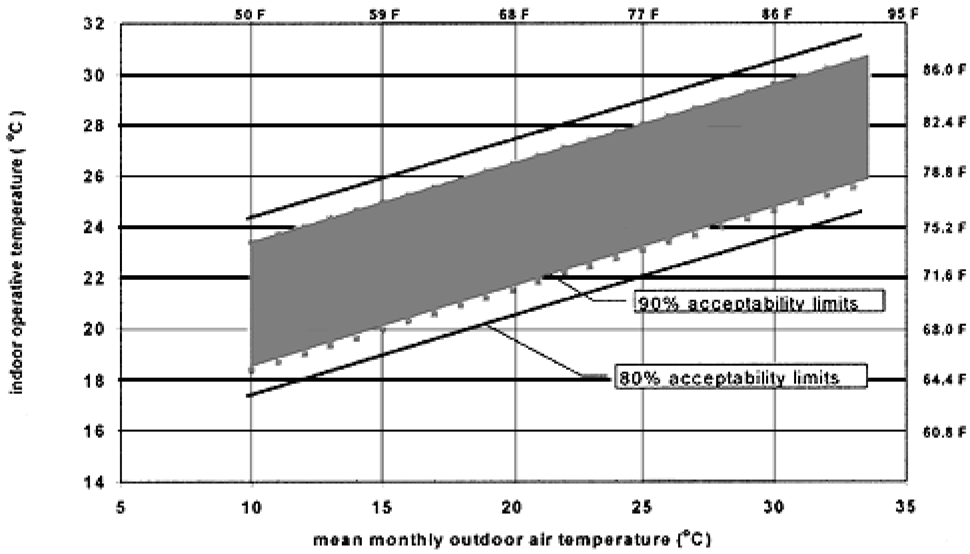

Figure 2.13. Acceptable operative temperature ranges. (From ASHRAE Standard 55-2009).

In this standard, the following equation can be also used for calculating comfort temperature.

$$T_n = 0.31T_{ave} + 17.8 \quad (10°C \leq T_{ave} \leq 33.5°C) \qquad (2)$$

where

T_n : neutrality temperature

T_{ave}: monthly mean outdoor air temperature (as cited in La Roche, 2012).

Another standard for adaptive comfort model is the European standard EN15251. It is similar to ASHRAE but EN15251 uses data of Smart Controls and Thermal Comfort (SCATs) projects as database while the ASHRAE uses the field experiments of deDear and Brager. The equation used for EN15251 is as follows:

$$T_n = 0.33T_{ave} + 18.8 \qquad (3)$$

where

T_n : neutrality temperature

T_{ave}: monthly mean outdoor air temperature (as cited in La Roche, 2012).

2.3.1.3. Thermal Comfort Studies in Educational Buildings

As previously indicated, people are affected by their surroundings, especially indoor environments in terms of physical and psychological health, productivity, and performance. In this sense, providing qualified indoor environments is significant as people spend most of their time inside of the buildings. An adult working in a typical modern desk job spends an average of 22 hours a day in her/his office and home, while students spend most of their time in educational buildings and their home. In connection with all of these, providing comfortable indoor conditions in educational buildings have become a critical issue in recent years for three main reasons.

First, indoor conditions play a determinative role in performance, productivity, attendance, and health of students and also teachers and a poor thermal environment due to high occupant density may lead to productivity and performance loss in classrooms (Zomorodian et al., 2016). Secondly, students are more easily and quickly affected by poor thermal comfort conditions depending on their age, their body, and difference in metabolism compared to adults (Katafygiotou and Serghides, 2014). Latsly, the energy consumption and greenhouse gas emission percentage in educational buildings are the third reason that makes them important in terms of thermal comfort. Educational buildings are considered as a large portion of building stock and they have high energy consumption within non-industrial energy usage of countries and they consume most of the energy to provide thermal comfort (Zomorodian et al., 2016). Besides, compared to office and residential cases, some differences are observed in terms of thermal environment requirements, activity, clothing, age, and adaptive opportunities. When these are taken into consideration, the indoor climate conditions of schools become special cases. Although thermal comfort studies in educational buildings were reported in 1968, over the last 10 years it has taken on a new significance, along with the awareness of the aforementioned issues.

Thermal comfort studies in the educational buildings generally focus on typical classrooms, which is where the students spend most of their time in. In their review of thermal comfort in educational buildings, Zomorodian et al. (2016) indicate that the studies have been classified according to several parameters including climate zone, educational stage, and the thermal comfort approach and sub-parameters that are year of study, country, continent, ventilation type, number of respondents, and the season of study. According to each parameter, it is possible to determine thermal comfort or preferred temperature in classrooms.

As the climate zone, the Köppen-Geiger climate classification has been used in the studies. The majority of the previous research work covers group C; temperate/mesothermal climates while there is no study for group E; the polar and alpine climate (Zomorodian et al., 2016). Most of the studies are carried out for the school term, which typically covers the winter and mid-seasons. Accarding to field studies conducted in different seasons and in different climate zone, the preferred temperature by students ranges between 16.7-29.2°C depending on the climate zone and indicated in Table 2.2.

Table 2.2. *Comfort temperature in each climate zone. (Zomorodian et al., 2016, p.899).*

Climate	Lower limit (°C)	Neutral (°C)	Higher limit (°C)
A	22	27.21	30.70
B	19	23.08	26.60
C	16	21.66	30.70
D	19.9	23.58	28.30

Another important parameter of thermal comfort in educational buildings is the educational stage, as explained earlier. Adults are used as subjects in studies of both steady-state and adaptive thermal comfort model, but comfort expectations and requirements vary across age groups because of metabolic rate, clothing, activity level, and adaptive action level. Thermal comfort issues in schools are typically addressed according to the age ranges:

1. Primary level (aged 7-11 or 10-15),

2. Secondary level (aged 12-17 or 16-18),

3. University level (aged 18-28) (Zomorodian et al., 2016 and Kim and de Dear, 2018).

Only the primary and secondary level will be discussed, the university level is outside the scope of this research/thesis.

The lower and upper comfort limits and the neutral temperature show differences in each age groups in the school buildings. In the review of Zomorodian et al. (2016), it is claimed that although the students prefer lower neutral temperature at small ages (Figure 2.14), it has been observed that students' sensitivity to temperature is lower compared to adults. This means that the time to respond to temperature also varies with age differences and the lower age groups responds later than usual. That is shown that thermal preferences and responses vastly differ depending on the age range as a result of differences between metabolic rate, the availability of adaptive opportunities, and variation of activity level. For primary level students, the comfort temperatures are 2°C-4°C lower than predictions of both steady-state and adaptive models, whereas thermal preferences of secondary level students are closes to adults compared to primary students.

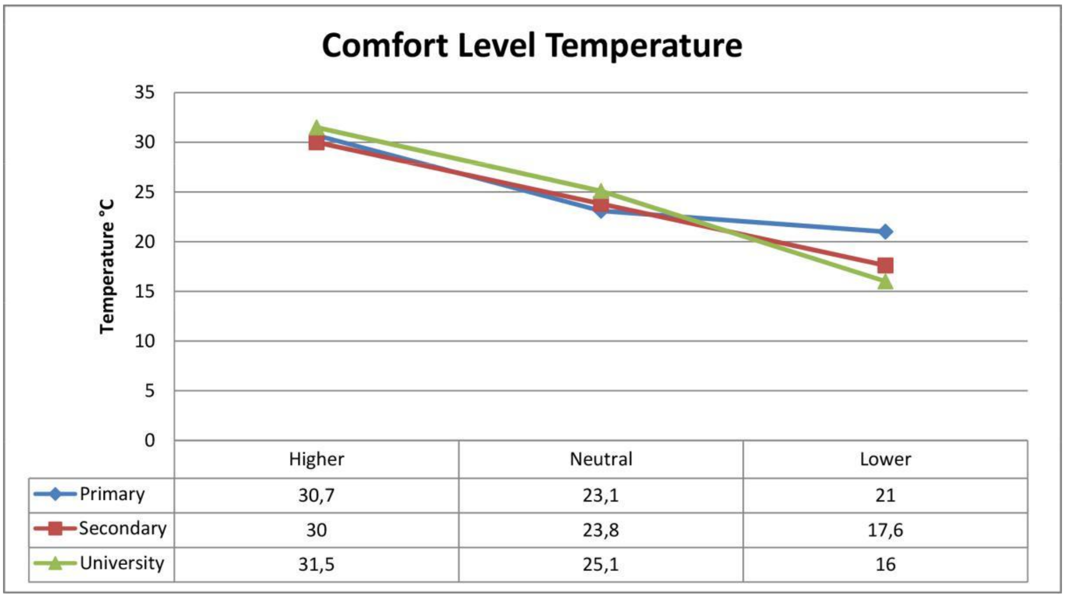

Figure 2.14. Comfort level temperature in different educational stage studies. (Adapted from Zomorodian et al., 2016).

As stated previously, the availability of adaptive opportunities in classrooms differ from offices or residential spaces. In general, the comfort conditions in the classrooms are determined according to the teacher's preferences or habits, i.e students are not active participants in terms of their thermal comfort (Kim and de Dear, 2018). Behavioral factors (activity level and clothing insulation) may restrict students' adaptive opportunities due to the school clothing policies and the need to remain still in the sitting position (Kim and de Dear, 2018). Although primary and secondary school students are in the same circumstances in regards to teacher's authority and behavioral factors, secondary school students have more opportunities to adapt to the environment and they have more reliable preferences in terms of thermal comfort compared to primary school students. In other words, they can modify their classroom environment through behavioral and physiological actions (Zomorodian et al., 2016).

In addition to climate zone and educational stage, indoor thermal comfort is related to the architectural and constructional characteristics of the buildings, namely building orientation, layout, space dimensions, window-wall ratios, external shadings, and material properties.

As pointed out earlier, thermal comfort studies are significant in terms of providing satisfactory conditions in the built environment, controlling energy consumption, and setting standards for the functioning of the buildings. In educational buildings, providing thermal comfort with minimum energy consumption under the current standards is the most challenging issues, since the students, especially in younger ages, have different thermal expectations and preferences and they are much more vulnerable to unsatisfactory conditions. In this research, this challenging issue will be addressed under the circumstances of students aged between 10-15 and the adaptive comfort model.

2.4. Architectural Design Solutions as Mitigation and Adaptation Strategies

2.4.1. Mitigation, adaptation, and sustainable development

Managing impacts and future risks of climate change is possible in two approaches; **mitigation** and **adaptation**. Fundamentally, mitigation is to *reduce the impacts of climate change* and adaptation is to *cope with the impacts of climate change* (Laukkonen, Blanco, Lenhart, Keiner, Cavric, & Kinuthia-Njenga, 2009, p.288). The aim of mitigation is to balance the level of anthropogenic CO_2 emissions within a specific timeframe and to observe quick improvement. It is easily applied to different area from global level to individual level that includes technical and infrastructural investments, renewable energy implementation and improving energy efficiency (Laukkonen et al. 2009). On the other hand, the aim of adaptation is to reduce vulnerability to the harmful effects of climate change. It is mostly implemented at the local level and over long-term horizons contrary to mitigation (Laukkonen et al. 2009). Although mitigation and adaptation strategies are operated different level and time, they both seek to avoid the potential damages of global climate change, and there should be a *synergy* or simultaneous supporting between them to achieve a sustainable future. In other words, sustainable future or development requires managing many threats and risks, including climate change and this is possible with both mitigation and adaptation strategies.

In the recent years, sustainability has been referred to the definition of the Brundtland Report. The report defines sustainability as follows; “sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission, 1987, p.8). The concept gained much boarder attention after this report. As Paden (2012) claims, however, this definition represents an anthropocentric approach because it brings human welfare to the forefront, and implies that nature should be conserved for human needs and welfare. In time, sustainability has already evolved from a human-centered standpoint to a nature-centered one after environmental problems become global in scale. Sustainability is about respect for ecology and ecological balance to provide a healthy ecosystem, environment, and human welfare. From this point of view, the profile of climate change mitigation and adaptation strategies should be strengthened with sustainable development.

These strategies should be implemented at many levels and at many sectors or fields, however, regarding the aim of this thesis, strategies only for buildings are focused.

2.4.2. Mitigation and adaptation strategies in the buildings

Buildings represent an integral part of both low-carbon and sustainable future, and so as, both mitigation and adaptation to climate change impacts have become crucial issues in the built environment. The aims of mitigation and adaptation within the built environment are to provide reducing impacts on the environment, optimizing project design, extending the life-cycle of projects and healthier and more comfortable living conditions for the users. In accordance with these objectives, the built environment or buildings should be designed or adapted to be compatible with their local climates, environments, and occupants. Bioclimatic design principles are based on the way these purposes and concurrently they are in line with the definition of sustainable development. Fundamentally, bioclimatic approach is the interactions of biological, climatological and building physics principles through building and space design to solve the challenge of climate control in a systematic way (Olgyay, 1963 and Nguyen, 2013) and it highlights the importance of the local climate impacts on through the form and fabric of the building (Olgyay, 1963). It addresses the following principles:

- climate types and requirements;
- microclimate: sun path, wind and rain;
- adaptive thermal comfort;
- vernacular and contextual solutions;
- passive and active systems;
- development of responsive forms.

Mitigation and adaptation strategies in architectural design are simply the concretization of the bioclimatic approach in building design practice to cope with the impacts of the changing climate. The strategies should be developed and implemented for all impacts of climate change on the built environment but in this study, the strategies only for global warming are taken into consideration and the other strategies are out of the scope of this study.

Global warming is the most important impact of climate change and it has been one of the observed effects of it for a long time. Although warmer winters will have a generally positive impact on our buildings, warmer summers and springs that have already reached a level of discomfort will affect the design and performance of buildings the most. As cited in “Design for future climate: opportunities for adaptation in the built environment”, research carried out by CIBSE and Arup shows that many existing buildings have already performed poorly with the exception of the advanced naturally ventilated examples and this situation will become worse in the future climatic conditions (Gething, 2010). Mitigation and adaptation strategies in building design are essential to manage successfully the risks of changing climate and to provide comfortable spaces. The appropriate strategies differ depending on the scale, from neighborhood to building scales.

As stated previously, surroundings or neighborhood of buildings have a great influence on outdoor temperature, UHIs effects, outdoor and indoor comfort and the performance of buildings and for this reason, the strategies at neighborhood scale are significant to cope with increasing temperature in many ways. The key measures for the neighborhood scale are solar control, green and blue infrastructure, natural ventilation, and replacement or selection of cool urban materials.

Natural flows of heat and indoor heat inputs constitute the temperature of building zones and while passive design strategies (use more the principle of bioclimatic architecture) are related to optimizing the building performance by the use of natural flows heat, active design strategies use more advanced technology (Hacker, 2005 and Bergman, 2013). At the building scale, passive and active design strategies should be considered to respond to the increase in temperature. The key passive design strategies include thermal mass, solar orientation, high-performance windows and glazing, double-envelope construction, solar shading control, natural ventilation and air circulation, insulation, cool roofs, and material selection. On the other hand, some of the active design strategies include solar thermal collectors, photovoltaics, wind energy, mechanical system, lighting controls, and green roofs. Table 2.3 summarizes the design strategies for increased air temperature. Moreover, essential steps that combine passive and active design strategies are identified in IPCC's AR4 report that can be listed as followed:

1. building orientation, thermal mass, and shape;
2. high-performance envelope specification;
3. maximization of passive features (daylighting, heating, cooling, and ventilation);
4. efficient systems meeting remaining loads;

5. highest possible efficiencies and adequate sizing of individual energy-using devices;
6. proper commissioning of systems and devices (IPCC, AR4, 2007).

Table 2.3. Mitigation and adaptation design strategies for increased temperature (Gething, 2010)

Key

Climate trend	
☼	Hotter, drier summers
(icon)	Warmer, wetter winters
⚠	More extreme events

Climate information	
P	Primary issue
S	Secondary issue

Time	
(icon)	Short – 10 years
(icon)	Medium – 25 years
(icon)	Long – 50 years

Climate	Design opportunities	Temp – summer mean*	Temp – summer mean max*	Temp – duration of hot periods (Weather Generator)**	Temp – summer mean min (night)*	Temp – warmest night of the season*	Temp – winter mean*	Temp – winter extremes, min and max*	Wind – summer mean**	Wind – summer still periods**	Wind – direction**	Wind – summer extremes**	Wind – winter average**	Wind – winter extremes**	Sunshine – average (Weather Generator)**	Rainfall – summer average*	Rainfall – summer droughts (Weather Generator)**	Rainfall – summer extremes*	Rainfall – winter average*	Rainfall – winter wet periods (Weather Generator)**	Rainfall – winter extremes*	Time: Short	Time: Medium	Time: Long
Climate	**Design opportunities: Keeping cool – building design**	**Climate information**																				**Time**		
☼	Shading – manufactured	P	P	S	S	S				P	S	S		S	P		S					Short	Medium	
☼	Shading – building form	P	P	S	S	S				P	S	S		S	P		S							Long
☼	Glass technologies	P	P	S	S	S				P	S	S			P		S						Medium	
☼	Film technologies	P	P	S	S	S				P	S	S			P		S					Short		
☼	Green roofs / transpiration cooling	P	P	S	S	S				P	S	S			P		S						Medium	Long
☼	Shading – planting	P	P	S	S	S				P	S	S			P		S					Short	Medium	Long
☼	Reflective materials	P	P	S	S	S				P	S	S			P		S					Short	Medium	
☼	Conflict between maximising daylight and overheating (mitigation vs adaptation)	P	P	S	S	S				P	S	S			P		S					Short	Medium	Long
☼	Secure and bug-free night ventilation	P	P	P	P	P				P	S	S			P		S					Short	Medium	
☼	Interrelationship with noise and air pollution	P	P	P	P	P				P	S	S			P		S						Medium	Long
☼	Interrelationship with ceiling height	P	P	P	P	P				P	S	S			P		S						Medium	Long
☼	Role of thermal mass in significantly warmer climate	P	P	P	P	P				P	S	S			P		S							Long
☼	Enhancing thermal mass in lightweight construction	P	P	P	P	P				P	S	S			P		S						Medium	Long
☼	Energy efficient / renewable powered cooling systems	P	P	P	P	P				P	S	S			P		S						Medium	
☼	Groundwater cooling	P	P	S	S	S				P	S	S			P	S	S		P				Medium	
☼	Enhanced control systems – peak lopping	P	P	S	S	S				P	S	S			P		S					Short	Medium	
☼	Maximum temperature legislation	P	P	P	P	P				P	S	S			P		S						Medium	Long
Climate	**Design opportunities: Keeping cool – external spaces**	**Climate information**																				**Time**		
☼	Built form – building to building shading	P	P	S	S	S				P	S	S			P		P							Long
☼	Access to external space – overheating relief	P	P	S	S	S				P	S	S			P		P							Long
☼	Shade from planting	P	P	S	S	S				P	S	S			P		P					Short	Medium	Long
☼	Manufactured shading	P	P	S	S	S				P	S	S		S	P		P					Short	Medium	
☼	Interrelationship with renewables	P	P	S	S	S				P	S	S			P		P						Medium	
☼	Shading parking / transport infrastructure	P	P	S	S	S				P	S	S			P		P					Short	Medium	
☼	Role of water – landscape / swimming pools	P	P	S	S	S				P	S	S			P		P				S		Medium	Long
Climate	**Design issue and opportunities: Keeping warm**	**Climate information**																				**Time**		
(Warmer, wetter winters)	Building fabric insulation standards						P	P					S	S	P								Medium	Long
(Warmer, wetter winters)	Relevance of heat reclaim systems						P	P					S	S	P								Medium	
(Warmer, wetter winters)	Heating appliance design for minimal heating – hot water load as design driver						P	P					S	S	P							Short	Medium	

2.4.3. Key phases of mitigation and adaptation strategies in existing buildings

As buildings generally remain standing for a period ranging between 40-100 years and a large proportion of the existing building stock will still exist in 2050 (IPCC, AR5, 2014). Mitigation and adaptation strategies are keys to improve the performance of existing buildings. Although energy savings of 50-90 percent in existing buildings have been achieved in studies conducted through implementation of the strategies throughout the world (IPCC AR5, 2014), the implementation of the strategies in existing buildings involves complex processes that have many challenges and opportunities. As mentioned earlier, buildings have a dynamic relationship between their environment, their occupants, and their services and this relation leads to many uncertainties that make difficulties in the implementation of the strategies (Ma et al., 2012). These uncertainties can be expressed as climate change, services change, human behavior change, government policy change, etc. In addition to the uncertainties, the financial limitations, the long lasted payback period, and overestimation of savings are considered as challenges (Ma et al., 2012). On the other hand, the implementation of the strategies has positive impacts on existing buildings that provided:

- Energy efficiency
- The better indoor environment included air quality, thermal comfort, and visual comfort
- Healthy and productive occupants
- Less vulnerability
- Less negative impacts on the environment
- Reducing operating cost.

Ma et al. (2012) also address the improvement of nations’ energy security, the corporation of social responsibility, reduction of energy prices and creation of more livable spaces with the help of the strategies.

Mitigation and adaptation of existing buildings emphasize intervention strategies for improving the performance and increasing the physical resilience of buildings to extreme weather and climatic events (IPCC, AR5, 2014). In the literature, terms such as renovation, refurbishment, re-modeling, reinstatement, retrofitting, rehabilitation, and recycling of buildings are frequently used for an intervention of existing buildings, depending on the level and the scale of the interventions. Giebeler (2005) defines the retrofitting as the upgrades in existing buildings that can be either fixing or repairing insufficiencies in the building performance or complying with required standards. In accordance with this terminology and definition, the mitigation and adaptation strategies in existing buildings are comparable to retrofitting in buildings and some principles of retrofitting can be engaged with these strategies.

Many of the aforementioned passive and active strategies can be applied to both the existing buildings and new buildings. Some key phases, however, should be considered when applying them to the existing buildings. Ma et al. (2012) categorize the process of building retrofitting into five major phases, as followed: 1) Project setup and pre-retrofit survey, 2) Energy audit and performance assessment, 3) Identification of retrofit options, 4) Implementation of the options, 5) Validation and verification.

Similar to Ma et al., another approach to retrofitting is proposed by Jafari and Valentin (2017). They identify 6 steps: 1) Building energy simulation, 2) Identification of potential retrofitting alternatives, 3) Formulation of energy consumption and total life-cycle cost, 4) Development of optimization methodology, 5) Development of optimum energy retrofit budget, 6) Analysis of outputs.

The UK Climate Impacts Program (UKCIP) (2003) has developed a framework for taking account of climate risks and uncertainties to help decision-makers implement climate change adaptation. There are eight stages in the framework: 1) Identify problem and objectives, 2) Establish decision-making criteria, 3) Assess risk, 4) Identify options, 5) Appraise options, 6) Make decision, 7) Implement decision, 8) Monitor, evaluate and review (Figure 2.15). The framework has been applied in the case studies from various fields including the built environment.

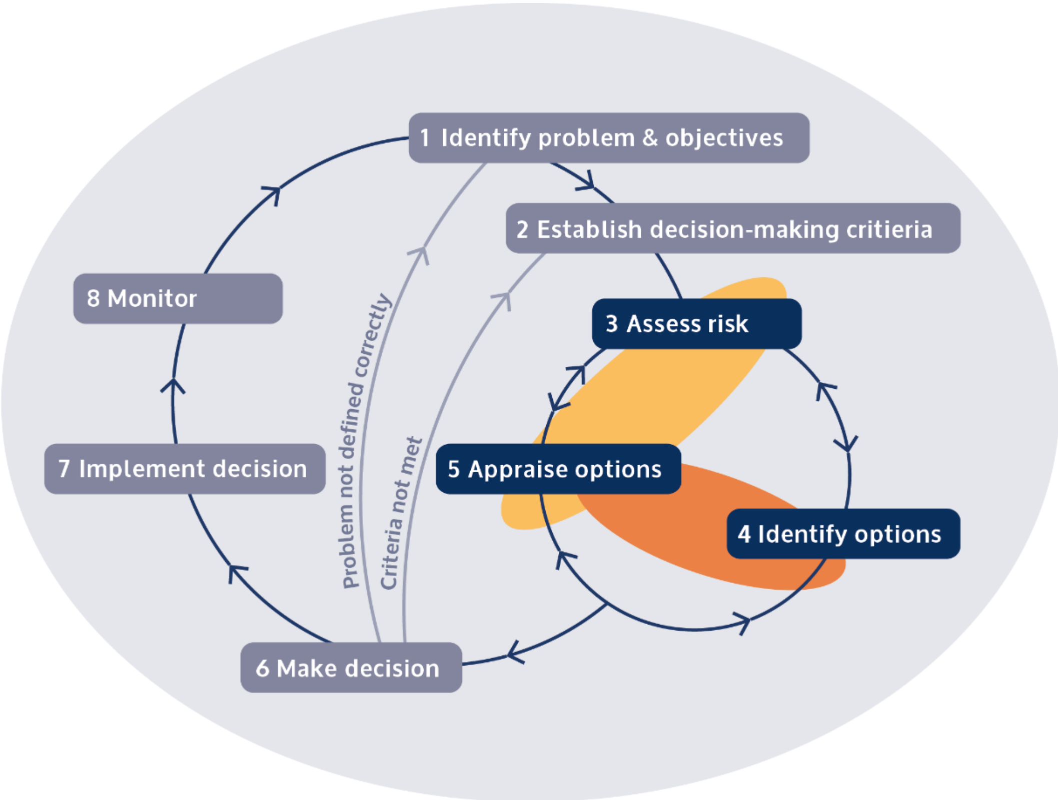

Figure 2.15. Risk based decision-making framework (UKCIP 2003)

These approaches aim to find the most effective strategies and to achieve enhanced energy performance while maintaining satisfactory service levels and acceptable indoor thermal comfort for a building but the success of a building adaptation depends on several other factors: policies and regulations, client resources and expectations, retrofit technologies, geographic location, building type, size, age, occupancy schedule, operation and maintenance, energy sources, utility rate structure, building fabric, services systems, human factors, and other uncertainty factors (Ma et al., 2012). Moreover, each building type should be assessed within their own vulnerability to climate change and the fundamental differences between different building types need to be taken into account when implementing the strategies.

CHAPTER 3

A DESIGN METHOD FOR CLIMATE CHANGE RESILIENCE

In the previous section, an extensive literature review on architectural design solutions as mitigation and adaptation strategies, climate change, urban heat island, and thermal comfort were presented. The following considerations were identified as well:

- Climate change is a critical and vital problem for which designers and architects should take responsibility. However, there is a general tendency not to acknowledge the impact and responsibility of this crisis.
- The lack of an architectural design approach for climate change is observed both in practice and in architectural education. Architectural design is in need of a critical reconsideration of the built and natural environments as part of critical factors such as weather, climate, and human activity, behavior, and needs.
- The knowledge gap exists with respect to how the environmental impact of the existing buildings can be mitigated, and the ways in which they can be adapted in the global and local climate.
- Existing building stock significantly contributes to climate change and environmental degradation with a large amount of energy consumption and greenhouse gases emissions.
- The performance of buildings depends on the climate they are exposed to. The deteriorating climatic conditions influence the energy performance and thermal comfort of existing buildings and also the health, productivity, and performance of their occupants in a negative way.

- The UHI effect is an important criterion in terms of building performance and has extreme impacts. However, the UHI effect is generally not included in the performance analysis and this leads to inaccurate results.

The main goal of this thesis is to develop a new design method that addresses these problems. For this purpose, a framework is proposed to support designers for the processes of designing for climate resilience in existing buildings by using a simulation-based quantitative approach.

The proposed method aims to develop design solutions as mitigation and adaptation strategies to improve energy performance and thermal comfort in existing buildings in accordance with the necessity of the changing climate. The balance between all of these is the challenge in this study. It is important to consider that intervention scenarios are not independent and sometimes, they can conflict with each other or they have a similar impact. Based on the modeling and simulation process, the proposed method helps designers to understand the different alternatives and to select the best options to balance between comfort, energy requirements, predicted climate conditions, and contextual situations.

The method used in structuring the strategies and the analyzing processes has some requirements, as followed:

- Gathering existing building information
- Climate data analysis for climate change and the UHI effect
    - The generation of future weather data projections
    - The generation of modified data with urban heat island effect
    - A comparative climate analysis
- Analysis of the current building performance
    - Performance evaluation criteria
    - 3D modeling
    - Development of simulation model
    - A comparative performance assessment

- The development of intervention scenarios for climate change mitigation and/or adaptation
    - Identification and implementation of potential intervention scenarios
    - Comparative performance assessment

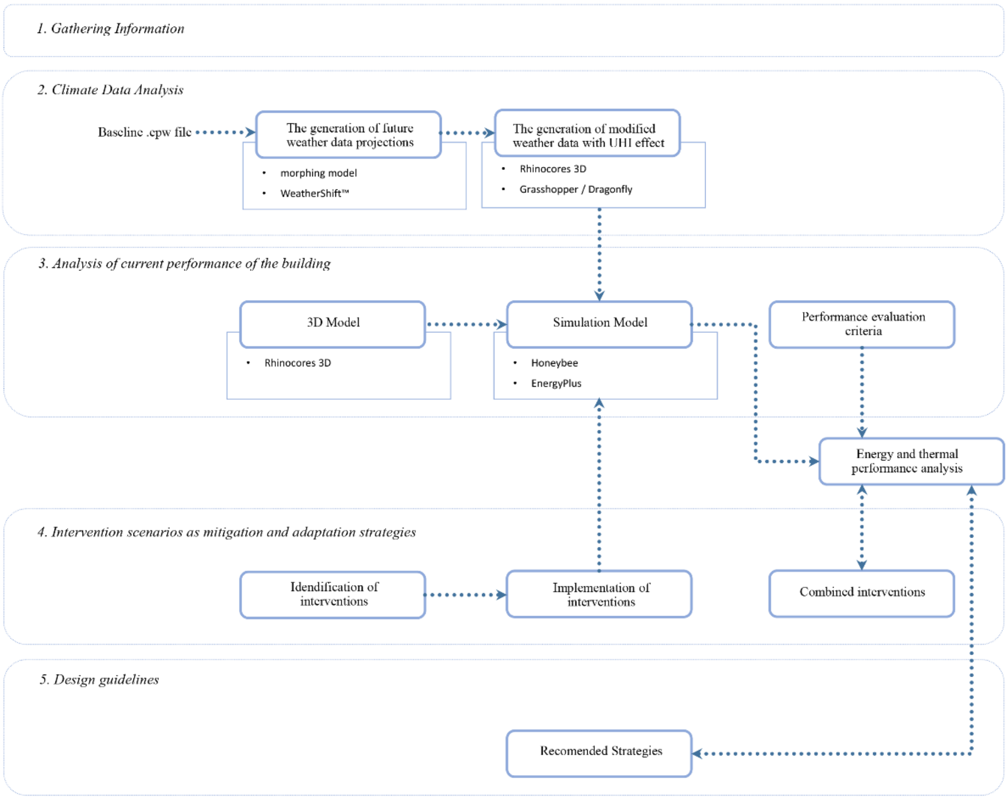

Figure 3.1. Methodology flowchart

3.1. Gathering existing building information

Before climate and performance analysis, detailed information about the building is required in order to obtain better and more accurate results. The information should be ranged from the neighborhood scale to the building material scale. The neighborhood scale in which the building is located is important because it affects the local climate and also acts as contextual shading. In this scale, buildings height, roads, all kind of pavements, soil and green areas, and other elements that cause shadow are needed. Furthermore, detailed information and research on building scale is needed, as follows;

- Geometric properties of buildings included architectural drawings, the height of floors, envelope shape, area of each zone, and glazing ratio.
- Non-geometric properties of buildings included construction date, material details, equipment, internal loads, heating-cooling or HVAC system details, schedule, and user profile.

When the need arises, user and/or owner surveys can be conducted to gather information.

3.2. Climate data analysis for climate change and the UHI effect

A climate analysis is needed to provide clear understanding how climate change and UHI affect the temperature and predictions for energy demand and thermal comfort for the future. Therefore, weather data containing different information and their comparisons are required in this kind of study.

3.2.1. Generation of future weather data

In order to analyze and compare the climatic conditions and to be able to make building performance predictions for the future, projections of future climate are essential to generate. It is stated in the AR5 report of IPCC (2014) that

> *It is not possible to make deterministic, definitive predictions of how climate will evolve over the next century and beyond as it is with short term weather forecasts...It is possible to understand future climate change using models and*

to use models to characterize outcomes and uncertainties under specific assumptions about future forcing scenarios (IPCC AR5, 2014, p.1034).

As IPCC pointed out, a model should be used for the generation of the projections and in this study, the widely used morphing model coupled with WeatherShift™ tool which will be presented in the following chapter was selected as a model and generator tool.

3.2.2. Generation of modified weather data with UHI effect

Weather data sets are generally collected at airports, outside of the urban context. Although these data provide hourly detailed information for the whole year, they do not represent accurately the urban local climate conditions (La Roche, 2012). For this reason, in order to carry out more accurate analysis, the UHI effect is required to be measured and to be incorporated into the weather data. It can be measured by the microclimate station that is installed in a selected context or with the numerical model of the context. In this study, the numerical model was proposed to quantify UHI effect.

3.2.2.1. 3D modeling

A volumetric representative 3D model of the selected context is required to calculate the UHI effect. For this, information about building geometry, roads, pavements, green areas, trees are needed.

3.2.2.2. Development of simulation model

The simulation can be developed using various tool. The selected tool has importance because it influences the parameters required for the simulation model. In this study, among these tools, Dragonfly which will be presented in the following chapter was selected.

- **Building parameters:** Geometric and non-geometric properties of buildings need to generate large scale phenomena. Geometric data of buildings includes information of envelope shape, area, glazing, and the number of floors while non-geometric data includes the year of construction and program of buildings. The envelope properties such as glazing ratio, solar heat gain coefficient (SHGC), wall albedo, and roof albedo can be defined by the user.
- **City parameters**: Not only are buildings typology needed but also the surrounding context included traffic, vegetation and pavement information are needed to generate the UHI-modified weather file.

3.2.3. A comparative climate analysis

In this phase, comparisons and analysis between the baseline year weather, generated future weather, and their modified data with UHI are required to be conducted for a clear understanding of the impacts of climate change and UHI different data. Plenty of different variables can be analyzed, such as hourly, monthly and yearly temperature, wind speed and direction, humidity, total sky cover, solar radiation data, and so on. In this study, the data were examined in terms of monthly minimum, average, and maximum mean outdoor dry bulb temperature, heating degree days (HDD) that will be explained in the following chapter.

3.3. Analysis of building performance

3.3.1. Performance evaluation criteria

As the first step, the performance evaluation criteria is necessary to decide because different performance criteria affects the intervention scenarios to be selected. In this study, energy demand and thermal comfort were taken into account as performance criteria.

3.3.2. 3D model

The 3D model of the selected existing building is required to be prepared by the assist of 3D modelling tools. The floor heights, program and openings of the building should be provided.

3.3.3. Development of simulation model

The energy simulation can also be developed by the help of several different tools. EnergyPlus was used for this research and the required information about the tool will be given in the next chapter. The following parameters should be provided and set: zone program, building load, zone schedules, zone construction, air flow, contextual shading elements, and weather data. There are also some sub-parameters that will be given in the case study section.

3.3.4. Performance assessment

In this phase, the results are evaluated in accordance with the specified performance criteria. It is an important step to be determined the energy demand and discomfort areas that play a role as a criterion in identifying the intervention scenarios. The assessment should be carried out both for the baseline year and the future climate modified with UHI to analyze and compare the results.

3.4. Intervention scenarios as mitigation and adaptation strategies

3.4.1. Identification and implementation of potential intervention scenarios

In this step, it is significant to first define the objective because the process of identification of intervention scenarios develops according to this objective. In this study, the objective is the design consideration that comprehends its advantages of reduced energy consumption and providing thermal comfort for climate change impacts. After the definition of the objective, criteria that would be effective in the process are needed to be specified. They help to narrow down and to better define the limits of alternatives.

It is also necessary to determine the scale of the intervention to be performed. There is a broad spectrum that relates to different scales ranging from component to deep intervention. The component or material interventions can guarantee to improve the performance of buildings and they are easy to apply. On the other hand, deep interventions can provide much greater improvement to building performance and more possibilities to address the problems of buildings (The American Institute of Architecture [AIA], n.d.). They are efficient ways to be able to keep the buildings operational and to improve the performance without the need for complete demolition and reconstruction. Furthermore, deep interventions allow for a wide range of materials and visual design language (The American Institute of Architecture [AIA], n.d.). In other words, it is possible to see the influence of the architect through the deep intervention. In this study, both intervention scales were included to obtain and analyze the different impacts of both of them.

After the identification process, the intervention scenarios are needed to be implemented in the simulation model. One factor at a time (OFAT) method was proposed for this study. In this study, all scenarios are implemented on an individual basis and results are obtained in the same way.

3.4.2. Performance assessment

As in the building analysis performance step, performance assessment is a necessity also in this phase. Firstly, the scenarios are evaluated according to the specified performance criteria and at the same time, they are evaluated comparatively.

The analysis of the individual intervention gives the necessary estimation about the building's response, but they yield inferior results. Strategies that give the best and positive results are determined and combined to produce higher improved performance and also to analyze the results of their interaction with each other. Finally, combined scenarios are implemented into the simulation model again and their performances are evaluated.

CHAPTER 4

CASE STUDY

In the previous chapter, the method for the impact of the current and future climatic conditions modified with urban heat island effect on the performance of existing educational buildings was presented. This chapter aims to present a demonstration of the proposed method by means of its application on the representative case study that is a secondary school building in Ankara.

4.1. Case Description

In order to examine the performance of existing buildings in the future climatic scenario, a typical secondary school building was selected as a representative case study that has most common or typical characteristics in terms of typology, construction, heating, and cooling. The reasons for the selection of this building as a case study are as follows;

- The surrounding context,
- The year of construction ,
- The orientation of the building,
- The age range of students,
- Ease of gathering information.

The building is located on the campus of Middle East Technical University (METU) in Ankara, Turkey. The site lies adjacent to the campus forest to the south, and an urban high density to the north. On the campus, the office and warehouse buildings, belonging to METU Directorate of Construction and Technical Works, and METU Science and Technology Museum buildings are situated around the building. Two main boulevards of Ankara, Dumlupınar and Bilkent Boulevards, lie on north and west boundary of the campus area. On Dumlupınar Boulevard, high-rise office buildings are located whereas on Bilkent Boulevard, there are 1.312.349 m^2 city hospital and some buildings belonging to the Ministry of Religious Affairs. Figure 4.1 and 4.2 show the context elements including buildings, roads, and forested area.

Figure 4.1 Aerial images of the site from Google Earth

Figure 4.2. Aerial photographs of the surrounding of the case building

The building is a private school as a part of METU Development Foundation Schools. Several educational buildings, including a kindergarten, primary, secondary and high school education levels are located around the case building. In Figure 4.3, the site plan drawing indicates the case study building that is A-B blocks and the other school buildings.

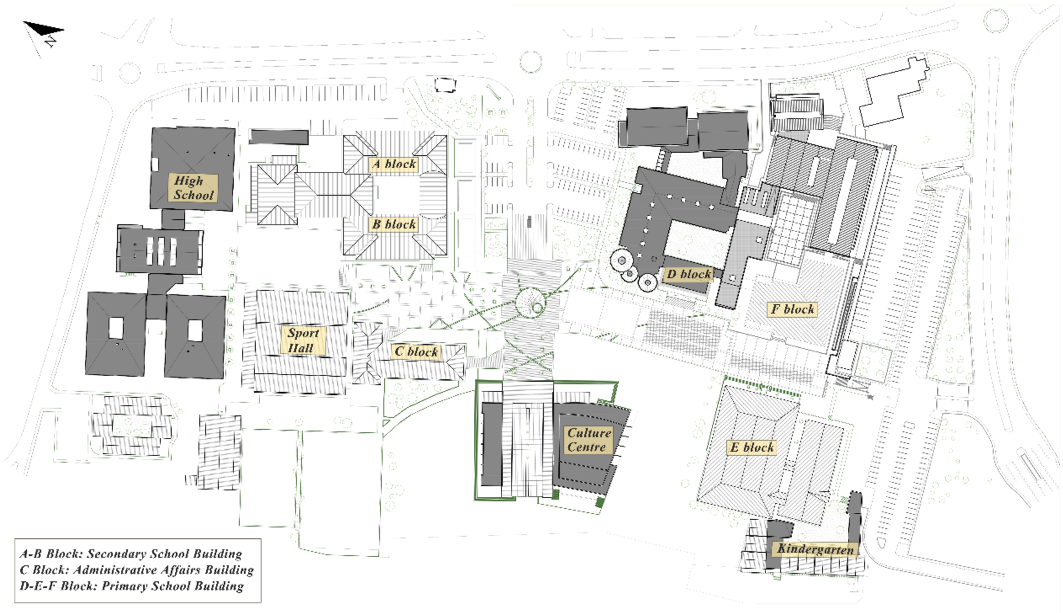

Figure 4.3. Site drawing of METU Development Foundation Schools

The secondary school building was completed in 1996. It is situated around a courtyard and has a northeast-southwest alignment. It consists of 2 blocks named A and B, and three floors with a height of 3.20 m. The building has 76 classrooms, 18 offices including administrator rooms, psychological counselor rooms, and staff rooms, 6 teacher's rooms, one library, one cafeteria, one kitchen, 3 storages and 4 WCs on each floor within a total area of 8911,20 m^2 (Table 4.1). In addition, the plan details of all floors can be seen in Appendix A.

Table 4.1. *The zone type details*

Zone Type	Ground Floor Zones		First Floor Zones		Second Floor Zones		TOTAL	
	Number of Zones	Total Area(m²)	Number of Zones	Total Area(m²)	Number of Zones	Total Area(m²)	Total Number	Total Area(m²)
Classroom	18	874,25	29	1430,50	30	1702,85	77	4007,60
Office	7	253,80	10	312,70	1	48,27	18	614,77
Teacher's Room	–		1	73,25	5	219,46	6	292,71
Library	–		1	173,85	–		1	173,85
Cafeteria	1	610,00	–		–		1	610,00
Kitchen	1	627,48	–		–		1	627,48
Storage	1	18,60	–		2	48,54	3	67,14
WCs	4	150,00	4	150,00	4	150,00	12	450,00
Staircase	4	82,65	4	82,65	4	82,65	12	247,95
Corridors		600,70		623,70		595,30		1819,7
TOTAL	**32**	**3217,48**	**45**	**2846,65**	**42**	**2847,07**	**119**	**8911,20**

The facade is covered with pressed bricks (Figure 4.4). The external and internal walls are made up of bricks without insulation. The roof is a pitched roof with a complex shape. It is uninsulated and covered with clay tiles. Windows are double glazed with an aluminum frame.

Figure 4.4. The case building from outside

Concerning the heating system, the school has a gas-fired central heating system. The heating system operates mostly from November to March. Furthermore, offices and teacher's rooms are ventilated with the split type air conditioner that consists of an outdoor unit and an indoor unit during the cooling period. The other spaces of the building are ventilated naturally.

Schools in Turkey operate 5 days a week from in the middle of September to in the middle of June with one 2-week holiday breaks at the end of January. The time schedule is continuous from 08:25 to 15:45 for lessons with six small breaks and one lunch break. The occupants' number of each classroom is 23 or 24 students and the total number of students is 987. In addition to students, 94 teachers, 8 administrative staff, and 13 cleaning staff are occupants of the building and there are 1102 occupants in total.

4.2. Climate data analysis for climate change and the UHI effect

4.2.1. Generation of future weather data

As pointed out in the previous chapter, this research is based on the simulation and the simulation tools use weather files based on statistical weather data collected over long periods of time to calculate the performance of buildings. Weather data is frequently provided in .epw files which are a special weather format containing weather data for 8760 hours of the year. They include all required information such as geographical location, sun position, temperature, wind speed and direction, humidity, total sky cover, and solar radiation data. Moreover, to be able to analyze performance for the future, the future weather data projections are needed. The widely used morphing methodology was used together with the WeatherShift™[2] tool to obtain the future data. Morphing methodology is a basic concept that obtains weather data to future time frames by modifying a historical 8760 (hourly) dataset based on future projections, initially developed by Becker, Halker, and Powell (Becker et al., 2005). The algorithms use three operations to modify the data;

1) a shift is applied when an absolute change to a variable is required,
2) a stretch or scaling factor when the change is projected in a percentage
3) a combination of both shifting and scaling may be used to adjust present-day data to reflect future projections (Belcher, Hacker, and Powell 2005).

[2] For further information refer to http://www.weather-shift.com/

To obtain morphing the weather data, another existing tool was used, WeatherShift™. WeatherShift™ has been built upon the morphing methodology and it *uses data from global climate change modeling to produce .epw weather files adjusted for changing climate conditions* (“WeatherShift” 2016). The tool blends 14 of the more recently simulated global climate models into cumulative distribution functions (CDF) for the RCP 8.5 and 4.5 emission scenarios. 14 of the global climate models are BCCCSM1.1, CanESM2, GFDL-CM3, GFDL-ESM2M, GISS-E2-R, IPSLCM5A- LR, IPSL-CM5B-LR, BCC- CSM1.1, CSIRO- Mk3.6.0, GFDLESM2G, GISS-E2-H, HadGEM2-ES, IPSL-CM5A-MR and NorESM1- M.

In this study, under the RCP4.5 and RCP8.5 emission scenarios, the weather data projections for the years 2060-2080 were generated and used.

4.2.2. Generation of modified weather data with UHI

As was pointed out in the literature review, the current weather data does not explicitly take into account weather data differences between the location of the building and the airport where the weather data is collected because of UHI effect. In order to carry out more accurate analysis, UHI effect is required to be calculated using the statistical weather data files in .epw format in this study. In this section, the 3D modeling, simulation tools, the development of simulation model, and the results are examined.

4.2.2.1. 3D Modeling

The area approximately 800 meters radius of the case building with 101 buildings were modeled. In order to calculate UHI-modified climate data, the following datasets were used: geometric and non-geometric properties of buildings and the information of weather.

The geometric data of buildings including shape, footprint area, envelope characteristics, and the number of floors were extracted from the site plan drawing of

METU Development Foundation Schools, Gismo[3], Cadmapper[4]. The site plan drawing has detailed geometric information about the buildings, green area, road and pavement in the school area. The footprints of other buildings and the roads were derived from Gismo and Cadmapper and all data were superposed. These are only 2D geometric data but a 3D model of the surrounding context of the building is required to be developed. Massing 3D model generation processes were conducted within the Rhinoceros 3D CAD environment which "can create, edit, analyze, document, render, animate, and translate Non-Uniform Rational B-Splines (NURBS) curves, surfaces, and solids, point clouds, and polygon meshes[5]."

As shown in Figure 4.5, the 3D model is just volumetric representations of buildings to be required for simulation and it is sufficient to model the buildings as a box according to their heights and geometrical characteristics. Structural components, internal divisions within zones and the glazing frames were excluded from the model. Moreover, their slope roofs were ignored and they were modeled with a flat roof. The city elements including trees, roads, all kind of pavements and soil areas were also modeled without any detail. Moreover, the difference in elevation was ignored and was not modeled. Simplification of the components was necessary for two main reasons. The first reason is that the simulation program, used in this study, cannot handle more geometric detail. Secondly, the simple model provides to reduce the calculation time and thus, it enables to more alternatives to be tested.

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[3] Gismo enables automatic generation of urban environment and terrain geometry based on location's latitude-longitude coordinates/or address and radius. This includes connection with openstreetmap website and generation of buildings, trees, roads, rivers and other map elements. https://www.grasshopper3d.com/group/gismo, June 2019.

[4] Cadmapper transforms data from public sources such as OpenStreetMap, NASA, and USGS into neatly organized CAD file. https://cadmapper.com/, June 2019

[5] https://www.rhino3d.com/6/features, June 2019.

Figure 4.5. The image of 3D model for UHI generation

Building heights in the model were based on data from site drawing, the feature of Google Earth street view, and observations from the site. The height was generally estimated according to the average floor height from all other buildings in the same program. The building heights range from 4-10 meters inside of the METU campus while there are mostly high rise office buildings that vary between 15-50 meters in terms of height outside of the campus. The heights and geometry of buildings in the college area are completely accurate but there is a decrease in the accuracy of the properties of outward buildings.

4.2.2.2. Development of simulation model

The UHI modified weather file was developed by the assist of Dragonfly. Dragonfly is an open source and free which "is a graphical algorithm editor tightly integrated with Rhino's 3-D modeling tools[6]". Dragonfly is used for the modeling and estimation of large-scale climate phenomena, such as urban heat island, future climate change, and the influence of local climate factors such as topographic variation. With the help of the Urban Weather Generator and CitySim, the microclimate or UHI created by the

[6] https://www.grasshopper3d.com/, June 2019.

building context can be generated as an epw file, making it possible to obtain more accurate comfort and energy analysis (Appendix B).

During simulation modeling to produce .epw for micro-climate in dragonfly, a set of criteria are required to be met which are as following:

Building Parameters: Geometric and non-geometric properties of buildings are needed to generate large scale phenomena. Geometric data of buildings include information of envelope shape, area, glazing, and the number of floors while non-geometric data includes the year of construction and program of buildings. The envelope properties such as glazing ratio, solar heat gain coefficient (SHGC), wall, and roof albedo can be defined by the user.

Buildings geometry including envelope shape and area information was assigned based on the 3D model. The number of floors of buildings is generated based on the height and the floor height of buildings and it ranges between 1-15.

In Urban Weather Generator, there are 3 periods in terms of year of construction: built prior to 1980, 1980 to present and new construction. According to the description in Urban Weather Generator, “this feature is used to determine what constructions make up the walls, roofs, and windows based on international building codes over the last several decades”. In the neighborhood, pre-1980’s buildings do not exist and one building is new construction. The rest of 100 buildings were assigned to 1980 to present.

The 16 building programs are listed by the Dragonfly component and the following options are available: full-service restaurant, quick service restaurant, hospital, small hotel, large hotel, small office, medium office, large office, mid-rise apartment, outpatient, primary school, secondary school, stand-alone retail, strip mall, supermarket, and warehouse. In this study, there are seven kinds of usage included 6 primary and 2 secondary schools, 12 small and 10 large offices, 9 mid-rise apartments, one full-service restaurant, and 25 warehouses. Since sporting and cultural program are not available in the program template, the sports hall and the cultural building were assumed as respectively the warehouse and office.

Envelope properties contain glazing ratio, SHGC, wall and roof albedo, and roofs covered in vegetation. According to the definition of the program, a glazing ratio is *a number between 0 and 1 that represents the fraction of the exterior wall surface occupied by windows.* In this study, each building has its own glazing ratio and it ranges between 0.25-0.90. Solar heat gain coefficient (SHGC) is the percentage of incident solar radiation transmitted through the window as heat. As the SHGC increases, the solar gain potential through a given window increases. It is measured on a scale from 0 to 1. The information about the window type of the school buildings was obtained from general directorate of construction of METU Development Foundation Schools and windows of the other buildings were assumed to have the same SHGC value that is 0.80[7].

Albedo is the reflectivity of a surface that has a high albedo reflects a lot of solar radiation from the sun back into the atmosphere, whilst a surface that has a low albedo reflects little solar radiation, absorbing it instead. It is also measured on a scale from 0 to 1.

City Parameters: Not only are buildings typology needed but also the surrounding context included traffic, vegetation and pavement information are needed to generate the UHI-modified .epw file.

The traffic parameters are schedule and sensible heat in Dragonfly. Schedule for traffic is a list that *sets the fraction of the anthropogenic heat*. This list can be defined for each hour of the typical weekday and weekend. On campus, the denser traffic is observed on weekdays from 08.00 to 10.00 and from 16.00 to 19.00 and the other hours on weekdays and all weekend are off-peak hours in terms of the traffic. On the other hand, since the roads around the campus are one of the main lines for Ankara's

[7] http://www.isicam.com.tr/tr/profesyoneller-icin/profesyoneller-icin-urun-katalogu/isicam-c-standart, June 2019.

transportation, heavy traffic can be observed every day of the week. According to description in the dragonfly, sensible heat represents the anthropogenic heat that originates from automobiles, street lighting, and human metabolism in Watts per square meter of pavement (W/m^2). The sensible heat values were specified as 6 W/m^2 on the campus area and 10 W/m^2 outside of the campus (Sailor, 2011).

Albedo, start and end months, and latent of tree and grass are needed to be defined for vegetation parameter. In Ankara context, vegetation generally starts in April to participate the energy balance of the urban area in Ankara context and it completely ends in October. The albedo and latent of trees and grass were assumed respectively 0,25, 0,7 and 0,5 that is typical vegetation values.

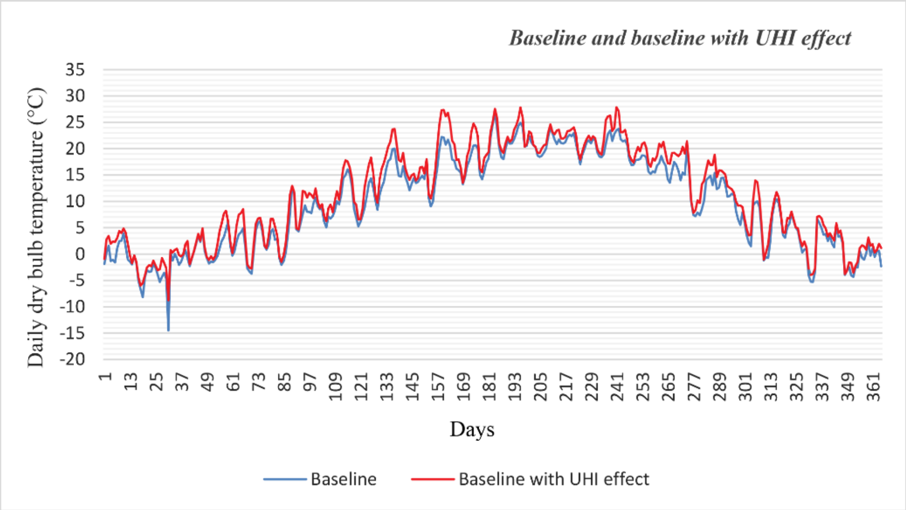
In addition to albedo, two different kind of material properties are needed for pavement component that are thermal conductivity and volumetric heat capacity. Thermal conductivity is described as a materials' ability to conduct heat and its unit is W/m-K. If a material has low thermal conductivity, heat transfer occurs at a lower rate. The volumetric heat capacity describes *the ability of a given volume of a certain substance to store heat while undergoing a given temperature change*[8]. Its unit is joule per kelvin per cubic meter (J/m3-K). In this study, the weighted average of different pavement types was calculated according to the area percentages. The thermal conductivity was calculated as 1,02 W/m-K in the campus area and 1,20 W/m-K outside of the campus. The volumetric heat capacities are 1582124,34 J/m^3-K in the campus and 1386490,92 J/m^3-K outside of the campus and he albedos are 0,19 and 0,23 respectively.

4.2.2.3. Results

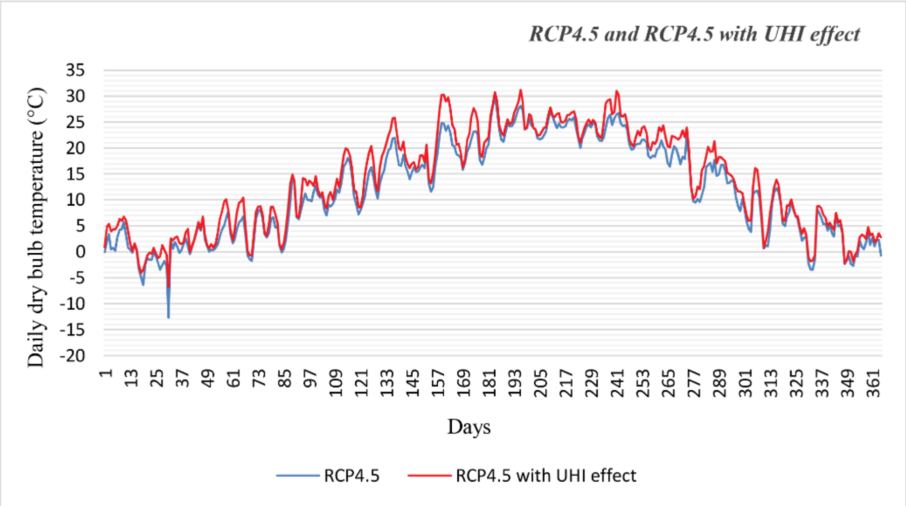
The existing epw file was modified 3 times to baseline years, the 2060-2080 projections under the RCP4.5 and RCP8.5 scenarios and 3 projected .epw files were

[8] https://enacademic.com/dic.nsf/enwiki/33701, June 2019.

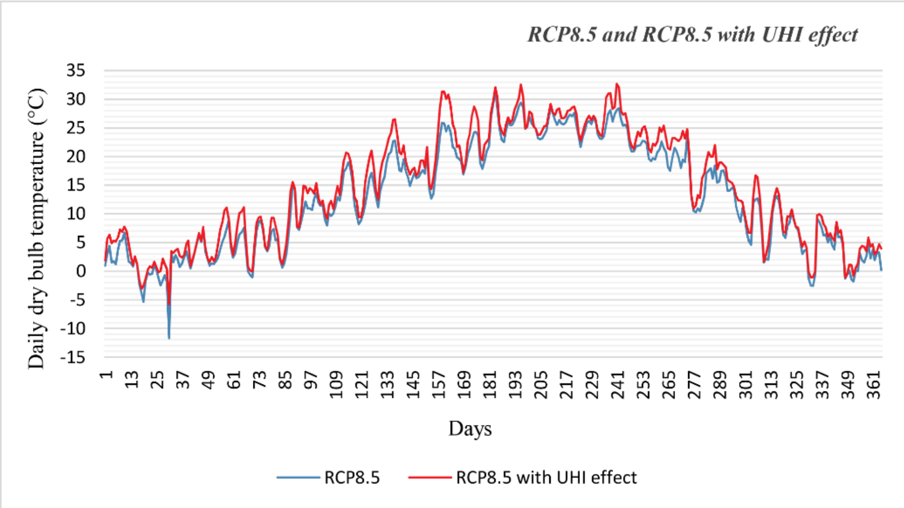
obtained. As expected, the temperature of the projected data differs from the temperature of the weather data collected from the airport in this study. Figure 4.6 shows the daily results for 3 different scenarios. However, the results of this study showed some increase in temperature and a possible explanation for this is that the neighborhood scale, which is mainly composed of woodland areas, was modeled instead of the urban scale. The maximum temperature difference was recorded as 5,7°C for baseline years and 5,9°C for both RCP4.5 and RCP8.5.



(a)



(b)

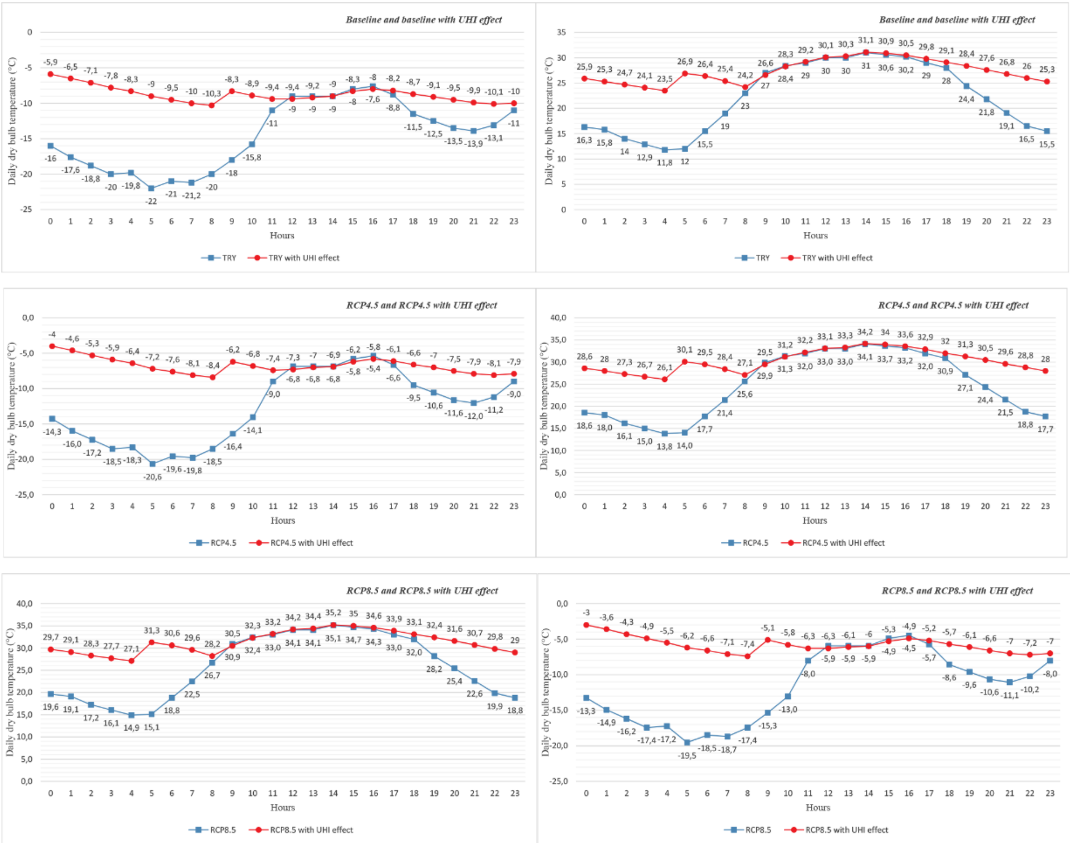


(c)

Figure 4.6. Daily average dry bulb temperature graphs for (a) baseline years, (b) 2060-2080 under the RCP4.5 emission scenario, and (c) 2060-2080 under the RCP8.5 emission scenario

Consistent with the literature, the results indicated that UHIs reach the highest point in the early morning hours (Rizwan et al., 2008). The temperature change graphs for the 31st of January and 9th of June, when the maximum change is observed, are given in Figure 4.7 and the maximum temperature differences were recorded at 5 am for both dates.

In this section, the UHI-modified weather data with and the base weather data were compared. In the next section, the results will be discussed in more detail and a comparative analysis will be presented.



(a) (b)

Figure 4.7. Hourly average dry bulb temperature graphs. (a) 31st of January, and (b) 9th of June

4.2.3. A comparative climate analysis

As discussed previously, although the climate change may be global, its impacts, related to current and future, vary according to the different regions and different climate zones in the world and the precautions and solutions should be discussed for the regional or local context. Therefore, the climate conditions in which the building is located and the effects of climate change in that area should be examined. As mentioned earlier, the case building is located in Ankara, Turkey. For this reason, climate conditions in Ankara, different weather data and projections are studied in detail.

Ankara is located in the interior high plateau of Turkey and it has characteristics of Csa Climate with warm and dry summers and long, cold and snowy winters. It can be broadly divided into two periods: the heating period, from October until the end of March and the cooling period, from April until September. On average, the warmest months are July and August and the coolest month is January. Table 4.2 indicates ninety-year climate data for Ankara.

Table 4.2. *Ninety-year climate data for Ankara (Turkish State Meteorological Service, January 2019).*

Climate data for Ankara (1927–2017)													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	16.6 (61.9)	21.3 (70.3)	27.8 (82.0)	31.6 (88.9)	34.4 (93.9)	37.0 (98.6)	41.0 (105.8)	40.4 (104.7)	37.7 (99.9)	33.3 (91.9)	24.7 (76.5)	20.4 (68.7)	41.0 (105.8)
Average high °C (°F)	4.1 (39.4)	6.3 (43.3)	11.4 (52.5)	17.3 (63.1)	22.3 (72.1)	26.6 (79.9)	30.2 (86.4)	30.3 (86.5)	25.9 (78.6)	19.8 (67.6)	12.9 (55.2)	6.4 (43.5)	17.8 (64.0)
Daily mean °C (°F)	0.2 (32.4)	1.6 (34.9)	5.7 (42.3)	11.3 (52.3)	16.1 (61.0)	20.1 (68.2)	23.5 (74.3)	23.4 (74.1)	18.8 (65.8)	12.9 (55.2)	7.1 (44.8)	2.4 (36.3)	11.9 (53.4)
Average low °C (°F)	−3.3 (26.1)	−2.4 (27.7)	0.5 (32.9)	5.2 (41.4)	9.6 (49.3)	12.8 (55.0)	15.7 (60.3)	15.9 (60.6)	11.7 (53.1)	7.0 (44.6)	2.4 (36.3)	−0.8 (30.6)	6.2 (43.2)
Record low °C (°F)	−24.9 (−12.8)	−24.2 (−11.6)	−19.2 (−2.6)	−7.2 (19.0)	−1.6 (29.1)	3.8 (38.8)	4.5 (40.1)	5.5 (41.9)	−1.5 (29.3)	−9.8 (14.4)	−17.5 (0.5)	−24.2 (−11.6)	−24.9 (−12.8)
Average precipitation mm (inches)	39.5 (1.56)	35.0 (1.38)	38.6 (1.52)	42.3 (1.67)	51.2 (2.02)	34.2 (1.35)	13.7 (0.54)	11.5 (0.45)	17.8 (0.70)	27.6 (1.09)	31.7 (1.25)	43.9 (1.73)	387.0 (15.24)
Average precipitation days	12.1	11.1	10.7	11.0	12.1	8.4	3.4	2.6	4.0	6.8	8.0	11.6	101.8
Average relative humidity (%)	79	75	65	58	57	51	43	41	46	56	70	78	60
Mean monthly sunshine hours	83.7	110.2	161.2	195.0	263.5	303.0	353.4	334.8	276.0	207.7	138.0	77.5	2,504
Mean daily sunshine hours	2.7	3.9	5.2	6.5	8.5	10.1	11.4	10.8	9.2	6.7	4.6	2.5	6.8

As previously pointed out, consequences of climate change on buildings depends on different climate zone, the environment in which the building is located, and building types and for this reason, analyzing weather data is an essential part of this study. In order to understand clearly the impacts of climate change and UHI different data are required to be analyzed and be compared which are as following:

a) Baseline year
b) Baseline year with UHI-modified
c) 2060-2080 weather data under RCP4.5 emission scenario
d) 2060-2080 weather data under RCP4.5 emission scenario with UHI-modified
e) 2060-2080 weather data under RCP8.5 emission scenario
f) 2060-2080 weather data under RCP8.5 emission scenario with UHI-modified

These data of Ankara are compared in terms of monthly minimum, average, and maximum mean outdoor dry bulb temperature, heating degree days (HDD), and cooling degree days (CDD). Heating Degree-Days (HDD) and Cooling Degree-Days (CDD) aim to estimate heating and cooling loads of buildings and to monitor and analyze the energy and the indoor quality of existing buildings based on historical data (Day, 2006). They can be defined as the temperature differences between the outdoor air temperature and a base temperature multiplied by the number of days that the differences exist. The base temperature is *a balance point temperature* and it can differ from building to building. In this study, the base temperatures for heating and cooling are 18.3°C and 23.3°C respectively.

Ladybug was used for the calculation of the HDD and CDD, Similar to Dragonfly, Ladybug is free and open source environmental plugins for Grasshopper3D to *help designers create an environmentally-conscious design* and it is an interactive and user friendly tool to import EnergyPlus Weather Files (.epw), to analyze the radiation, sunlight-hours, and comfort of the building masses and to create 2D and 3D graphics and more (Roudsari, Pak, & Smith, 2013). In this study, Ladybug was used to import and modify the .epw file. As mentioned in the previous section, the .epw file contains all the hourly climate information, and ladybug allows to read and make calculations based on the data in the weather files. The above mentioned six weather data were imported into Ladybug environment and then, they were calculated as monthly minimum, monthly average and monthly maximum temperature data. The modified data were written to Microsoft Excel with the aim of visualization.

The results with and without UHI-modification show that monthly outdoor dry bulb temperatures have an increasing trend as expected. The graphs for all scenarios are given in Figure 4.8. The average increase for RCP4.5 varies between 1.6 °C-3.2 °C while the average increase for RCP8.5 varies between 2.6 °C-4.7 °C during the whole year. The results with UHI-modification indicates almost the same variability, as can be seen from Figure 4.10. The largest change is observed in July and August but in these months, the building is not in use. Therefore, the temperature increase in these months will not be taken into account in this study. The IPCC (2018) reports have shown that a half-degree increase in temperature is vital importance, for this reason, the temperature changes which reach up to around 4° C in spring seasons are one of the major problems that will influence the building performance.

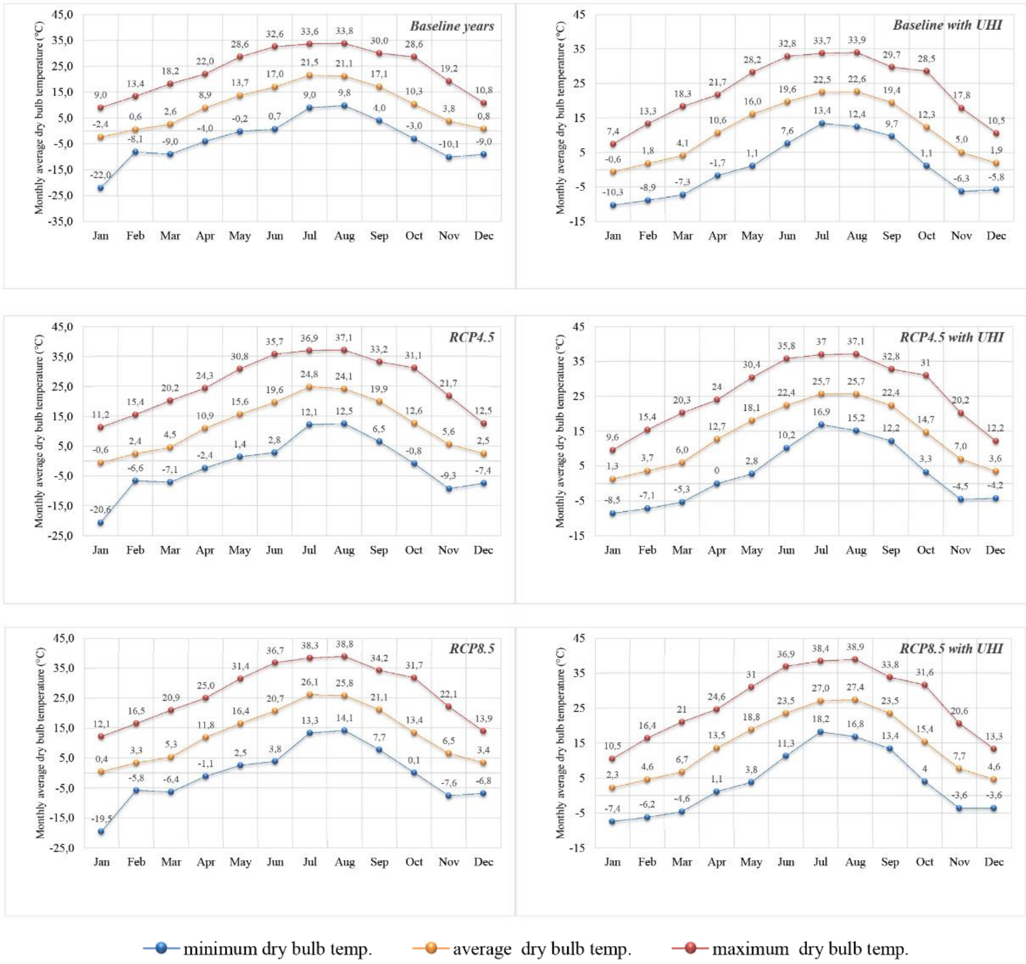


*Figure 4.8.*Monthly minimum, average, and maximum dry bulb temperature graphs

It is calculated that HDD increases whereas CDD decreases consistently in all the weather files, because of the temperature increase in the future and the results of HDD and CDD are consistent with the expectations. Monthly HDD and CDD are given in Figure 4.9 and 4.10. The values peak in January for HDD and in August for CDD.

However, as stated before, since the building is not used in July and August, the results, recorded in these months, were not considered as critical. Annual results showed that HDD values will decrease 549,70°C-day for RCP4.5 and 790,54°C-day for RCP8.5 whereas HDD values with UHI-modification decrease 505,38°C-day for RCP4.5 and 699,88°C-day for RCP8.5. For CDD, the values increase 134,19°C-day and 216,37°C-day and the values with UHI-modification will increase 183,15°C-day and 287,98 for respectively RCP4.5 and RCP8.5 scenarios.

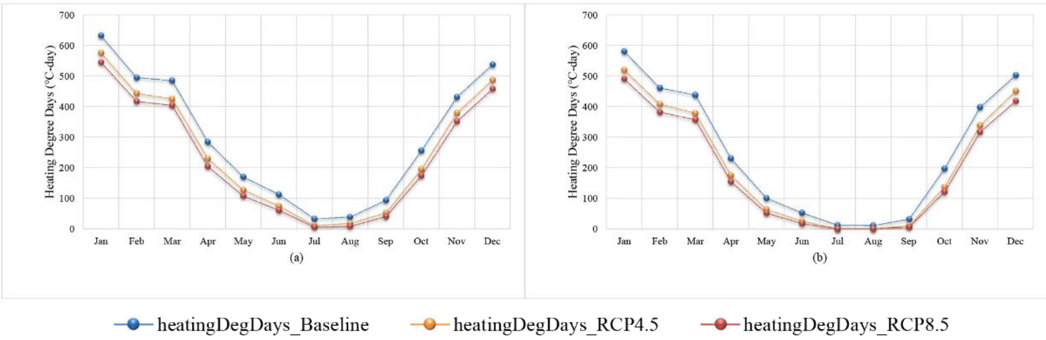


Figure 4.9. Graphs of monthly HDD (a) without UHI (b) with UHI

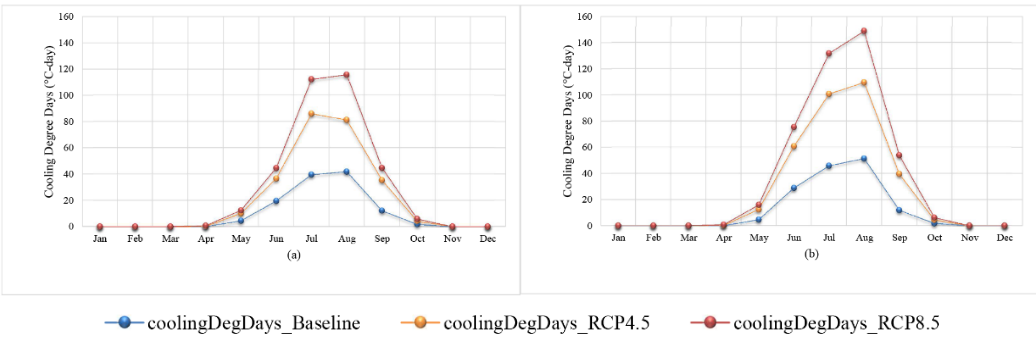


Figure 4.10. Graphs of monthly CDD

As RCP8.5 is the high concentration climate change scenario, the greatest changes were observed in the results of this scenario. Considering that these changes will also dramatically affect building performance, in this study, the 2060-2080 projections under the RCP8.5 with UHI-modification scenario was used to simulate and analyze the future performance of the case building.

4.3. Analysis of building performance

4.3.1. Performance evaluation criteria

In order to analyze the performance of the building under the effects of changing the climate, the following criteria were taken into account:

- Energy use/consumption
- Thermal comfort

4.3.1.1. Energy use

Energy use is an important criterion that should be analyzed for building performance. The parameters to evaluate this metric are as follows: heating, cooling, solar heat gain, lighting, equipment, people gain, mechanical, natural ventilation, opaque and glazing conduction, and total energy requirement. In this research, the monthly heating (Q_H), cooling (Q_C), the solar gain (Q_{SG}), and energy balance (Q_T) were evaluated in all analyses. They were measured in kWh per floor area (kWh/m^2). Each metric was analyzed according to the zone type and/or the orientation of each zone type in the case study.

4.3.1.2. Thermal comfort

As the climate becomes more unstable, extreme, and hotter, it will become difficult to provide stable and comfortable indoor environments without increasing energy use and emission. For this reason, thermal comfort is one of the significant criteria for building performance analysis.

In this research, a great majority of the case building's zones are ventilated naturally, except for offices and teacher's rooms. Therefore, the thermal comfort was calculated based on the ASHRAE 55-2013 adaptive comfort model. As stated in the literature review section, in this standard, and in this study, the following equation is used for comfort temperature:

$T_n = 0.31T_{ave} + 17.8$ $(10°C \leq T_{ave} \leq 33.5°C)$ (2)

where

T_n : neutrality temperature

T_{ave}: monthly mean outdoor air temperature (La Roche, 2012).

As shown in Figure 4.11, ASHRAE 55 presents two ranges, 90%, and 80% acceptability limits. Although the standard states that acceptable indoor temperatures should be calculated using the 80% acceptability limits (ASHRAE 55, 2013), in this study, the 90% acceptability limits were used in order to achieve a higher standard of thermal comfort.

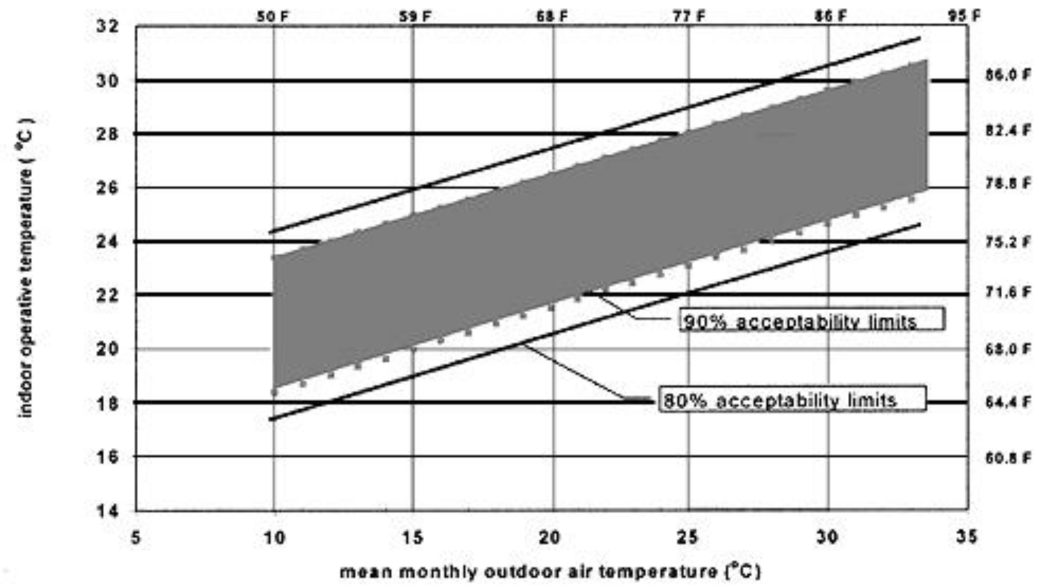


Figure 4.11. Acceptable operative temperature ranges. (From ASHRAE Standard 55-2009).

The following criteria need to be evaluated for the assessment of indoor overheating risks of the case building.

Indoor operative temperature: It can be defined as *the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients* (ASHRAE, 2009, p.3). Operative temperature (T_o) can be expressed as;

$$T_o = A\,T_a + (1 - A)\,T_{mrt} \qquad (4)$$

where

T_o : operative temperature,

T_a : mean air temperature,

T_{mrt} : mean radiant temperature,

A : function of the relative air speed (ASHRAE, 2009).

In this study, the mean operative temperatures of each zone were calculated hourly using this equation by the simulation tool.

Comfort temperature limit (T_{comf}): A stream of temperature values in degrees Celsius indicating the highest possible temperature in the comfort range for each hour of each zone. Comfort temperature limit values were obtained from the simulation tool.

Occupied hour (i): This criterion sets the number of occupied hours. In this study, the building is used 5 days a week from 08:00 to 17:00 and there is no usage on weekends and in June and August. Only occupied hours were considered for the analysis as other times are excluded from estimating in this research.

Indoor overheating degree (IOD): IOD is a thermal comfort metric introduced by Hamdy, Carlucci, Hoes, & Hensen (2017) and IOD quantifies the degree of indoor overheating for different thermal comfort limits in different zones of a building taking into account the particular occupant's behavior and the adaptation opportunity (Hamdy et al., 2017). Also, both the intensity and the frequency of indoor overheating are considered for IOD quantification. IOD can be expressed in the following equation:

$$IOD = \frac{\sum_{i=1}^{N_{occ(z)}} \left[max\{To_{i,z} - TL_{comf,i,z}, 0\} \times t_{i,z} \right]}{\sum_{i=1}^{N_{occ(z)}} t_{i,z}} \qquad (5)$$

where

z: zone,

i: occupied hour,

$N_{occ(z)}$: total occupied hours of z in a given calculation period,

t: time step (1 h),

$To_{i,z}$: operative temperature at the time step i in the zone z,

$TL_{comf,i,z}$: comfort temperature limit at the time step i in the zone z.

In this study, each zone type were calculated by using this equation and only positive differences of (Toi,z - TLcomf, i,z) are taken into the summation.

4.3.2. 3D Modeling the building

The building was modeled for energy and thermal comfort analysis primarily. 3D of the building was prepared within the Rhinoceros 3D environment. The 2-D geometric inputs for the model were obtained from Baobab Architecture and from the school management (see Appendix A). Similar to the neighborhood model, each zone is represented as a volume in the form of a box without any detail and only floor heights, program and openings were provided in the Rhino environment (Figure 4.12). The first reason for this simplification is that the other required details of performance analysis can be assigned in the tool used for simulation and this will be explained in detail in the next section. As mentioned previously, the second reason is the reduction of the computational time for the sake of more alternatives to be put to test.

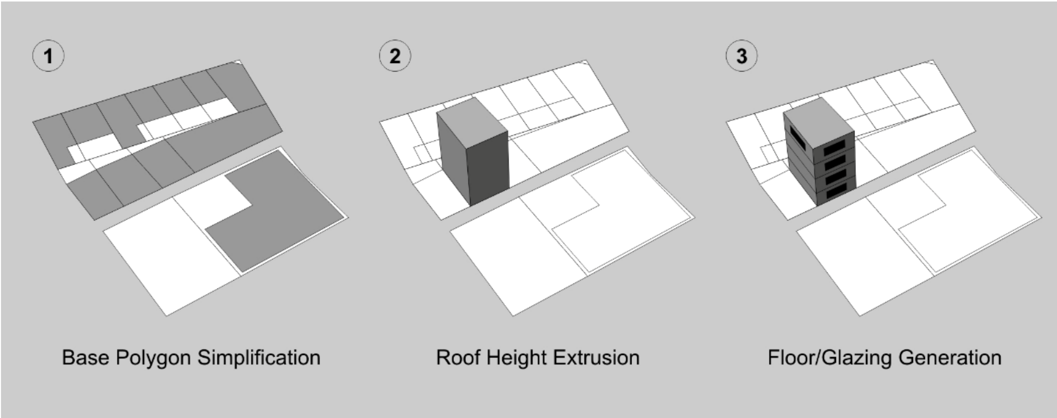


Figure 4.12. The modeling steps (Davila, Reinhart & Bemis, 2016)

In the case building, the heights of the floors are 3.2 meters, but differences in the height of the cafeteria and kitchen are observed that are 3.9 meters and 2.9 meters respectively. The roof is tilted roof originally but it was assumed as a flat roof and was modeled in this way.

The building was modeled in 10 different programs included classroom, office, teachers' room, library, cafeteria, kitchen, storage, WC, and corridor are modeled (Table 4.3).

There are various sizes of window openings. Table 4.4 shows the window-wall ratios (WWR) in total and in accordance with the orientation.

Besides, the context geometries that have just the possibility of shadowing on the building and trees were added in the model as shading objects.

Table 4.3. *Programs of the building's zones*

Zone Type	Ground Floor Zones	First Floor Zones	Second Floor Zones	TOTAL
Classroom	18	29	30	77
Office	7	10	1	18
Teacher's Room	—	1	5	6
Library	—	1	—	1
Cafeteria	1	—	—	1
Kitchen	1	—	—	1
Storage	1	—	2	3
WCs	4	4	4	12
Staircase	4	4	4	12
Corridors				
TOTAL	32	45	42	119

Table 4.4. *Window-wall ratio*

	Total	Northwest	Northeast	Southeast	Southwest
Gross Wall Area (m²)	3684.70	754.86	1087.50	754.85	1087.50
Above Ground Wall Area (m²)	3661.95	754.86	1083.23	740.64	1083.23
Window Opening Area (m²)	752.37	107.77	239.36	156.31	248.93
Gross Window-Wall Ratio (%)	20.42	14.28	22,01	20.71	22.89
Above Ground Window-Wall Ratio (%)	20.55	14.28	22,10	21,10	22.98

4.3.3. Development of simulation model

The simulation model was developed by the assist of Honeybee[9] and EnergyPlus™[10] in this study. Like the Ladybug and Dragonfly described earlier, Honeybee is free and open source environmental plugins for Grasshopper3D and Dynamo. It provides the analysis on building masses but it is intended for advanced studies and shows more detailed results. It can subdivide the mass into several units and more importantly construction set, schedules and internal loads for each space based on the program can be assigned by the help of Honeybee. Moreover, Honeybee can extend users' ability

[9] For more information refer to https://www.ladybug.tools/honeybee.html

[10] For more information refer to https://energyplus.net/

to work directly Radiance for the daylight simulations, EnergyPlus and OpenStudio for the energy simulations and Berkeley Lab Therm and Window for the heat flow through construction details (Roudsari et al., 2013).

In Honeybee, simulation for energy and comfort run through EnergyPlus (EP) (v8.9) that is an energy analysis and thermal load simulation engine from the U.S. Department of Energy. EP is not a user interface and Honeybee provides a third-party interface for EP. It takes as input information related to building location, geometry, construction materials, and context geometries. It also allows the user to specify detailed loads and schedules related to occupancy, lighting, plug loads, and thermostat set points (Sailor, 2014). In addition, honeybee assigns these features as default values based on the zone program but EnergyPlus allows to overwrite the default values. After the building simulation model is fully defined, it is coupled with the weather data file. After setting up all essential inputs, EP writes the results of the simulation in different file formats included IDF, CSV, EIO, RDD, and HTML and they provide detailed reports on all aspect of the building performance.

A set of criteria are required to be met to develop a more accurate model which are as follows:

Building components: The geometry of each zone and the openings was assigned from the 3D model.

> ***Zone program:*** Firstly, the program of each zone should be determined according to the building program because Honeybee takes base on this program and assigns internal loads and schedules for each zone by default. As indicated many times, in this study, the building program is secondary school and zone programs are as indicated in Table 4.5 in the previous section.
>
> ***Building Load:*** Building internal loads are defined as equipment load, infiltration rate, lighting density, number of people, ventilation, and recirculated air in the simulation tool. For equipment load, infiltration rate, and ventilation loads, the default values that are given by Honeybee according to

the zone programs were used while the values for the number of people and lighting density loads were designated with respect to the current situation in the case building. Table 4.6 summarizes the internal loads.

Table 4.5. *Building internal loads*

Building Internal Loads	Zone Types									
	Classroom	*Office*	*Teacher's Room*	*Library*	*Cafeteria*	*Kitchen*	*Storage*	*WC*	*Staircase*	*Corridor*
Equipment Load (W/m²)	7,31	7,85	5,00	7,31	14,00	162,00	7,85	2,90	2,90	2,90
Infiltration Rate (m³/s-m²)	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002
Lighting Density (W/m²)	15,06	11,85	11,85	12,91	9,68	12,91	5,50	9,68	5,38	5,38
Number of People (ppl/m²)	0,04	0,01	0,07	0,22	0,68	0,006	0,05	0,09	0,10	1,10
Ventilation (m³/s-person and m³/s-m²)	),0047/0,000	,0023/0,000	),0023/0,000	),0047/0,000	),0035/0,000	),0035/0,000	),0023/0,003	0/0,0003	0/0,0003	0/0,0004
Recirculated Air (m³/s-m²)	0	0	0	0	0	0	0	0	0	0

Zone Schedules: Zone schedules provide a different kind of information about the building system and include occupancy, occupancy activity, heating set point, cooling set point, lighting, equipment, infiltration, and ventilation schedule.

The occupancy schedule defines the number of people in the space and the times of occupancy annually. Table 4.6 indicates weekday times of occupancy and the number of people for the different zones in the school building. Just for library, the number of users does not show full attendance at the times specified in Table 4.6. For other zones not shown in the table, a low density use schedule was assigned between 8am-17pm. On the weekends, there is no occupancy in the building. Moreover, one long holiday from June to August and one 2-week holiday breaks at the end of January also are factored in the schedules. Furthermore, the lighting schedules were set in line with occupancy schedules.

Table 4.6. *Schedules of the zones*

Time	Zone type					
	Classroom	*Office*	*Teacher's room*	*Library*	*Cafeteria*	*Kitchen*
08.00 - 08.25	+	+	+	-	-	+
08.25 - 9.05 (course start)	+	+	-	-	-	+
09.05 - 9.15	-	+	+	-	-	+
09.15 - 9.55	+	+	-	-	-	+
09.55 - 10.05	-	+	+	-	-	+
10.05 - 10.45	+	+	-	-	-	+
10.45 - 10.55	-	+	+	-	-	+
10.55 - 11.35	+	+	-	-	-	+
11.35 - 11.45	-	+	+	-	-	+
11.45 - 12.25	+	+	-	-	+	+
12.25 - 13.25	-	+	+	+	+	+
13.25 - 14.05	+	+	-	-	+	+
14.05 - 14.15	-	+	+	-	-	+
14.15 - 14.55	+	+	-	-	-	+
14.55 - 15.05	-	+	+	-	-	-
15.05 - 15.45 (course end)	+	+	-	-	-	-
15.45 - 17.00	-	+	-	+	-	-
Number of Users	987 (23 or 24 students for each classroom)	28	94	1081 (students+ teachers)	1102	12

Heating and cooling setpoints define the ideal temperature in the zones when heating and cooling are required. For classrooms, offices, teacher's rooms, library, and cafeteria, the heating setpoint was assigned as 22°C in occupancy hours and 19°C in non-occupancy hours while for other zones, the heating setpoint is 19°C for all times. The cooling setpoint was set 25°C just between 8 am - 5 pm for offices and teacher's rooms. This temperature defines when cooling starts.

Zone Construction: As EP has its own construction material library, it also allows the users to make custom construction materials. Thickness, thermal conductivity, specific heat capacity, and density need to be assigned for custom materials. As described earlier, thermal conductivity is a materials' ability to conduct heat and its unit is W/m-K. Specific heat capacity is the amount of heat energy required to raise the temperature of a substance per unit of mass. It is expressed as J/kg-K. For windows, different metrics included U-value, solar heat gain coefficient (SHGC), and visible transmittance (VT) should be assigned. Heat loss or gain in windows is measured by the U-value and the lower U-value indicates the *greater a window's resistance to heat flow* and the better thermal insulation of a window. As expressed in the previous section, the SHGC measures the transmission of the heat from direct sunlight through a window. It is expressed as a number between 0 and 1 and the low SHGC provides better solar control. The VT is the percentage of the visible wavelength of light transmitted through the glazing. It is also measured on a scale from 0 to 1 and the low VT refers to the insufficient daylighting and dark interior environment. Table 4.7 indicates the materials' physical properties of the school building. Materials of the ground floor, floor, and internal wall were kept unchanged throughout the analysis.

Table 4.7. *Construction and material details of the building*

Building Elements	Construction Details	Conductivity (W/mK)	Specific Heat Capacity (J/kgK)	Density (kg/m^3)	References
External Wall	90mm single layer of press-brick	0,42	900	2240	1
	240mm single layer of brick	0,33	900	600	1
	one layer of plaster (20-25mm)	0,51	1090	1200	1
Internal Wall	190mm single layer of brick	0,33	900	650	1
	2 layers of plaster (20-25mm)	0,51	1090	1200	1
Flat Roof	Gravel	0,36	840	1840	1
	Separation layer	—	—	—	—
	3mm waterproofing membrane	0,19	780	3000	1
	40mm levelling concrete	0,3	840	2200	1
	200mm concrete slab	2,5	840	2400	1
	one layer of plaster (20-25mm)	0,51	1090	1200	1
Floor	10mm marble tile	2,8	830	2680	2
	5mm levelling concrete	0.41	840	1200	1
	200mm concrete slab	2,5	840	2400	1
Ground Floor	50mm cement finish	1,4	837	2000	1
	3mm polyster felt	0,19	1500	25	1
	600mm XPS	0,035	1200	25	1
	150mm groundwork	2,5	860	2400	1
	100mm protective concrete	1,65	860	2200	1
	Waterproofing	0,19	780	3000	1
	100mm blinding concrete	1,65	860	2200	1
	Gravel	2	840	2000	1
		U Value (W/m^2K)	Solar Heat Gain Coefficient	Visible Trasmittance	
Window	16mm double glazed and aluminum frame	2,7	0,75	0.80	3

1- Apache Table. Retrieved February 10, 2019 from https://help.iesve.com/ve2018/table_6_thermal_conductivity__specific_heat_capacity_and_density.htm

2- Rohsenow, W. M., Hartnett, J. P., & Cho, Y. I. (1998). Handbook of heat transfer (Vol. 3). New York: McGraw-Hill.

3- http://www.isicam.com.tr/tr/profesyoneller-icin/profesyoneller-icin-urun-katalogu/isicam-c-standart

Set air flow: The ventilation system of the building is an important factor in the evaluation of thermal comfort and energy performance and it is required to be introduced in the simulation model for accurate impact analysis. The simulation tool provides 4 types of natural ventilation: 1 - No Natural Ventilation, 2 - Window Natural Ventilation, 3 - Custom Stack/Wind Ventilation, 4 - Fan-driven Ventilation. In the school building, all zones have window natural ventilation but in offices and teacher's rooms, the air conditioner is used as a cooling strategy. Therefore, window natural ventilation was assigned to all zones. The tool automatically calculates natural ventilation airflow based on zone's exterior windows, a specified fraction of operable glazing, and a specified fraction of the glazing height that is operable, and the indoor and outdoor temperature. Table 4.8 summarizes these parameters for natural ventilated and air-conditioned zones.

Table 4.8. *Natural ventilation parameters*

	Natural Ventilated Zones	Air Conditioned Zones
Minimum indoor temperature (°C)	23,5	23,5
Maximum indoor temperature (°C)	—	25
Minimum outdoor temperature (°C)	12	12
The fraction of operable glazing (%)	45	45
The fraction of operable glazing height (%)	100	100

Contextual shading elements: All contextual shading elements such as buildings, trees, and any other objects that affect building energy and thermal performance are necessary to introduce to the model. In this phase, the elements were added to the simulation model at the required level of details.

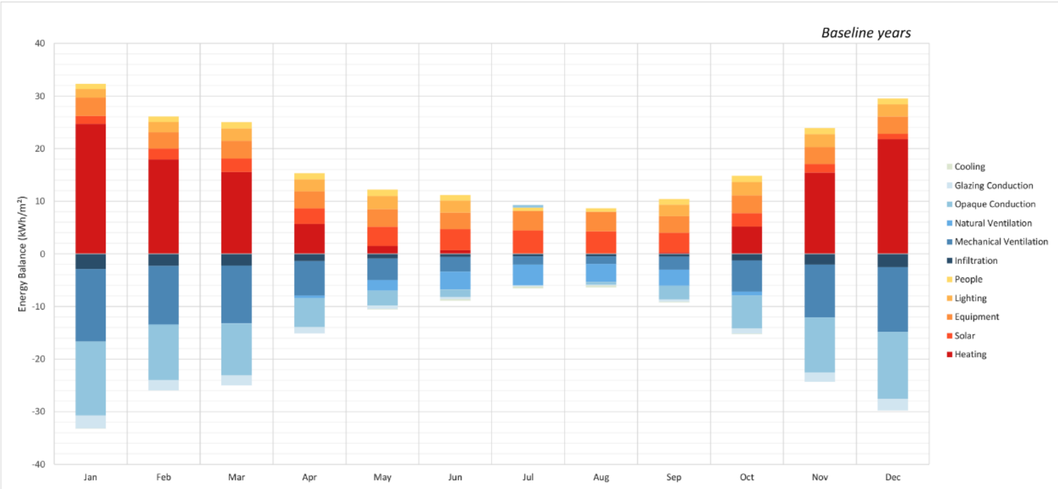
Weather data: As stated previously, weather data is a file that contains all hourly weather information for all the year. In this phase, baseline years, baseline years with UHI effect, and the year 2060-2080 representing RCP8.5 projections with UHI effect were used in order to compare to differences in results and evaluate the impact of climate change and energy on thermal performance while in all intervention scenarios, data of RCP8.5 with UHI effect was used.

4.3.4. Performance assessment

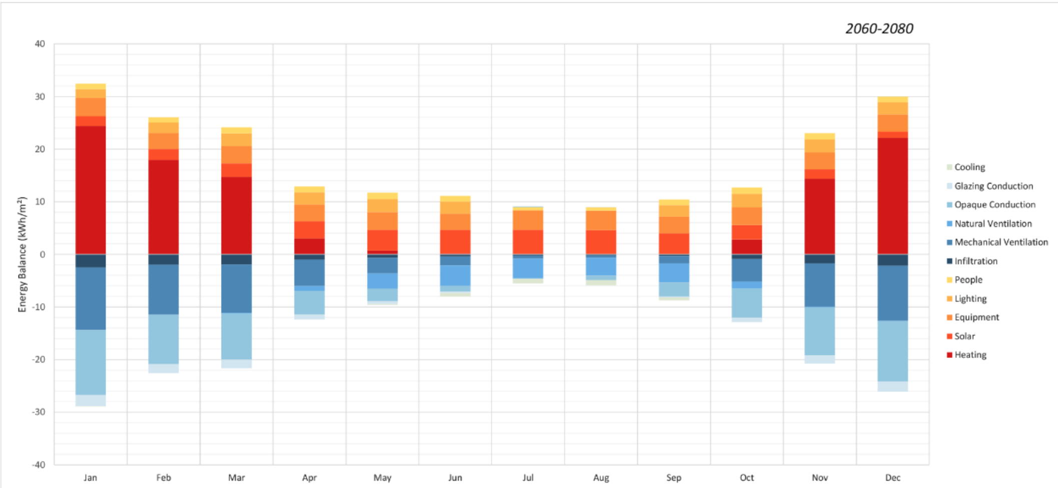
In this phase, energy and thermal performances are discussed the preliminary results of climate change impacts. The analysis was limited to zones with intensive use all day included classrooms, offices, and teacher's rooms. The full-year simulation was run using three separate weather data included baseline year with UHI-modified, and the year 2060-2080 representing RCP8.5 projections with UHI-modified. Obtained simulation results were written to Microsoft Excel with the aim of calculation of before mentioned metrics and visualization.

4.3.4.1. Performance assessment for energy demand

Energy demand in buildings can be affected by external and internal loads. In this study, internal loads remain constant throughout the analysis. The outdoor temperature as external load changes between two selected weather data and as specified in section 4.3, the difference of the average temperature reaches up to around 5°C. Requirements for heating (Q_H), and energy balance (Q_T) were observed to decrease while cooling (Q_C) and solar gain (Q_{SG}) showed an increase in the future. Figure 4.13 summarizes the energy balance of the building under two separate climatic conditions.



(a)

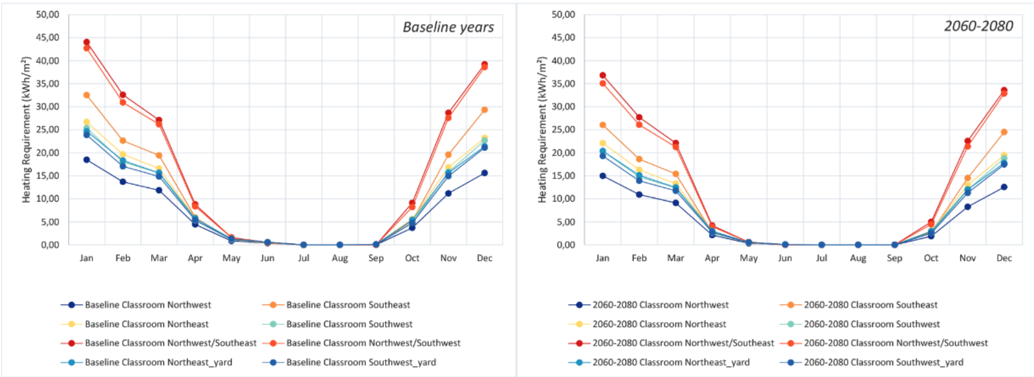


(b)

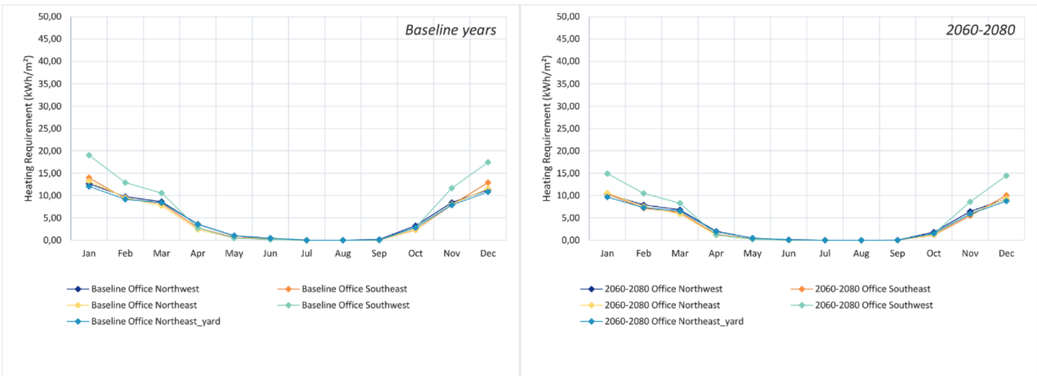
Figure 4.13. The energy balance graphs (a) baseline (b) 2060-2080 projections data

Other energy metrics were evaluated according to zone types and orientations.

Heating: School heating starts in October and continues up to March or sometimes April and the summary of the heating requirement (Q_H) for classrooms, offices, and teacher's rooms are respectively indicated in Figure 4.14.



(a)



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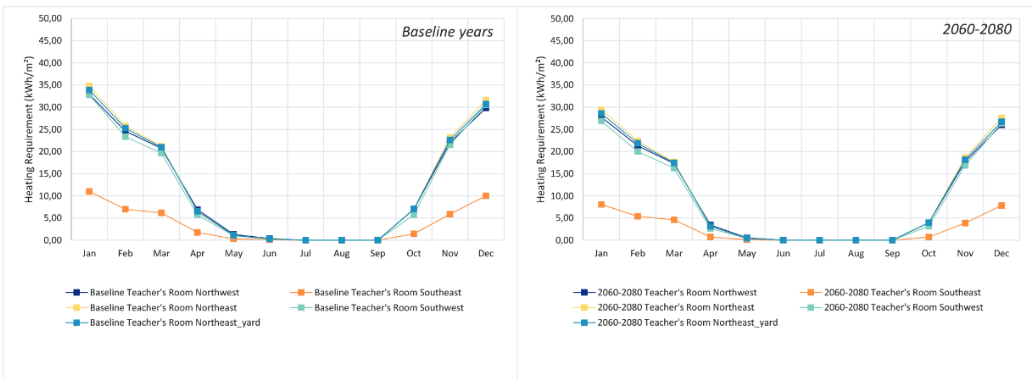


(c)

Figure 4.14. The requirements of heating demand for (a) classrooms (b) offices (c) teacher's rooms

From the data in Figure 4.14 (a), it can be seen that the highest demand is for classrooms facing two different orientations. The first reason is that different from other zones, these zones have two windows and have more surfaces to exchange heat which causes higher heat loss through glazing and opaque conduction. The second reason is that one of these orientations is northwest that does not expose the direct sunlight. In addition, after these zones, Q_H is higher in classes facing both the courtyard and the northeast or the courtyard and the northeast façade. This results from that the courtyard protects the building from solar radiation and increases the shading.

As the alteration in sun path affects heat gain and loss in a building and consequently, heating requirement. In line with this, Q_H of zones that are oriented the north is expected to be high. However, interestingly, northwest classrooms show the lowest results in this study. The reason for this is that the ground floor performs poorly in terms of heating and the zone located on the ground floor upgrades the heating demand. In the case building, there is no northwest facing classroom on the ground floor and therefore, the northwest facing classrooms demonstrate better results. In addition to the ground floor, the majority of heat gains and losses from the roof. Zones on the second floor consume more energy for heating or cooling. The detailed information about the storey of zones can be seen in Appendix A. In classrooms, the annual requirement of the heating (ΔQ_H) between baseline and the 2060-2080 projections showed a decrease in 20,00-39,05 kWh/m^2 range (20,37-24,95%).

The results, as shown in Figure 4.14 (b), indicate that the QH is the highest at the northwest offices while the lowest at the southwest offices. The requirement of the heating in office zones (ΔQ_H) decreased in 13,72-18,15 kWh/m^2 range (23,36-27,87%).

It can be seen in Figure 4.14 (c) that for the teacher's rooms, there is a rather remarkable result for the southeast facing room and its Q_H is very low compared to other rooms. There are 6 teacher's rooms that 5 of them are located on the second floor and one of them is located on the first floor in total in the building. In zones on the second floor, the Q_H is affected negatively by the roof and heating loss from opaque conduction from the roof. For this reason, the heating requirements for the first and second-floor show differences. In addition to this, the southeast-oriented zones receive more solar heat and therefore, they demand less heating load. In teacher's rooms, the heating demand (ΔQ_H) declined in 12.38-2.28 kWh/m^2 range (18.67-28.36%).

The annual ΔQ_H of the entire building in baseline years and in 2060-2080 shows in Figure 4.15. 7.72 percent reduction is observed in future climatic conditions.

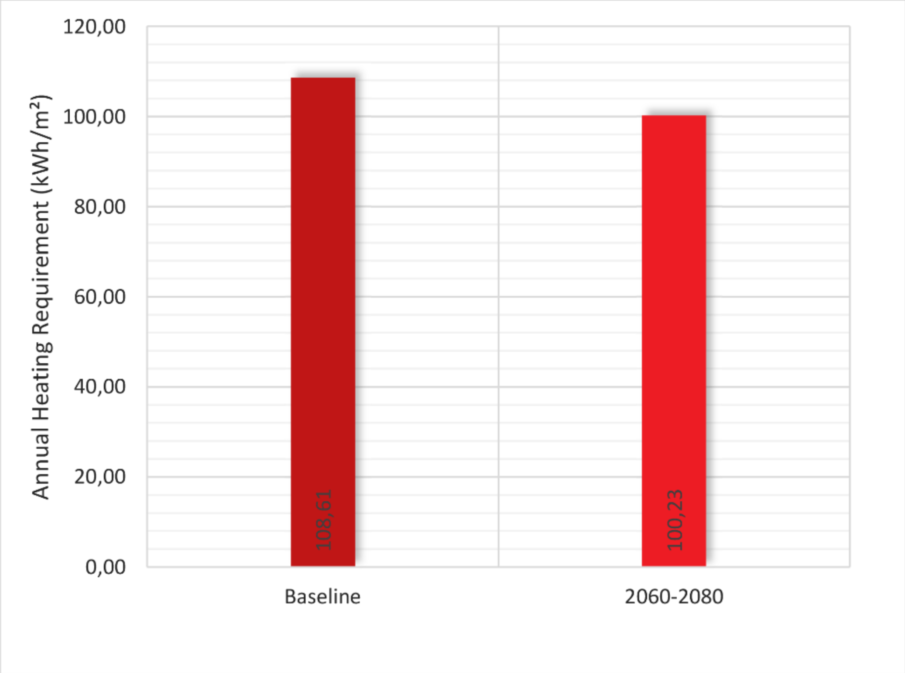
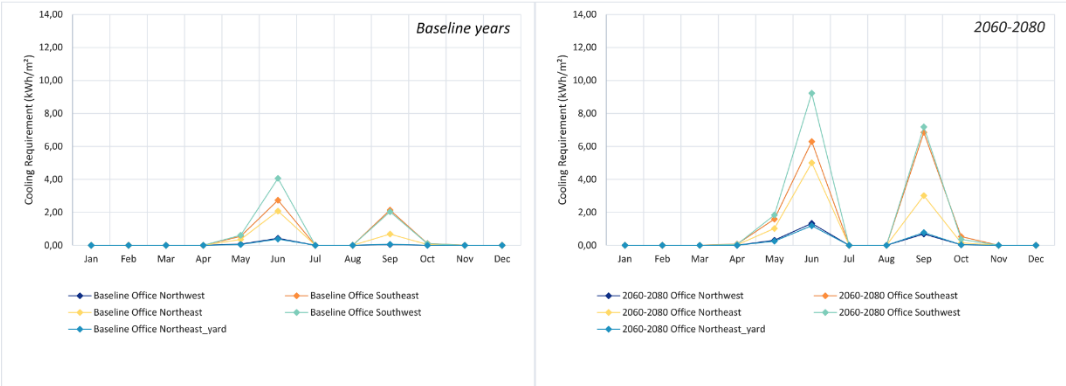
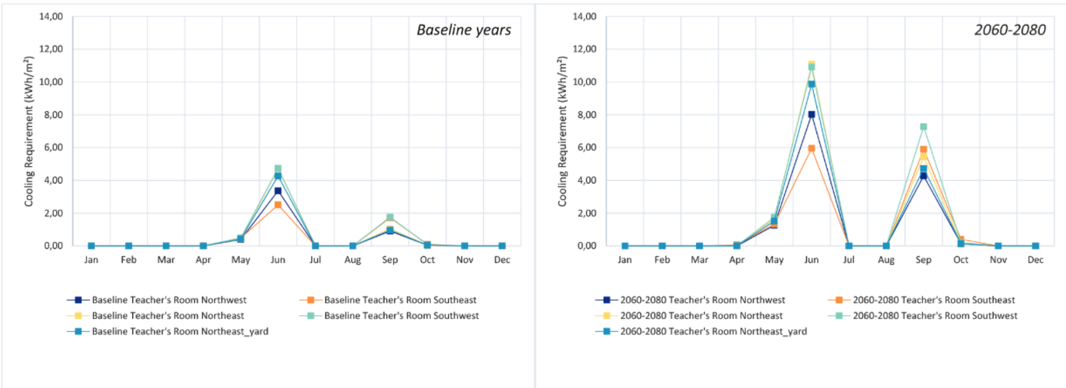


*Figure 4.15.*The annual heating requirement in the entire building in baseline years and future projections

Cooling: Cooling: Cooling requirement (Q_C) starts in May and ends in October and it was observed only in offices and teacher's rooms. July and August are excluded from calculation due to no usage in these months. Figure 4.16 shows the results for these zones under two climatic conditions. The highest demand was observed in zones facing southwest since the amount of sun falling on the southwestern surface is greater during the summer and consequently, the solar heat gain is much more than other directions. Northwest-oriented zones need too little cooling requirement.



(a)



(b)

Figure 4.16. The requirements of cooling demand for (a) offices (b) teachers' rooms

As predicted, the Q_C increases with warming temperature in the future climate. Increase in values of the cooling requirement (ΔQ_C) are 1.75-11.86 kWh/m^2 (63.50-78.23%) for offices and 8.83-13.10 kWh/m^2 (64.80-66.15%) for teacher's rooms.

The value between baseline and 2060-2080 increases 8.90 kWh/m^2 (68.50%), as shown in Figure 4.17.

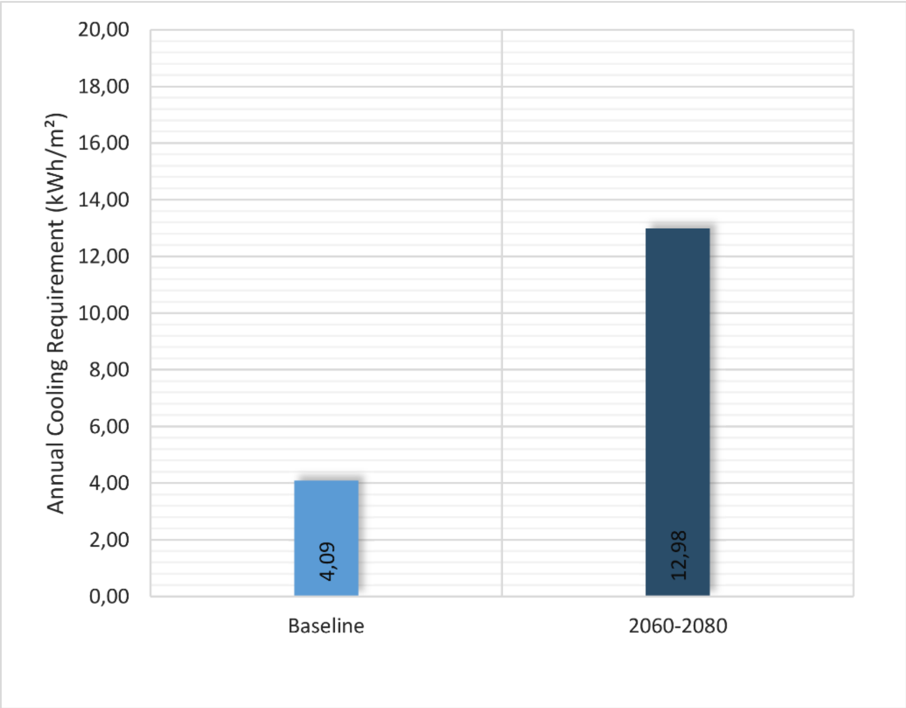
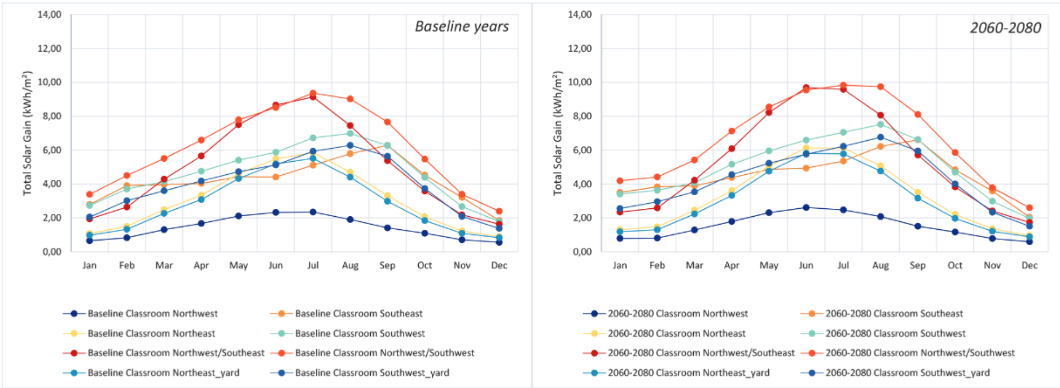
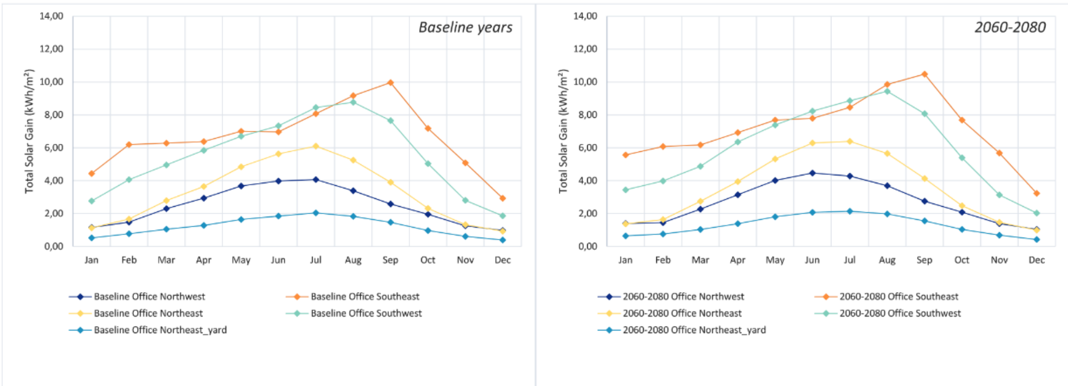


*Figure 4.17.*The annual cooling requirement in the entire building in baseline years and future projections

Solar gain: Solar gain heats buildings directly through an opening with short wave radiation from the sun. It is a significant part of the total internal heat gain of a zone and therefore, it can be beneficial to heat a building in a passive way. At the same time, it can cause discomfort and overheat. For these reasons, solar gain is one of the most important metrics in this research. Figure 4.18 summarizes results for solar gain in classrooms, offices, and teacher's rooms in baseline years with UHI-modified and 2060-2080 projections with UHI-modified.



(a)



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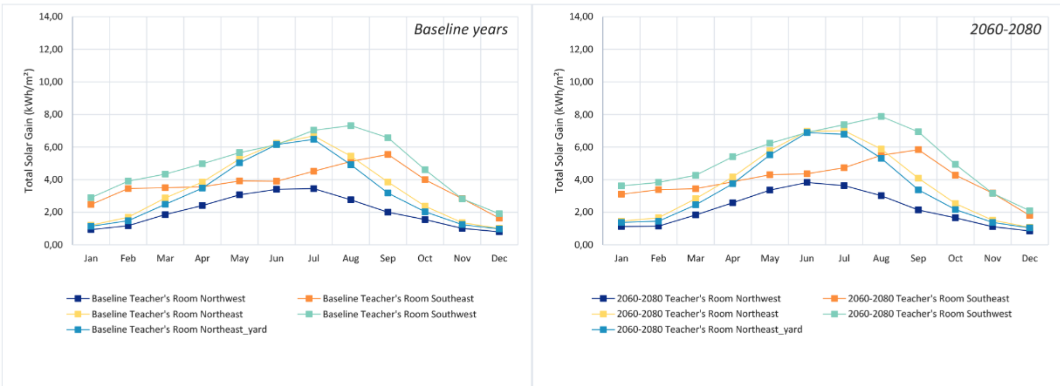


(c)

Figure 4.18. The total solar energy for (a) classrooms (b) offices (c) teacher's rooms

Similar to heating requirements, the highest solar gain is observed in classrooms facing two different orientation with two windows because they have more openings and more surfaces to gain heat, as shown in Figure 4.18 (a). These zones are followed by southwest-oriented classrooms in terms of Q_{SG}. The lowest gain is seen in northwest-oriented classrooms. Solar gain (ΔQ_{SG}) demonstrated an increasing trend in 1,29-5,57 kWh/m^2 range (7,38-7,60%) in classrooms.

As shown in Figure 4.18 (b), the highest solar gain is observed in southeast-oriented offices while the lowest solar gain is observed in offices facing both the courtyard and the northeast. The increases of solar gain (ΔQ_{SG}) range between 1,08-4,96 kWh/m^2 (7,30-7,50%) for offices.

It is apparent from Figure 4.18 (c) that for teachers' rooms, the southeastern zones gain more solar heat while the northwestern zones gain less solar heat. Especially in the summer, more solar gain observed in the northeast compared to the southeastern zones which can be considered as an unexpected result. The solar gain (ΔQ_{SG}) between baseline years and the 2060-2080 projections show a decrease in 1.85-4.45 kWh/m^2 range (7.38-7.64%).

Since many zones have similar window openings in terms of size, the solar gain has increased approximately the same rate. Furthermore, there are a couple of trees that block the Sun in the northeast direction and this situation causes solar gain to be lower than expected for all zones. Moreover, solar gain reaches the pick point in September in zones oriented the southeast while it reaches the pick point in June or August in zones with other orientations. This results from the sun path that is at a low angle during winter.

The annual ΔQ_{SG} between baseline years and the 2060-2080 projections increase in 2.58 45 kWh/m^2 (6.97%) (Figure 4.19).

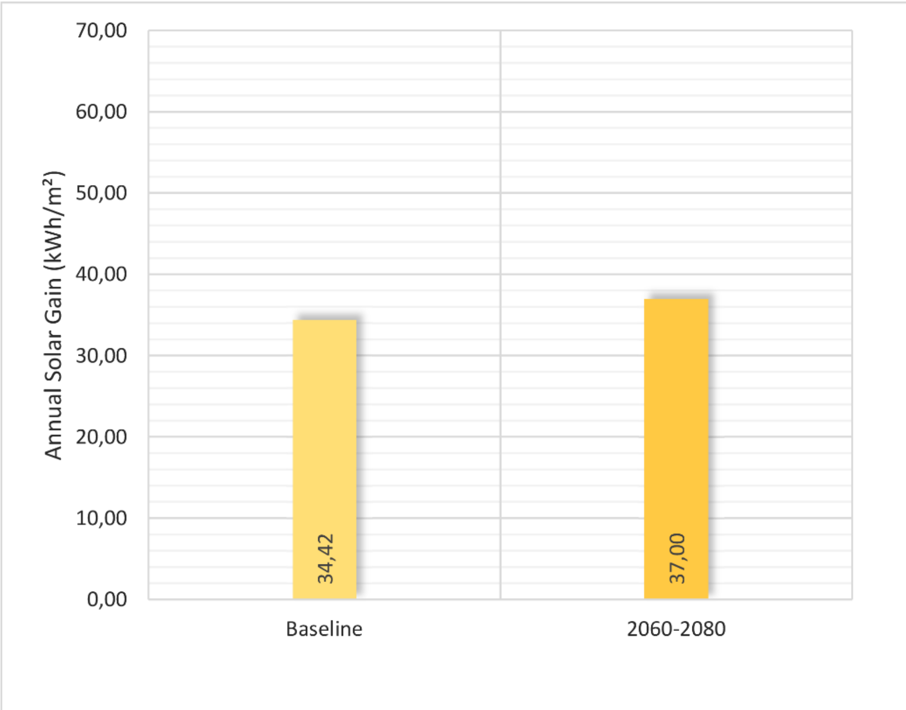


*Figure 4.19.*The annual solar gain in the entire building in baseline years and future projections

4.3.4.2. Performance assessment for thermal comfort

In this section, the thermal comfort analysis of selected zones is presented for the baseline years and 2060 projections. In light of the above-mentioned criteria, the indoor overheating degree (IOD) in the indicated zones was calculated and with the warming climate, the IOD values are expected to increase.

Significant overheating in the offices and teacher's rooms was not observed under both conditions, shown because air conditioners become active when the room temperature reaches 25°C in these zones (Figure 4.20 and 4.21). The single most striking observation to emerge from the data comparison was overheating in the southeast facing offices and teacher's rooms in February and October. However, it can be seen clearly from graphs that these IODs have minimal values and they can be omitted.

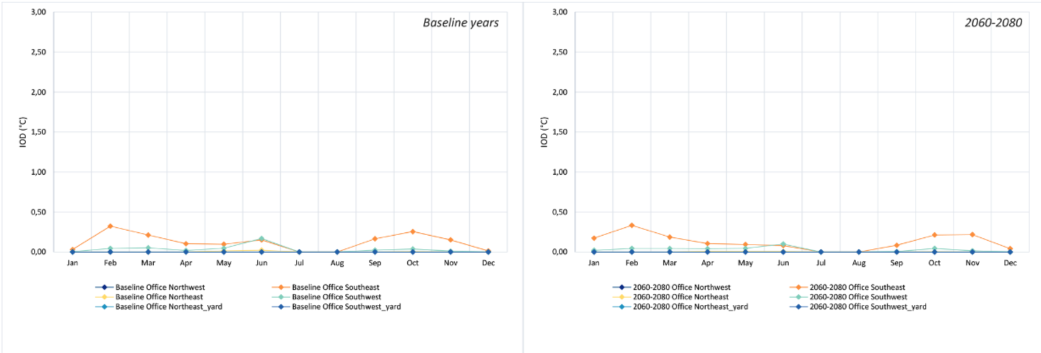


Figure 4.20. The IOD for offices

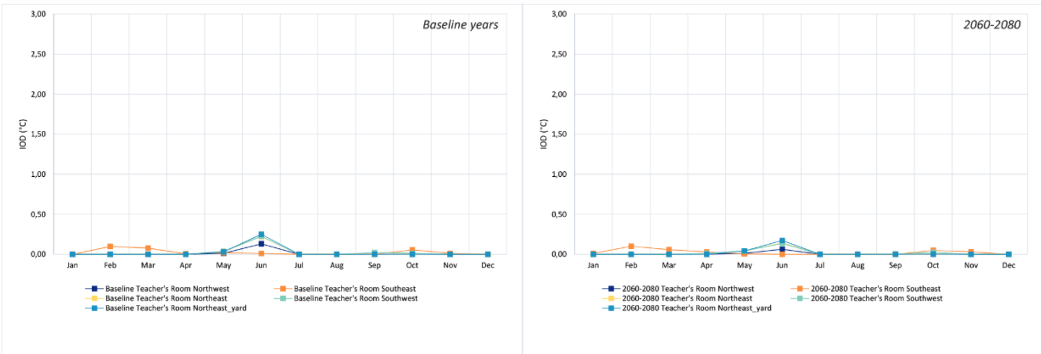


Figure 4.21. The IOD for teacher's rooms

Figure 4.22 indicates the IOD values for the classrooms. From the figure, it can be seen that the overheating starts to be observed in May and continues until October in general under both climatic conditions. June and August were excluded from the IOD calculation due to no usage in the building during these months. It can be noticed that the IOD of the southeastern and southwestern oriented classrooms are higher whereas the northwest facing classrooms show the lowest results for both climatic conditions. At this point, one of the issues to be considered is that thermal comfort requirements can be met more easily on the ground floor in many ventilated buildings. The thermal condition of zones on the top floor performs poorly compared to those on lower floors and the reason for this is the roof construction that store and emit heat (Holmes and Hacker, 2007). In this study, the ground floor classes lower the results. Not only the floor height and orientation, but also the surrounding zones and contextual shading elements affect the IOD of a zone. As mentioned earlier, the trees on the northeast side of the building that act as shading elements affect thermal performance by reducing. With the increasing temperature, it was observed that the indoor overheating degree in the classes will reach up to 2,76°C in 2060 in June.

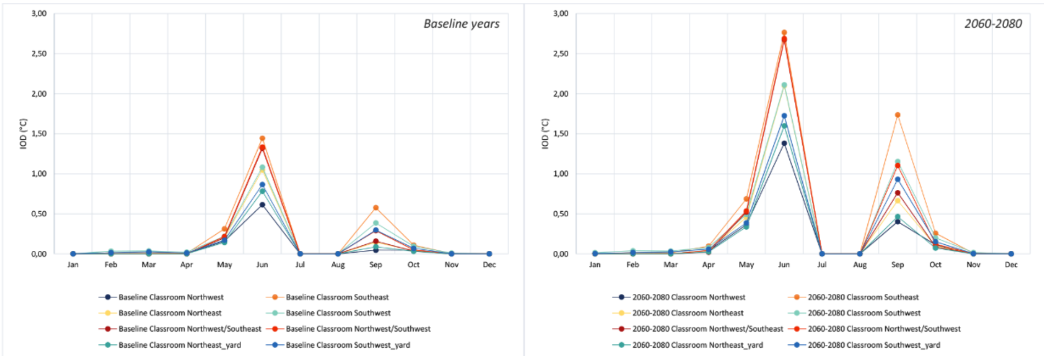


Figure 4.22. The IOD for classrooms

In this study, the thermal comfort criteria were calculated with equation of ASHRAE (Eq.2) that are suitable for adults. As previously mentioned in the literature review chapter, the temperature that people feel comfortable varies with age. Although secondary students as in the case study of this research are considered more similar to adults, studies show that the comfort temperature is 1,5°C low compared to adults (Zomorodian et al., 2016). For this reason, it should be noted that students probably feel more uncomfortable than the results.

In this section, the current and future performance of the school building were analyzed and compared. The results for two climate scenarios revealed that the building does not perform very well in its current state and it shows a tendency to deteriorate with increasing temperature in the future, especially in terms of thermal comfort. Moreover, the results clearly indicated the need for improvement and adaptation strategies. The next section, therefore, moves on to discuss these strategies and their impacts on the building performance.

4.4. Intervention scenarios as mitigation and adaptation strategies

In previous section, the results of 1-year simulations with future weather data revealed that the comfort requirements of the case-study school building were not satisfied because under the future climate condition, the discomfort periods are observed for 6 months from April to September. This section therefore looks for intervention scenarios as mitigation and adaptation design strategies with the aim of improving the building performance. Identification and implementation of potential intervention scenarios, and performance assessment will be presented.

4.4.1. Identification and implementation of potential intervention scenarios

As mentioned previous chapter, identification of the intervention scenarios starts to define the objective. In this study, the main objective is the design consideration that comprehends its advantages of reduced energy consumption and providing thermal comfort for climate change impacts. In other words, interventions are aimed to

- improve the building performance while reducing impacts on environment
- reduce the vulnerability of the building with the future climate observed in the analysis results
- reduce the overheating problems of the zones observed in the analysis results.

Objectives need to be followed by some criteria that would be effective in the selection, as noted below;

- Local climate and impacts of climate change on it

- Building or project features included geometry, orientation, typology, user profile and needs, schedule, and so on.
- Architectural approach

Since the selected building is located in Ankara, it is affected by the increasing temperature and solar radiation within the impacts of climate change and intervention scenarios are developed and applied accordingly.

Passive interventions were considered as a selection criteria because they do not directly contribute to building energy consumption and its associated CO_2 emissions and they provide a trade-off between energy performance and thermal performance. In line with the objectives and criteria, intervention scenarios were classified into 3 main categories: intervention through material replacement, through external shading elements addition, and through façade configuration change. Table 4.9 introduces proposed intervention scenarios accordance with their categories.

Table 4.9. *Intervention scenarios*

Main Categories	Sub-Category	Intervention Scenario No.	Definition
Material replacement	Wall	S.1	adding thermal insulation
		S.2	change of wall material with autoclaved aerated concrete blocks
	Glazing	S.3	solar control glazing-medium
		S.4	solar control glazing-high
	Roof	S.5	adding thermal insulation
		S.6	green roof
Sun shading addition	–	S.7	adding vertical fixed sunshade on the southwest and northeast-facing windows and horizontal fixed sunshade above southeast-facing windows
Facade configuration change	–	S.8	change of facade configuration with vertical fixed sunshade on the southwest, southeast and northeast-facing windows
		S.9	change of facade configuration with the inserted coloured frames

All of these scenarios were implemented individually and only the intervention to be applied was modified in the simulation program while the other parameters maintain without change. Details and analysis of the interventions will be given in the next section.

4.4.2. Performance assessment

In this section, the intervention scenarios implemented to the simulation model were evaluated in terms of energy demand and thermal comfort in the years 2060-2080 representing RCP8.5 projections with UHI-modified. First of all, current performance of the building and changing performance with each replaced factors were compared individually under the future climatic condition. After that, in line with evaluations of the results, scenarios that resulted in positive effects on both energy demand and user comfort were combined to provide higher improved performance of the building for increased temperature conditions. As stated before, the internal loads of the building remained constant throughout the implementation and simulation of different intervention scenarios.

In the following sections, for the entire building, the monthly energy balance and annual heating, cooling and solar gain changes according to various scenarios were examined comparatively. For cooling demand evaluation, the zones without air-conditioning were excluded from the results otherwise the cooling demand was obtained as a very low unrealistic value. Furthermore, in term of thermal comfort, the IODs in the classrooms were analyzed according to their orientation. The overheating in the offices and teacher's rooms were not examined because IOD was not observed in these zones due to air conditioning.

4.4.2.1. Intervention through material changes

In this stage, the interventions were carried out by the replacement materials or components of the envelope which provides the physical barrier between the exterior and interior environments enclosing a structure. External walls, glazing, and roof materials and their construction details were changed and their performance was evaluated in the following sections.

4.4.2.1.1. The effects of various external wall types

Thermal comfort and energy demand conditions in the case-study school building were examined using full-year simulations by varying the composition of external walls of the calibrated EnergyPlus models. Two different compositions were used: 1. adding thermal insulation 2. replacement of the wall material with autoclaved aerated concrete (AAC) blocks (Table 4.10). The reasons for their selection these two are as follows.

- easy to assess and apply,
- creating a constant condition of thermal comfort all the year-round,
- reducing the heating and cooling demand,
- environmental protection.

Table 4.10. *Construction and material details of the wall*

Intervention Wall Scenario	Construction Details	Conductivity (W/mK)	Specific Heat Capacity (J/kgK)	Density (kg/m³)	U-value (W/m²K)	References
Original	90mm single layer of press-brick	0,42	900	2240	1,23	1
	190mm single layer of brick	0,33	900	600		1
	one layer of plaster (20-25mm)	0,51	1090	1200		1
S.1	90mm single layer of press-brick	0,42	900	2240	0,46	1
	47,7mm EPS (Expanded Polystyren)*	0,035	1400	25		1
	190mm single layer of brick	0,33	900	600		1
	one layer of plaster (20-25mm)	0,51	1090	1200		1
S.2	90mm single layer of press-brick	0,42	900	2240	0,87	1
	250mm single layer of AAC blocks	0,24	1000	750		1
	one layer of plaster (20-25mm)	0,51	1090	1200		1
1- Apache Table. Retrieved February 10, 2019 from https://help.iesve.com/ve2018/table_6_thermal_conductivity__specific_heat_capacity_and_density.htm						
*The tickness of EPS is determined according to Thermal Insulation Requirements for Building (Ts 825) standard (Ts825, 2013).						

As can be seen in Table 4.10, the U-values (W/m^2K) changes significantly by changing the composition and material of the wall. U-value known as thermal transmittance is used to measure how effective a material or composite is an insulator. The lower U-value provides better insulation. In this case, U-values of external walls vary according to the physical and mechanical properties of the materials.

As a result of the interventions, a significant decrease in heating demand was observed as predicted. The annual heating requirement before and after modifications of the external walls are shown in Figure 4.23. ΔQ_H for whole building decreased by 25.55% and 21.65 % for S.1 and S.2 respectively. It is apparent from these rates and the graph, addition of thermal comfort is more efficient way to mitigate heating demand.

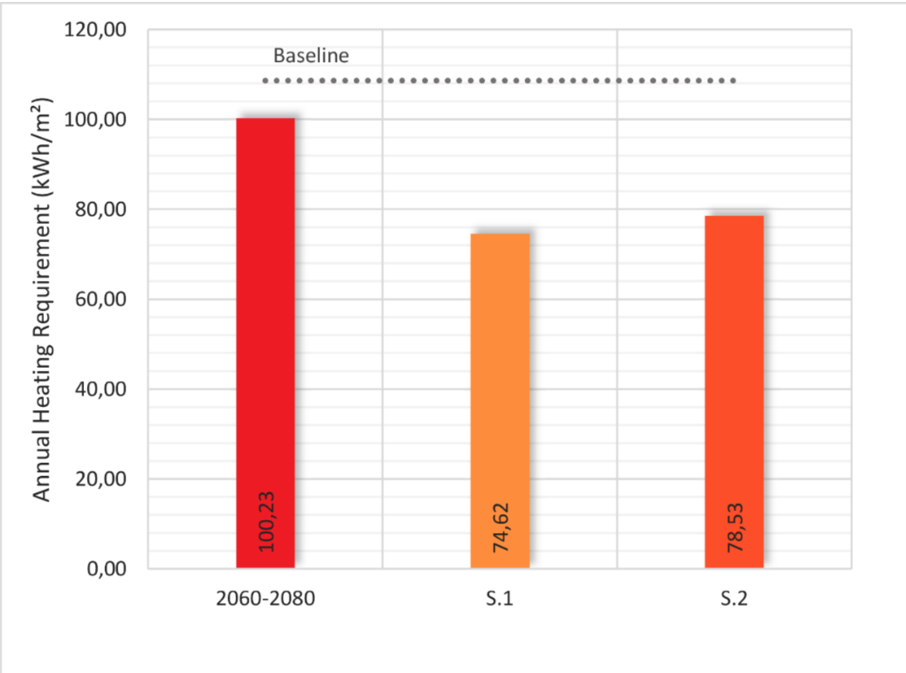


Figure 4.23. The annual heating requirement for various wall types in the entire building

AAC blocks and thermal insulation were expected to reduce heat transfer between the indoor and outdoor environments of buildings with different temperatures but these materials did not show influential results in the summer months. The reduction in ΔQ_C are 1.35 and 1.23 (10.30 and 9.50%) for S.1 and S.2 respectively, as shown in Figure 4.24. This is a rather disappointing outcome. This implies that the changes in the wall composition alone are not enough to cope with the increased temperature and to provide energy efficiency and comfort in this case study.

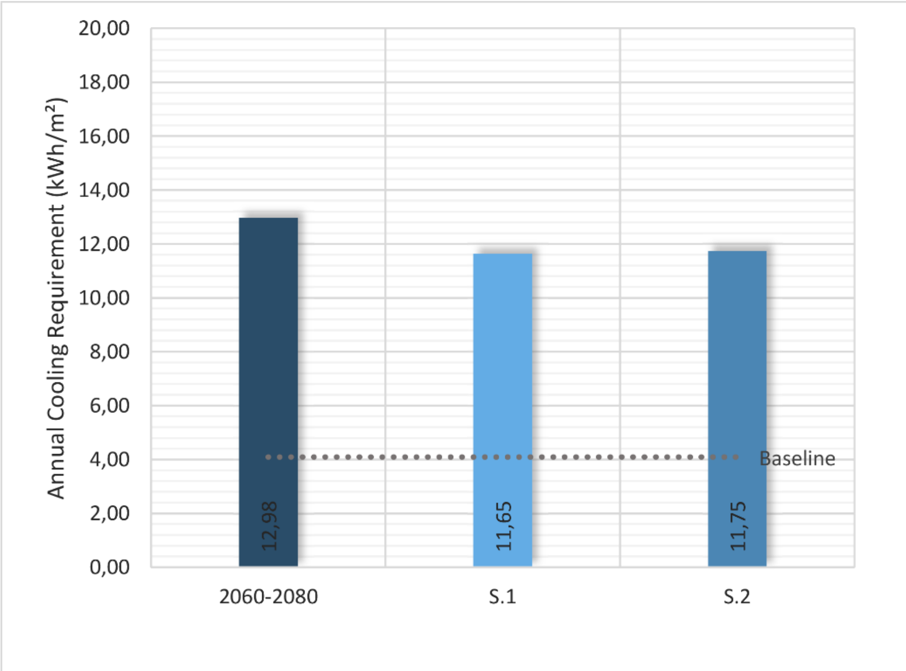
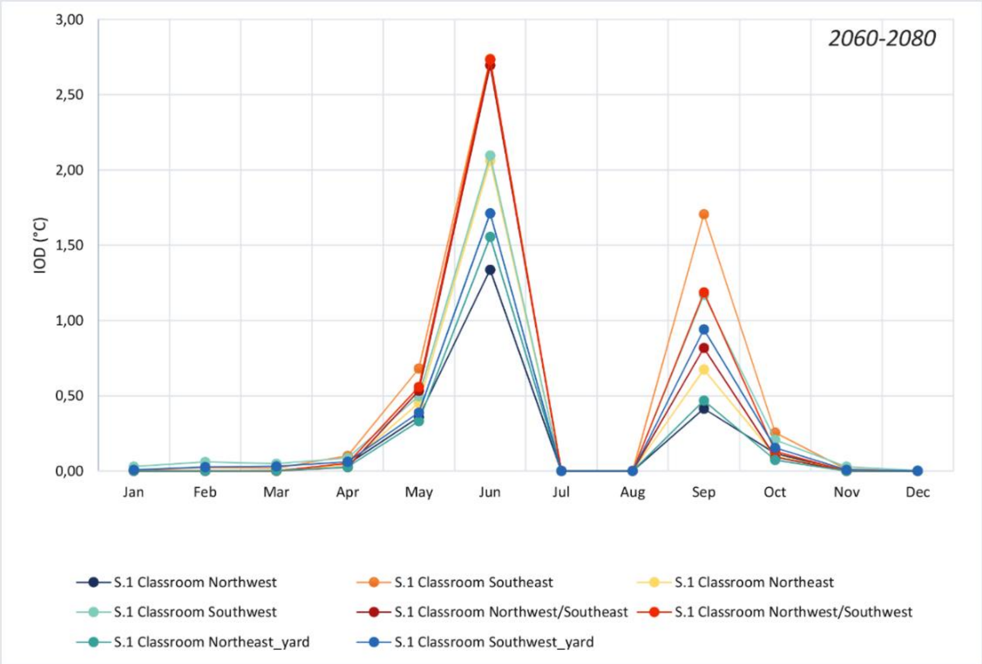


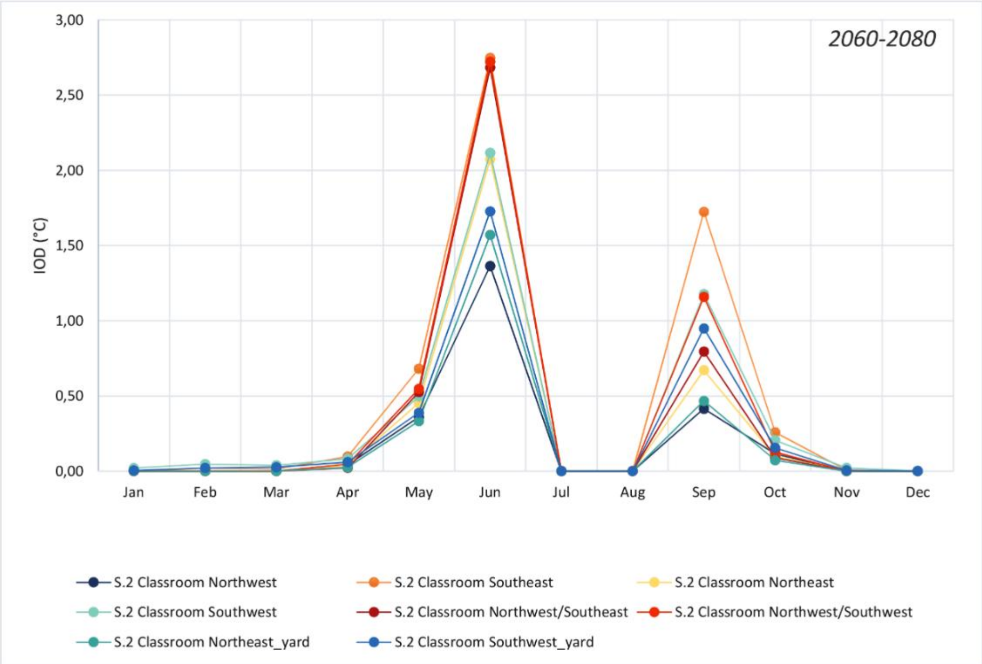
Figure 4.24. . The annual cooling requirement for various wall types in the entire building

There is no alteration in solar gain. As remarked in the previous section, solar gain is short wave radiation from the sun that is able to pass through opening or glazing. For this reason, the modifications of the wall composition do not affect it.

Indoor overheating degrees (IOD) of the classrooms after modifications of the external walls are shown in Figure 4.25. It can be seen in the graphs that for thermal comfort, in line with the results of cooling and the solar gain, the role of changes in wall compositions is insignificant in this case and they can be omitted. On the other hand, the modifications of the walls, especially adding thermal insulation can contribute to reduce heat loss and the requirements of heating load in winter.



(a)



(b)

Figure 4.25. The IOD for classrooms: (a) S.1 and (b) S.2

4.4.2.1.2. The effects of various glazing types

Windows are complex elements in the fabric of a building and they play an important role in the heat loss and heat gain, consequently, energy and thermal performance of a building. Improvement performance of windows depends on the efficiency of the frame, the glazing and the airtightness of the finished windows. In this study, intervention scenarios only for the glazing were developed in the purpose of improving indoor comfort and achieving building energy conservation. Table 4.11 indicates the properties of the current and modified glazing.

Table 4.11. *Performance values of the different glazing*

Intervention Glazing Scenario	Details	U Value (W/m²K)	Solar Heat Gain Coefficient	Visible Trasmittance	References
Original	16mm double glazed and aluminum frame	2,7	0,75	0.80	1
S.3	16mm double glazed and aluminum frame	1,3	0,54	0,76	1
S.4	16mm double glazed and aluminum frame	0,6	0,37	0,51	1
1- http://www.isicam.com.tr/tr/profesyoneller-icin/profesyoneller-icin-urun-katalogu/isicam-c-standart					

It can be seen from Table 4.11, all parameters for glazing were enhanced. As U-values decreases, the modified glazing provide better thermal insulation. Therefore, this situation reflected as a decline in ΔQ_H (Figure 4.26). The annual heating for the entire building decrease by 17.53% and 18.36% for S.3 and S.4.

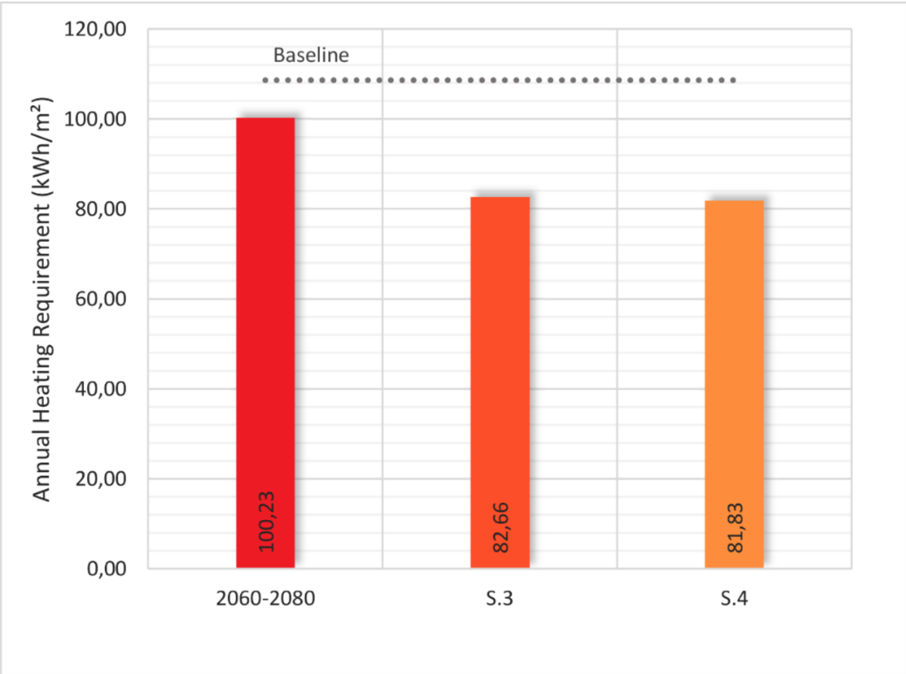


Figure 4.26. The annual heating requirement for various glazing types in the entire building

Solar heat gain coefficient (SHGC) and visible transmittance (VT) of the glazing were also decreased and these modifications provide better solar control. As a consequence of these, a serious reduction of the annual solar gain (ΔQ_{SG}) were monitored and in parallel with it, the average cooling requirement (ΔQ_C) and the IODs decrease. The values for solar gain and cooling are indicated in Figure 4.27 and Figure 4.28. The values of the decrease in ΔQ_C are 2.05 and 2.92 kWh/m2 (15.68 and 22.50%) and decrease in s ΔQ_{SG} are 12.17- 22.98 kWh/m^2 (32.88-62.10%) for the entire building.

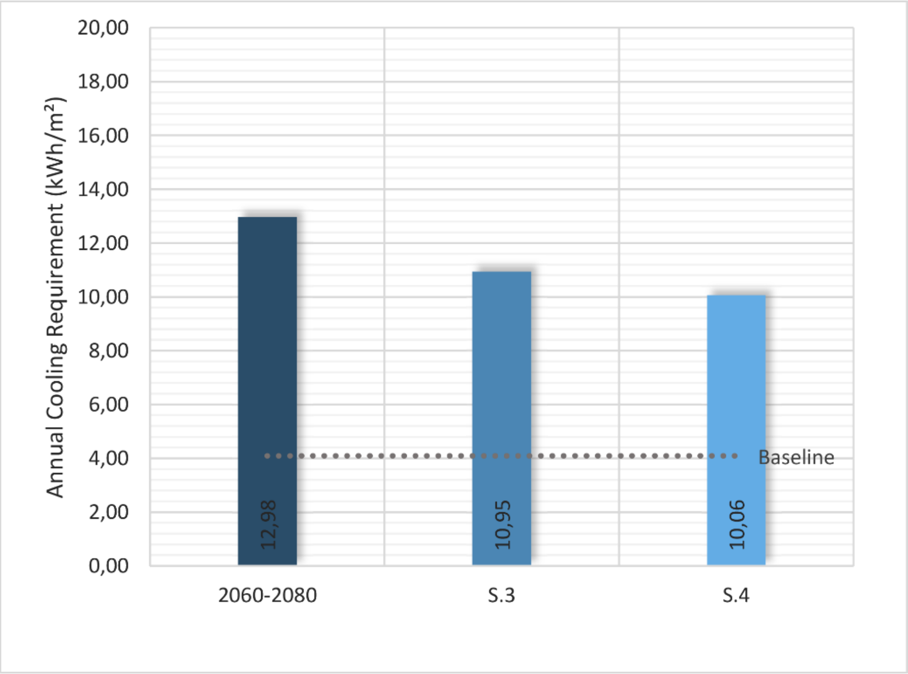


Figure 4.27. The annual cooling requirement for various glazing types in the entire building

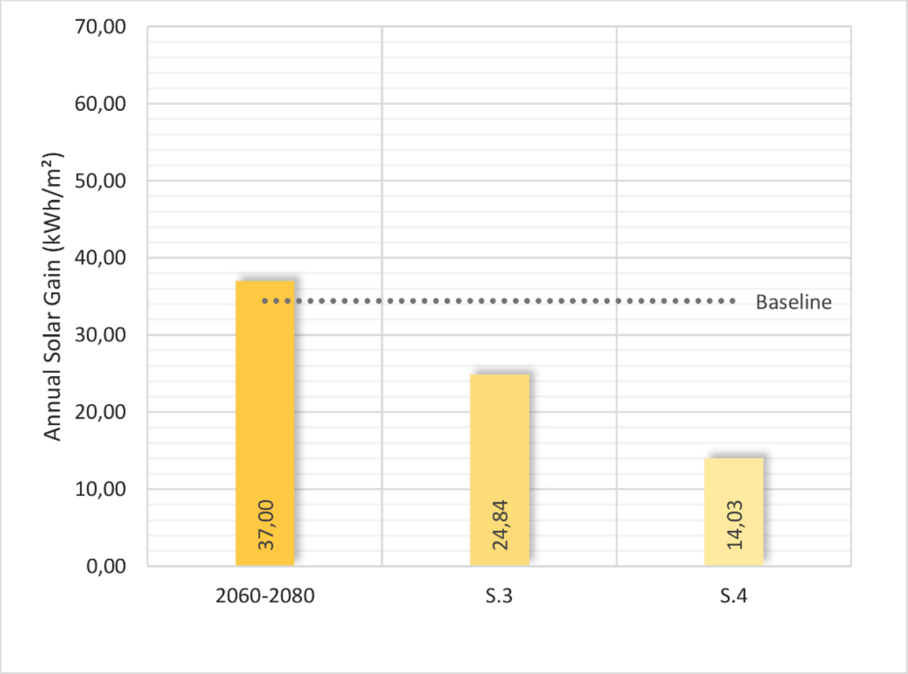
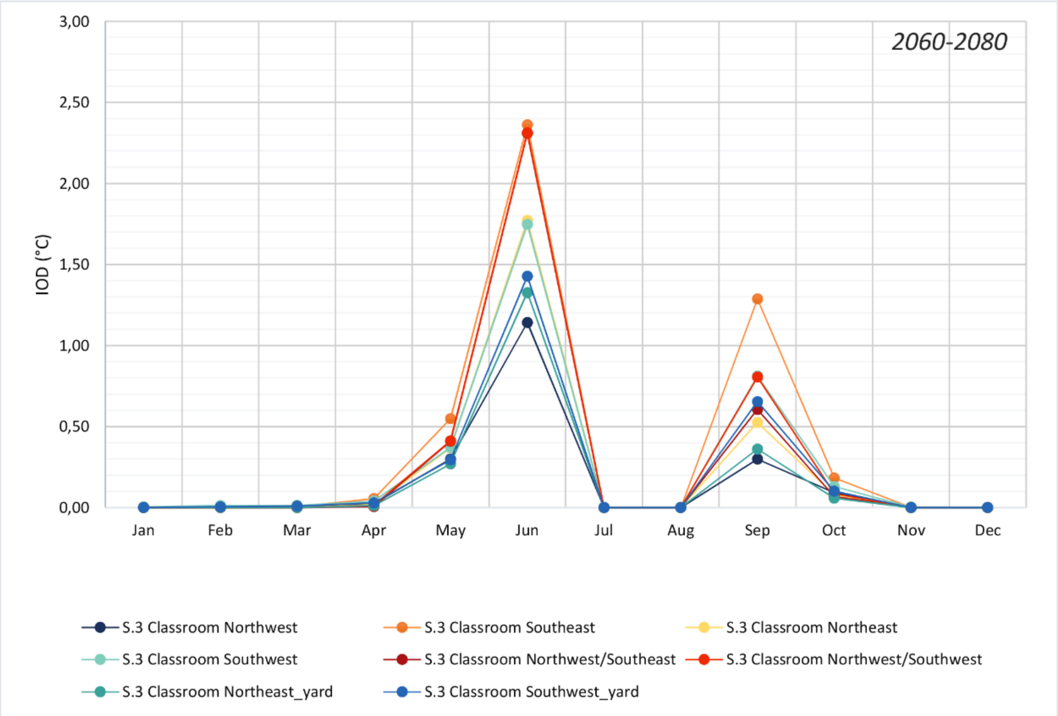
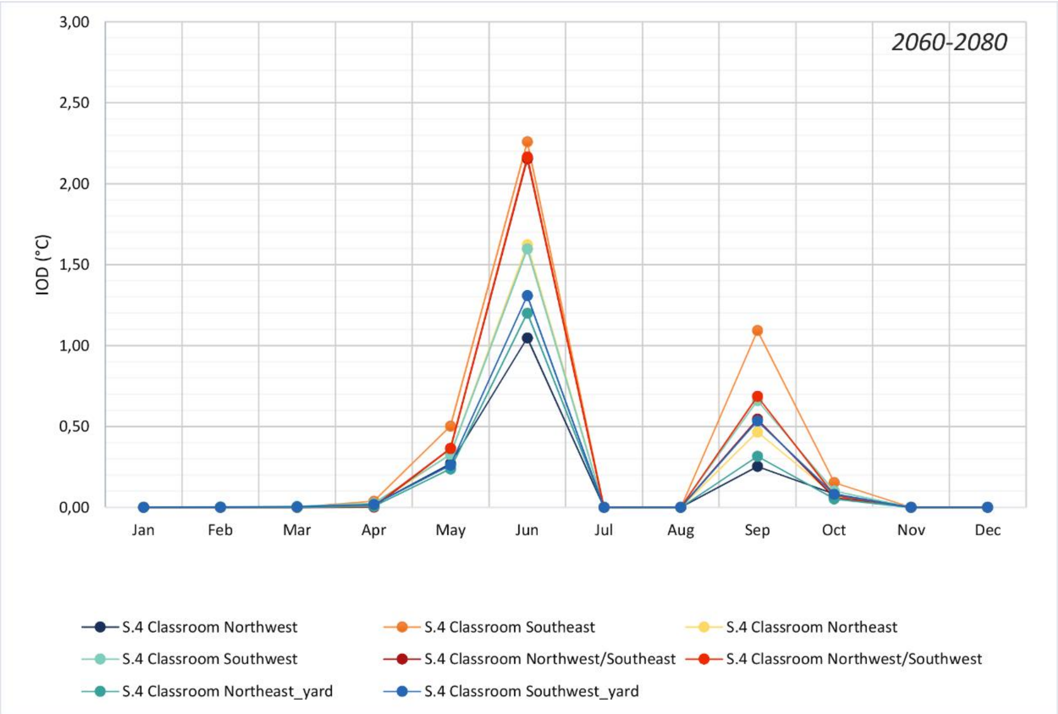


Figure 4.28. The annual solar gain for various glazing types in the entire building

Although there was not a very effective decrease for heating, a significant decrease in total solar gain was observed, especially in S.4, and a corresponding decrease in cooling demand and overheating risk. Indoor overheating degrees (IOD) of the selected zones before and after replacement of the glazing are shown in Figure 4.29. The graphs reveal that the thermal performance of the school with a solar control glazing was remarkably improved. The reductions of the IOD were obtained to about 1 °C. For both scenarios, as classes have about the same proportion of windows, they were affected at about the same rate.



(a)



(b)

Figure 4.29. The IOD for classrooms: (a) S.3 and (b) S.4

4.4.2.1.3. The effects of various external roof types

The roof of the case building has a form of a pitched roof with tiles but the roof was modelled as a flat roof and materials of the roof were also determined according to this situation. In line with the flat roof, thicken thermal insulation of the roof and the green roof were proposed as the intervention scenario. Table 4.12 summarizes the properties of the alternatives.

Table 4.12. *Construction and material details of the roof*

Intervention Roof Scenario	Construction Details	Conductivity (W/mK)	Specific Heat Capacity (J/kgK)	Density (kg/m^3)	U-value (W/m^{2}K)	References
Original	Gravel	0,36	840	1840	2,96	1
	Separation layer	—	—	—		—
	3mm waterproofing membrane	0,19	780	3000		1
	40mm levelling concrete	0,3	840	2200		1
	200mm concrete slab	2,5	840	2400		1
	one layer of plaster (20-25mm)	0,51	1090	1200		1
S.5	Gravel	0,36	840	1840	0,42	1
	Separation layer	—	—	—		—
	80mm thermal insulation	0,04	670	200		1
	3mm waterproofing membrane	0,19	780	3000		1
	40mm levelling concrete	0,3	840	2200		1
	200mm concrete slab	2,5	840	2400		1
	one layer of plaster (20-25mm)	0,51	1090	1200		1
S.6	Vegetation layer	—	—	—	0,41	—
	10mm roofing felt	0,19	837	960		1
	20mm drainage layer	0,45	1900	950		1
	60mm thermal insulation	0,035	1200	25		1
	10mm roofing felt	0,19	837	960		1
	3mm waterproofing membrane	0,19	780	3000		1
	40mm levelling concrete	0,3	840	2200		1
	200mm concrete slab	2,5	840	2400		1
	one layer of plaster (20-25mm)	0,51	1090	1200		1

1- Apache Table. Retrieved February 10, 2019 from https://help.iesve.com/ve2018/table_6_thermal_conductivity__specific_heat_capacity_and_density.htm

The majority of the solar radiation distributed in building gains from the roof. Therefore, with improvements to the roof, it is expected that a certain level of heat gain could be reduced to prevent overheating and high demand for the cooling load. However, surprising results were obtained in this research. For both roof interventions, heating demand shows a fairly effective decrease while cooling and IOD show a slight decrease which is not taken into account when compared with heating. It was expected that zones located on the second floor were affected the most by these modifications.

The annual ΔQ_H decreases by 41.38% and 43.19% for S.5 and S.6. (Figure 4.30). Addition of thermal comfort and green roof were obtain close results in terms of heating demand.

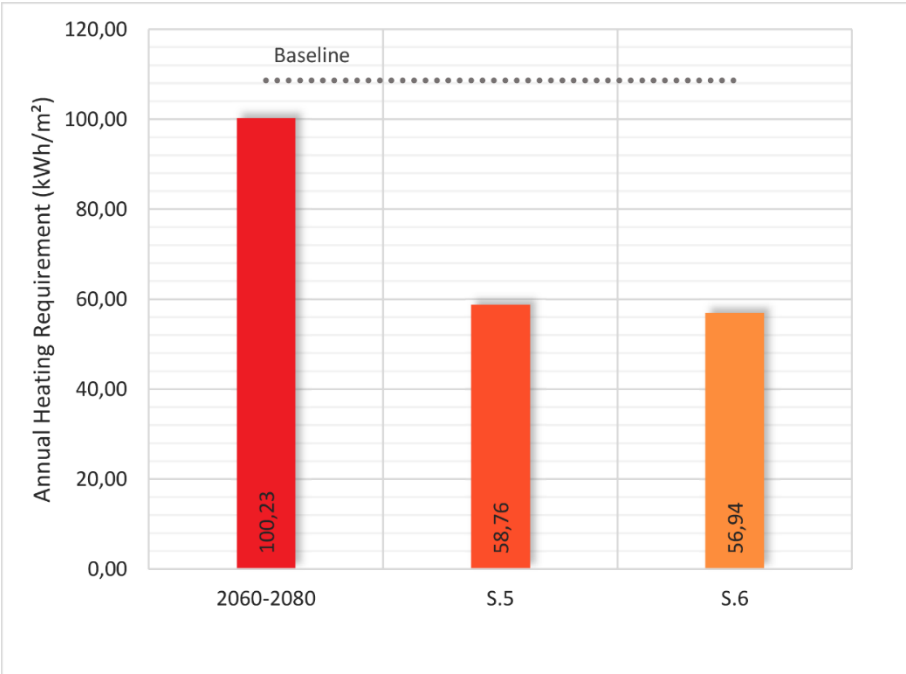


*Figure 4.30.*The annual heating requirement for various roof types in the entire building

The annual ΔQ_C was observed a minimal reduction by 0.17-0.06 (1.35-0.45%) for S.5 and S.6 respectively, as shown in Figure 4.31. It can be seen in the graph that the role of changes in roof compositions is insignificant for cooling demand in this case and they can be omitted.

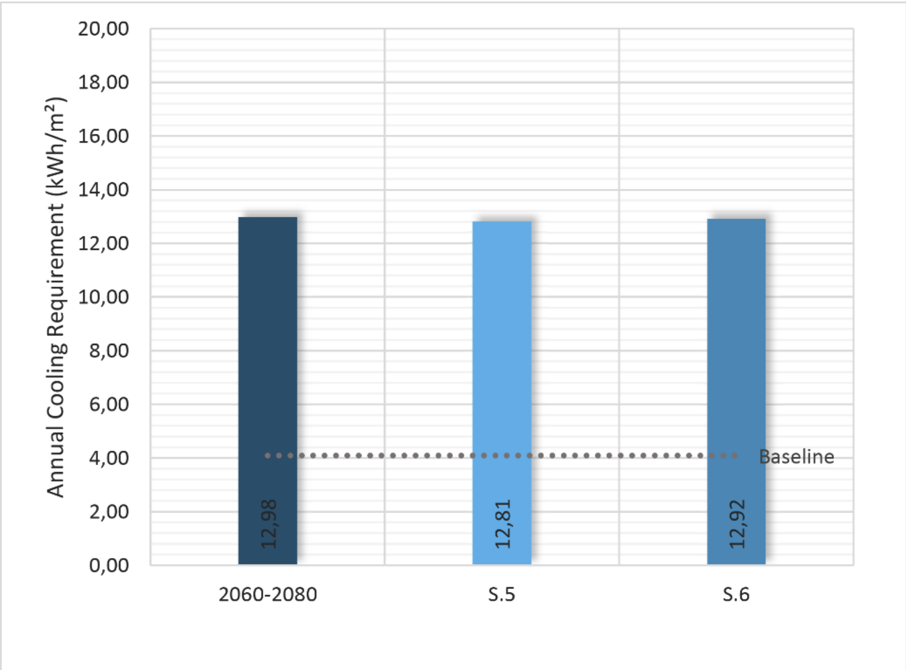
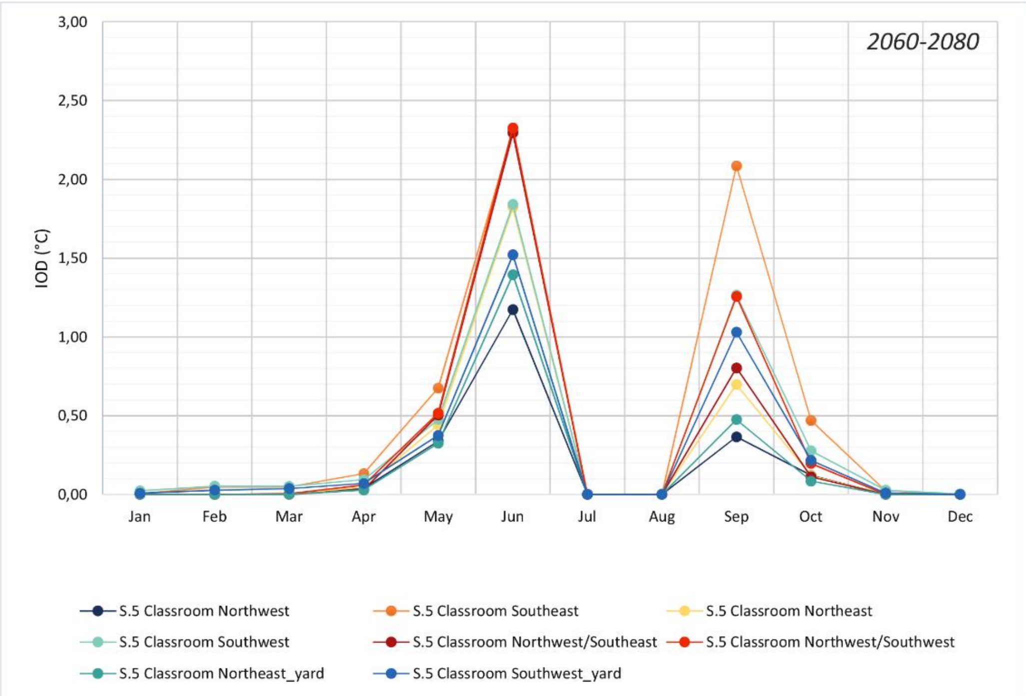


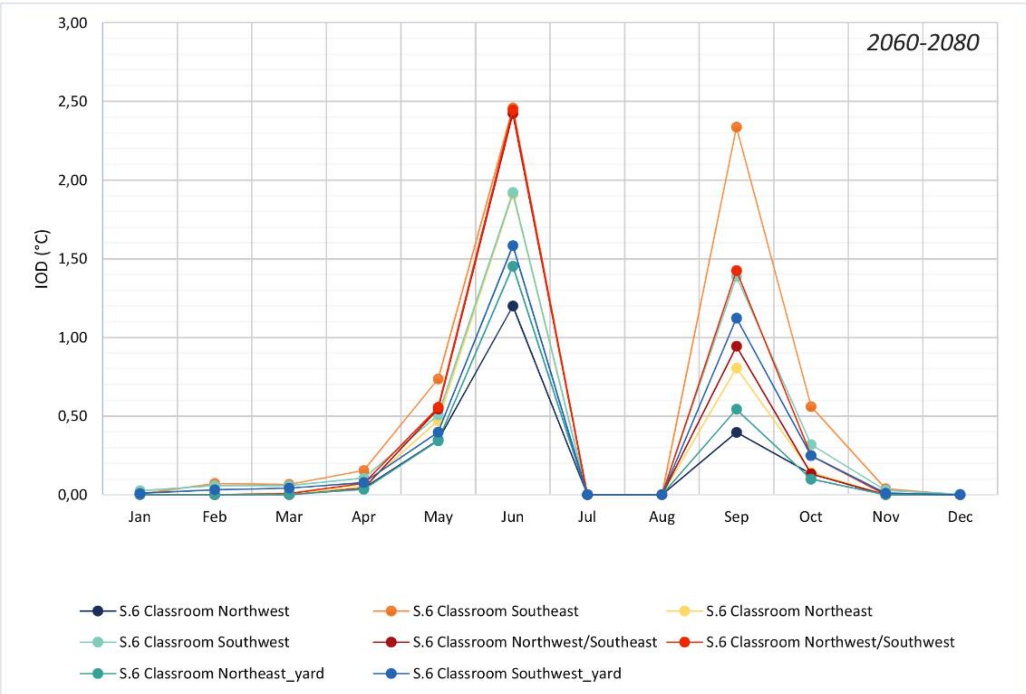
Figure 4.31.The annual cooling requirement for various roof types in the entire building

The modifications of the roof composition does not affect the total solar gain and the ΔQ_{SG} do not change.

It can be seen in the graphs that the role of changes in roof compositions lowered the overheating risk (Figure 4.32). The roof with thermal insulation layer (S.5) performed better than the green roof in this study and the expected results from the green roof could not be obtained.



(a)



(b)

Figure 4.32. The IOD for classrooms: (a) S.5 and (b) S.6

4.4.2.2. Intervention through external shading elements addition

Regarding the facts stated in the literature review, solar shading control is one of the ways of mitigation and adaptation to climate change. Along with the glazing type, it is an essential solution to provide energy efficiency and thermal comfort by controlling heat gain through openings. The orientation of an opening is the most important parameter in the design of the shading element. In winter and in summer seasons, the sun path shows variation linked to the orientation. In the northern hemisphere, the sun path is at a low angle during winters, south to east-west axis while it is at high angle, north to the east-west axis. Seasonal variations in the sun path do not seen on the east and west facing openings that receive uniform solar radiation through the year. Therefore, shading elements should be designed by taking into consideration the angle of the sun path in different orientations. Climate change does not have impacts on sun angle but with the warming temperature, solar heat gain is increasing and consequently, the need for the shading elements can grow.

In this study, as the selected case study are in the northern hemisphere, there is no need a shading elements on the northwest while fixed-vertical louvres on the southwest and the northeast facing windows and fixed-horizontal louvres on the southeast facing windows were assigned in the simulation model. The width of these elements were determined 80cm and their angles were applied as 0°. Six vertical louvres to each window on the southwest and the northeast and three horizontal louvres to each window on southeast were implemented.

Shading elements were applied as fixed elements, causing them to block the heat gain from the sun all year round and to reduce solar gain (Figure 4.33). These circumstances resulted in an increase in heating demand in winter and a decrease in cooling demand (Figure 4.34 and Figure 4.35). The annual ΔQ_H value is 85.62 and it decreases by 14.60 kWh/m2 (14.58%). 14% decrease is observed in ΔQ_C. The annual solar gain reduced by 22.85% in the entire building.

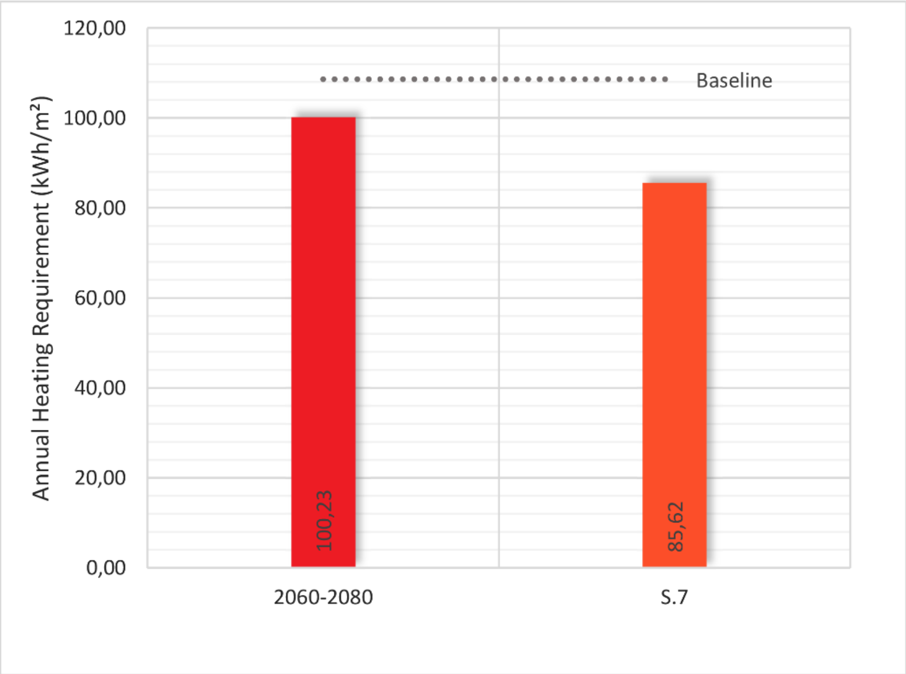


Figure 4.33. The annual heating requirement for S.7 in the entire building

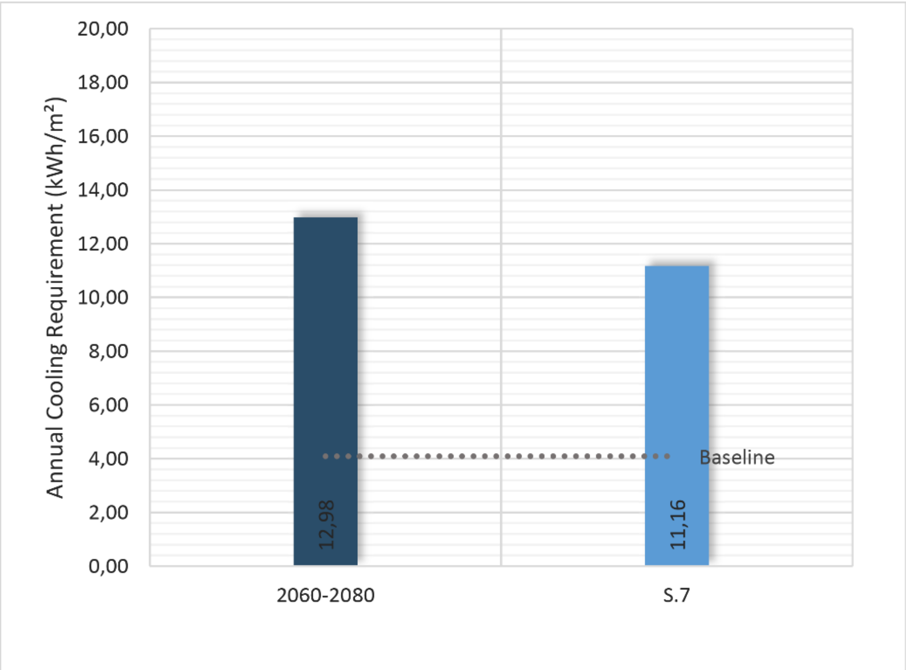


Figure 4.34. The annual cooling requirement for S.7 in the entire building

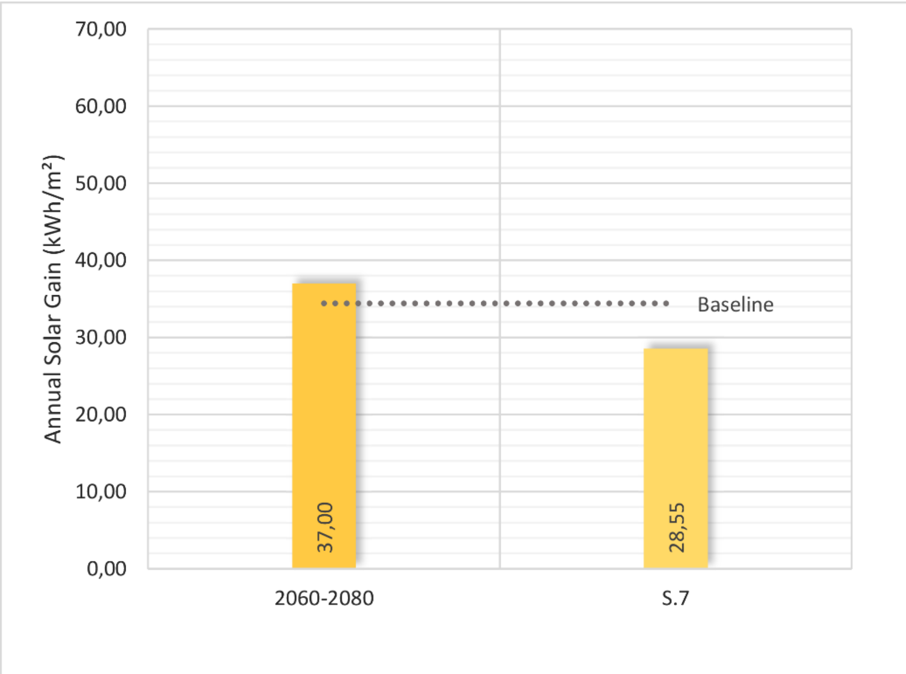


Figure 4.35. The annual solar gain for S.7 in the entire building

As a result of reduction in solar gain, the values of IODs showed a decrease (Figure 4.36). As noted above, they were only applied on the windows oriented southwest, southeast, and northeast and therefore, the results of classrooms, offices, and teacher's rooms facing these orientations were examined.

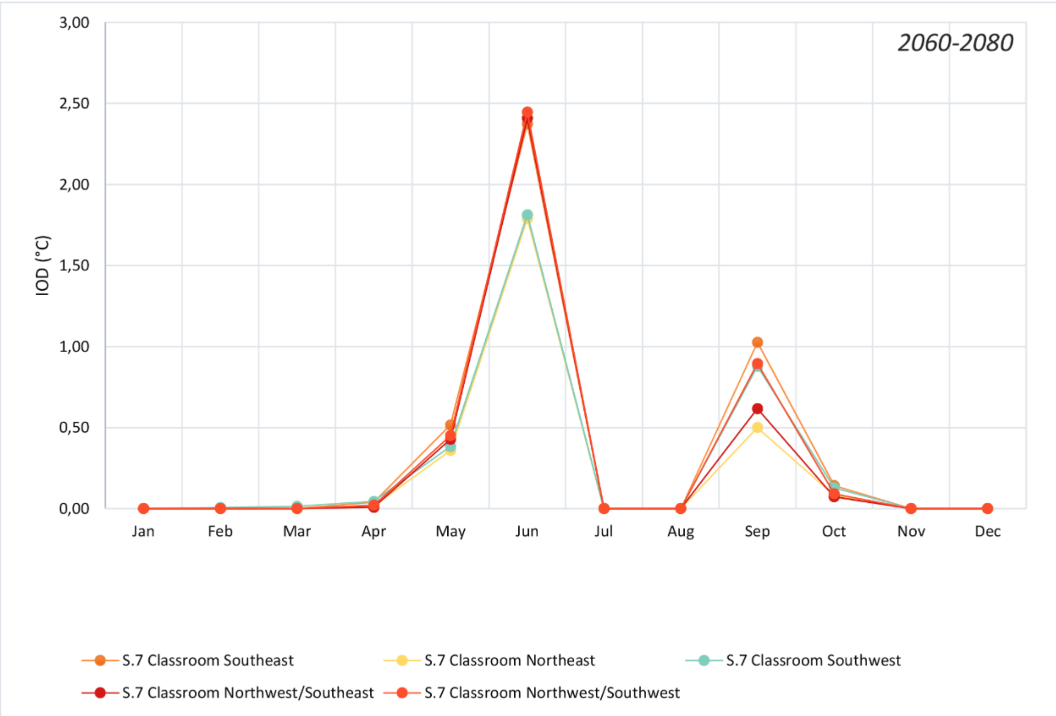


Figure 4.36. The IOD for classrooms for S.7

4.4.2.3. Intervention through façade configuration changes

As indicated in the literature review, educational buildings are different from other buildings in terms of occupancy profile, schedule, activity and clothing levels, different internal gains, and comfortable temperatures. A school is an educational institution designed to provide learning spaces and learning environments that is the diverse physical locations, contexts, and cultures in which students learn (Jetsonen, Johansson, Nuikkinen, & Sahlberg, 2011). In other words, a school should be a place that is physically, psychologically, and socially safe, promoting the child's growth, health, and learning as well as their positive interaction with teachers and other students. As stated clearly, the physical environment is an integral part of all this dynamic relationship. In line with these, school buildings should have flexibility, transparency, spatial variety, and active, passive, and personalized spaces and most importantly for this study they should link the indoor and outdoor places (Sanoff, 2001).

The performance, productivity, attendance, and health of students and also teachers highly depends on the quality of the indoor environment. This quality can be provided with lighting (visual comfort), natural ventilation (air quality), and thermal comfort. Under warming climatic conditions, a change in the facade configuration was proposed both to improve the quality of the indoor environment with promoting natural ventilation, natural lighting and link between the indoor and outdoor environment. Furthermore, this intervention is considered as deep intervention and it allows for a wide range of materials and visual design language, as stated in the third chapter.

The large window formats were proposed to provide a light and transparent atmosphere indoors (Figure 4.37). The window-wall ratio (WWR) was changed due to this format and Table 4.13 indicates the ratios according to main orientations. Window operable areas were increased from 45 percent to 70 percent. As the window area was increased, the solar gain increased and, consequently, substantial increase in energy use and overheating was observed in accordance with the analysis results. For this reason, two different methods have been proposed to provide shading. The first one is fixed external sun shading elements and the second proposal is that the colored shelf-like frames were inserted into façade (Figure 4.38 and Figure 4.39). Sun shading elements are designed randomly to add mobility to the façade. Their width is 80 cm. The frames are applied to create sufficient shading at a width of 1 meter. Moreover, it is aimed to both increase shading and improve the learning environments with the colored frames.

Figure 4.37. The proposed large window format

Figure 4.38. The proposed large window format with fixed sun shading elements

Figure 4.39. The proposed large window format with the colored shelf-like frames

Table 4.13.*Window-wall ratio for new facade*

	Total	Northwest	Northeast	Southeast	Southwest
Gross Wall Area (m²)	3684.70	754.86	1087.50	754.85	1087.50
Above Ground Wall Area (m²)	3661.95	754.86	1083.23	740.64	1083.23
Window Opening Area (m²)	1666.59	107.77	613.71	336.73	608.38
Gross Window-Wall Ratio (%)	45.23	14.28	56.43	44.61	55.94
Above Ground Window-Wall Ratio (%)	45.51	14.28	56.66	45.46	56.16

In general, architectural designs for facade are developed based on the premise of fitting new high performance curtain wall or window systems within existing building conditions. When the window area increases this much, it is necessary to use solar control glazing. In this case, however, the glazing properties remained to be able to make a comparative assessment with other scenarios and the current situation of the building under the future climatic conditions and in both cases there is no improvement in building performance. All energy performance criteria increase due to the reduplication of window areas and Figure 4.40, 4.41, and 4.42 indicate the annual heating and cooling requirement and solar gain.

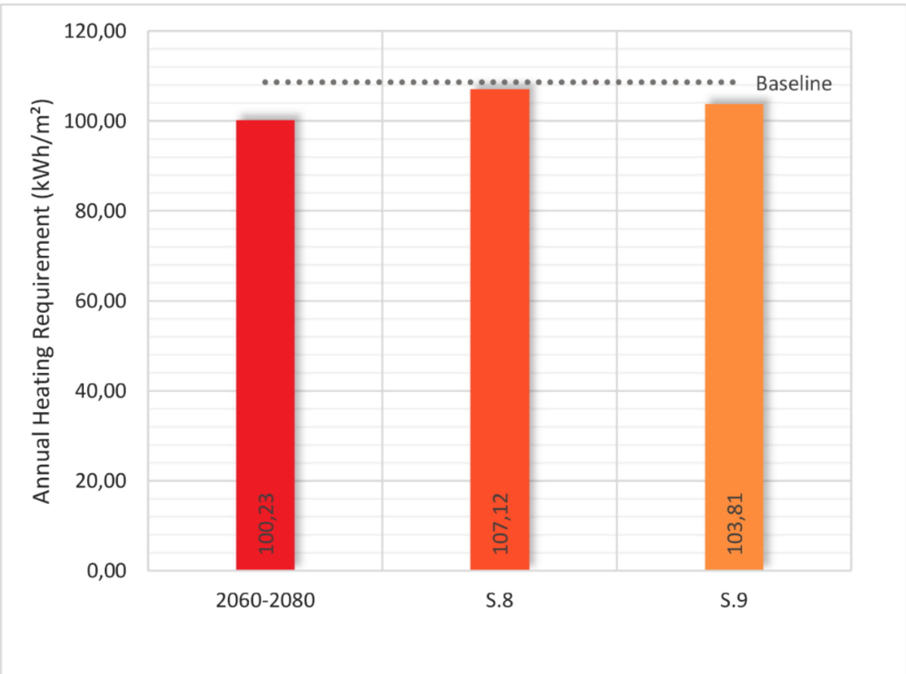


Figure 4.40. The annual heating requirement for various façade configurations in the entire building

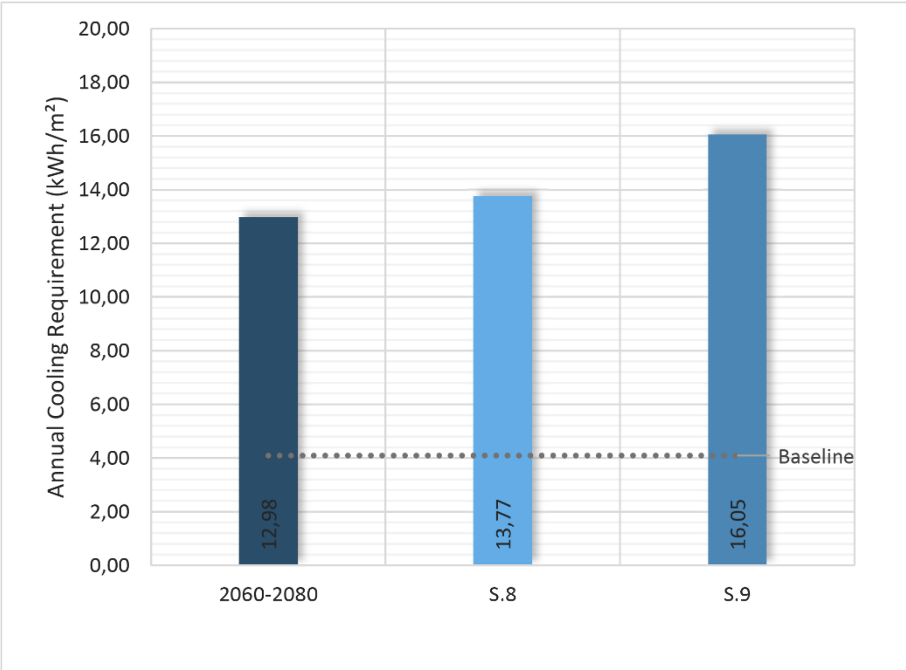


Figure 4.41. The annual cooling requirement for various façade configurations in the entire building

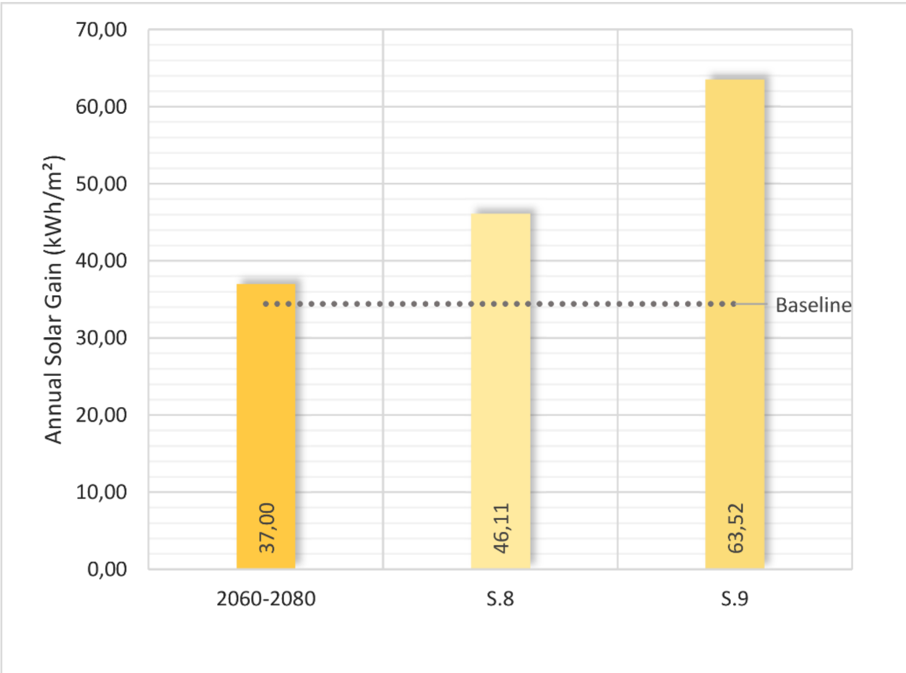
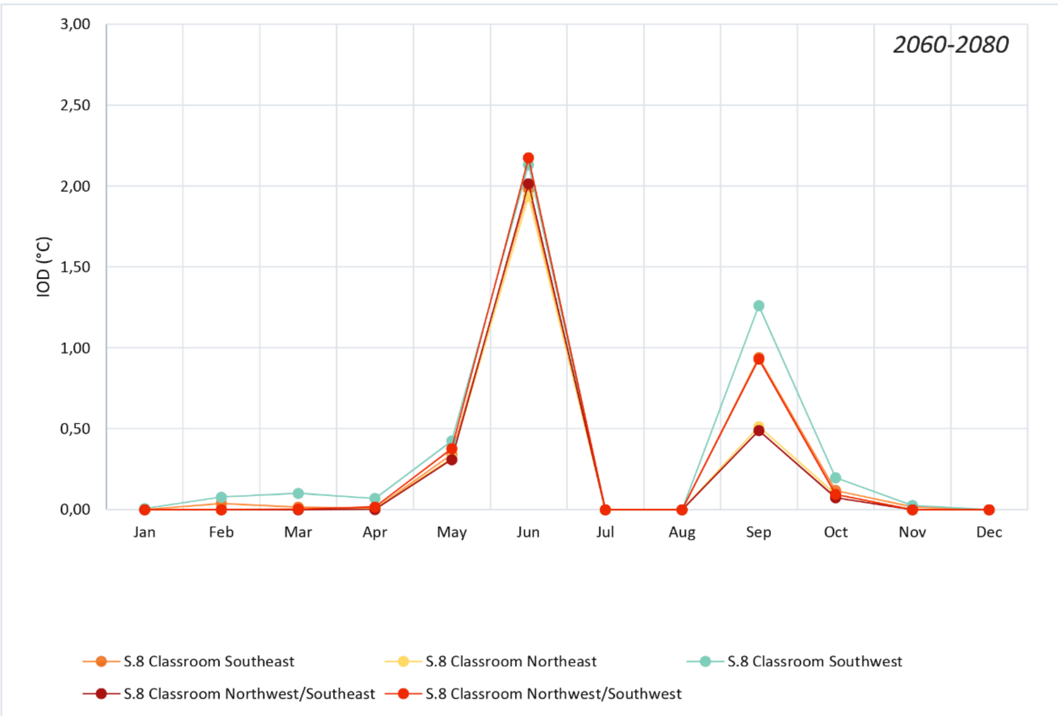
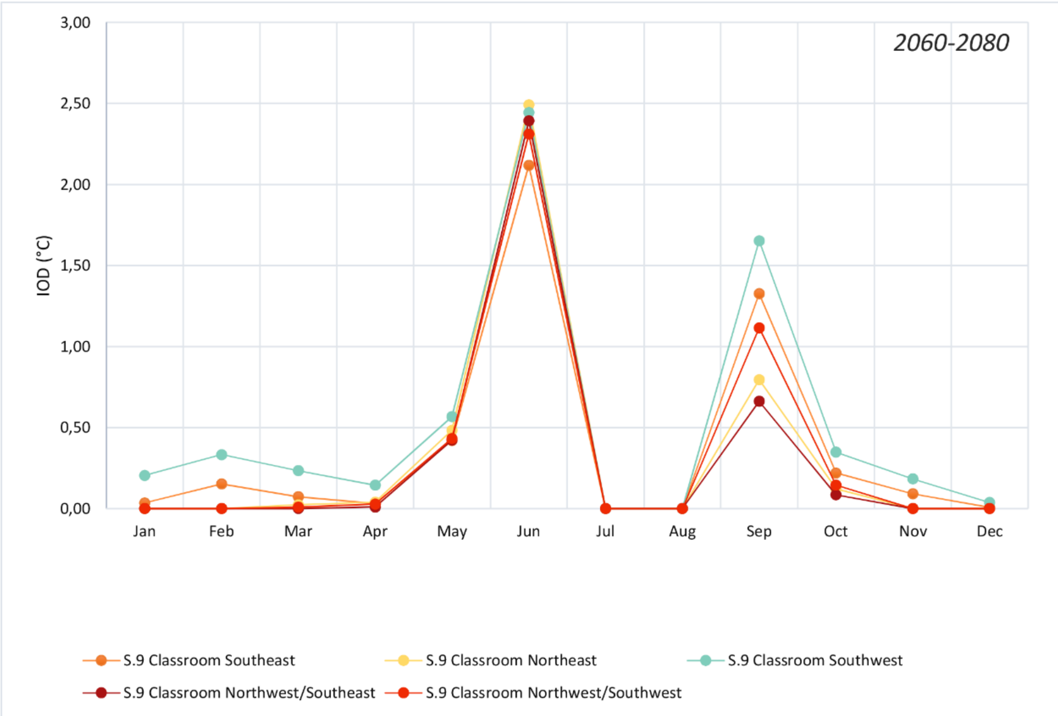


Figure 4.42. The annual solar gain for various façade configurations in the entire building

Heating demand is expected to decrease by reason of gaining more solar heat. However, conduction through glazing also rises, so the expected result for heating cannot be achieved. The S8 shows a larger increase in ΔQ_H because the sun shading elements block the sun in winter. Although it is tried to provide shade with frames, it is not enough to reduce excessive solar gain and more solar gain is observed in S.9. In parallel with the increase of solar gain, cooling demand shows a further increase in the same scenario. Moreover, the most striking result to emerge from the results is that IODs showed a reduction despite the increase in solar gain and cooling demand (Figure 4.43). In the same way as the intervention of shading elements addition, new configurations were applied only to the southwest-southeast-northeast facing windows, so classrooms facing only these facades were evaluated for IOD. As seen in graphs, the S.8 is more effective than the S.9 to reduce overheating risk because the sun shading elements in S.8 provide more sun blocking.



(a)

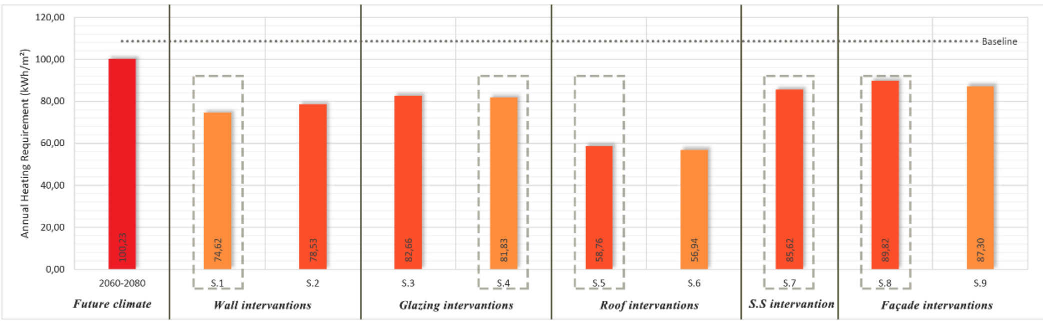


(b)

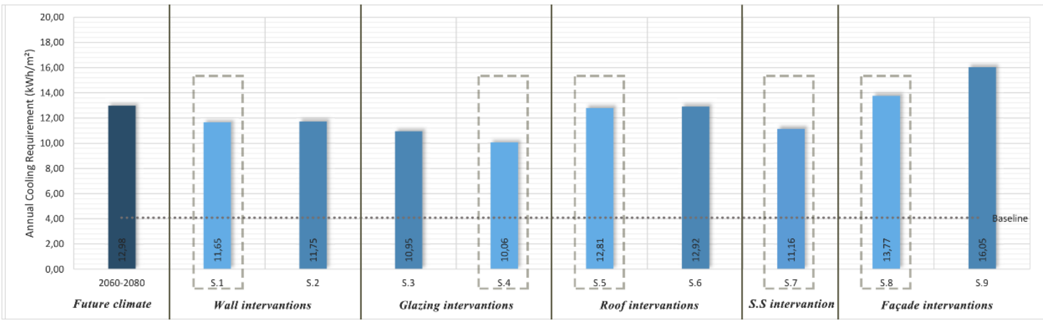
Figure 4.43. The IOD for classrooms for (a) S.8 and (b) S.9

4.4.2.4. The combination of the design strategies

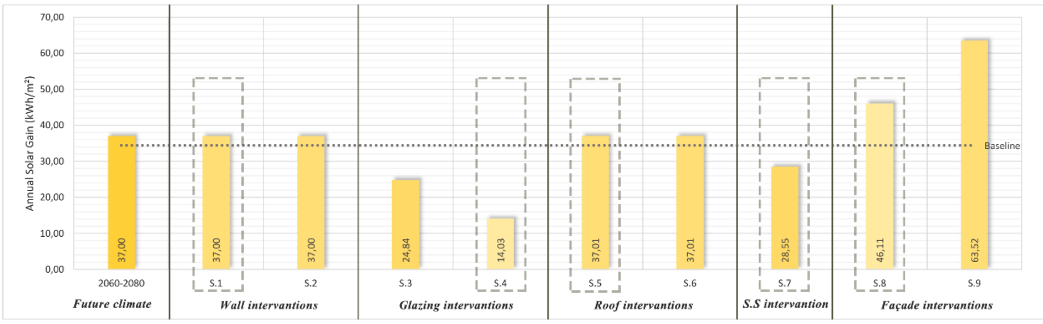
Mitigation and adaptation strategies as interventions that resulted in the most effective way on the performance of the building in future climate were combined together. the following figures summarize the energy criteria and IODs for all scenarios (Figure 4.44 and 4.45). According to these results, the combinations were identified, shown as in Table 4.14. These combinations were expected to produce higher improved performance.



(a)



(b)



(c)

Figure 4.44. The annual requirement (a) heating (b) cooling, and (c) solar gain for all the implemented intervention scenarios – Dash line indicates the selected scenario for combinations

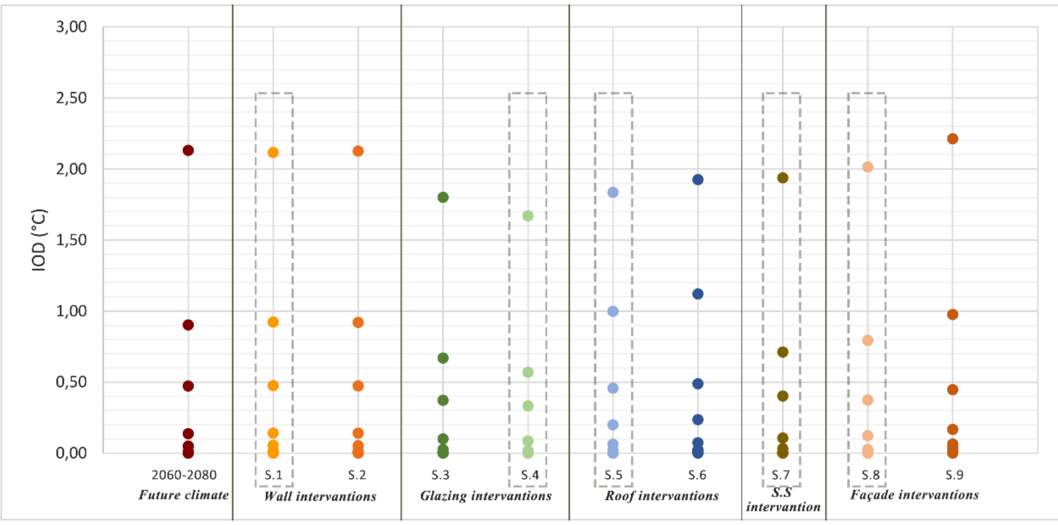


*Figure 4.45.*The monthly average IOD for all the implemented intervention scenarios – Dash line indicates the selected scenario for combinations

Table 4.14. *Detail of combined intervention scenarios*

Combined Intervention Scenario No	Combination Details
S.10	S.1 - adding thermal insulation on walls
	S.4 - solar control glazing-high
	S.5 - adding thermal insulation on roof
S.11	S.1 - adding thermal insulation on walls
	S.4 - solar control glazing-high
	S.5 - adding thermal insulation on roof
	S.7 - adding vertical fixed sunshade on the southwest and northeast-facing windows and overhangs above southeast-facing windows
S.12	S.1 - adding thermal insulation on walls
	S.4 - solar control glazing-high
	S.5 - adding thermal insulation on roof
	S.8 - change of facade configuration with vertical fixed sunshade on the southwest, southeast and northeast-facing window

Upgrading materials and components to be more efficient is a faster and cheaper approach to improving energy performance rather than deep intervention. For this reason, S.10 only covers intervention scenarios related to the materials. All criteria were evaluated and the materials with the most effective results were selected. Thermal comfort was determined as a priority criterion based on the results that can be seen in Figure 4.45. According to these, the addition of thermal insulation on both walls and roofs and the high quality solar control glazing were combined together.

As explained above, the intervention through the addition of sun shading elements gives a conflict results that although it reduces overheating risk, it causes the increase in heating demand. In scenario 11, shading elements are added to the S.10 to analyze the effects and interactions of these elements with improved material.

In the case of a façade or façade configuration changes, it is required to be accompanied by a quality window and/or glazing system, especially if the WWR is increased, as in this case. Therefore, the best material options and intervention through façade alteration were combined in S.12. In accordance with the individual performance results, the option with the sun shading was preferred among two different suggestions.

A significant decrease in the annual heating and cooling requirements, total solar gain, and IODs were achieved with all combined intervention scenarios, as illustrated in the following figures (Figure 4.46- 4.49). The decline values in ΔQ_H are 50.28-49.35, and 48.35 kWh/m2 (50.17-49.22 and 48.25%) for S.10, S.11, and S.12, respectively. 35.08-41.70, and 21.53 percent reductions in cooling demand were obtained as in same scenario order. The highest reduction rates were observed in solar gain that are 60.08-70.70, and 52.45 for S.10, S.11, and S.12.

Figure 4.46. The annual heating requirement for combined scenarios in the entire building

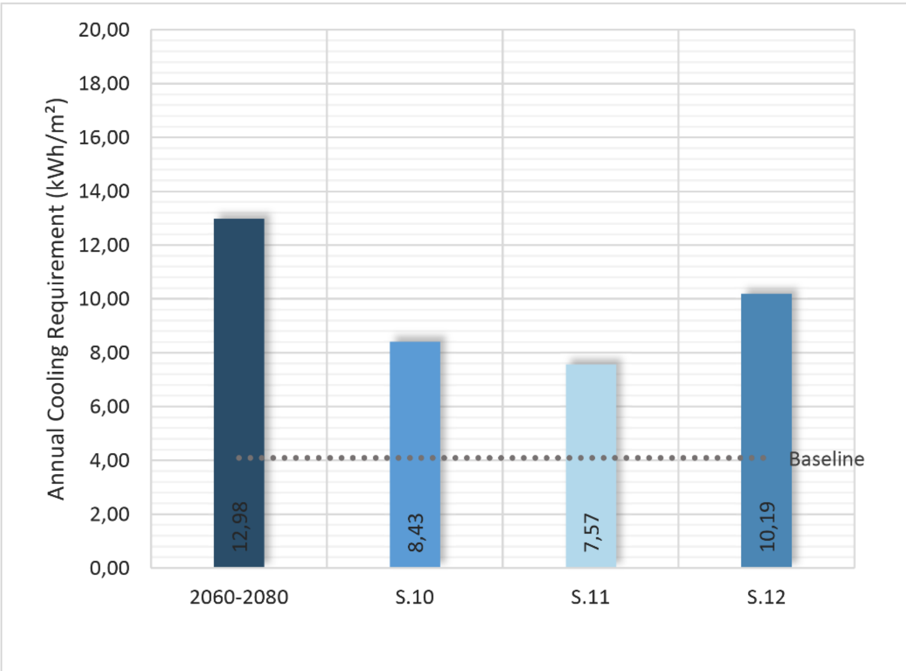


Figure 4.47. The annual cooling requirement for combined scenarios in the entire building

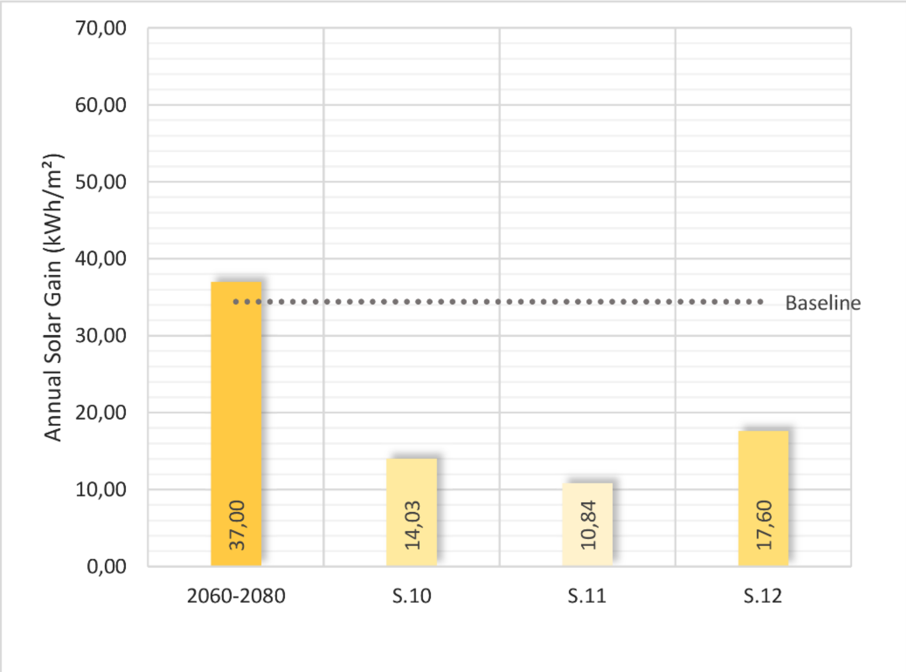
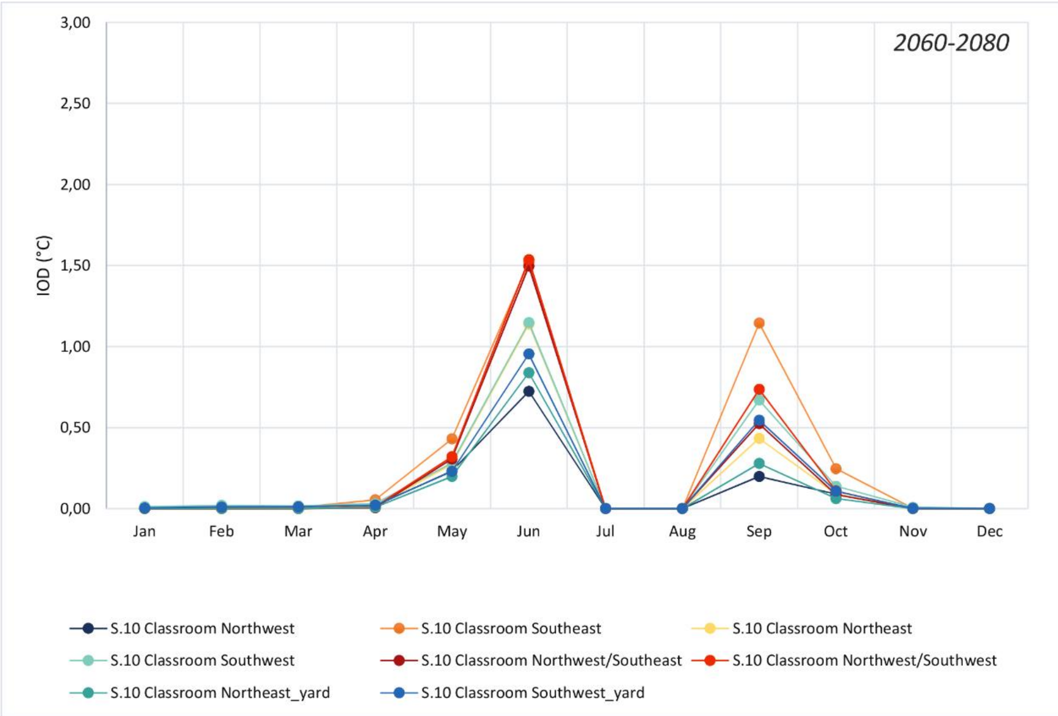
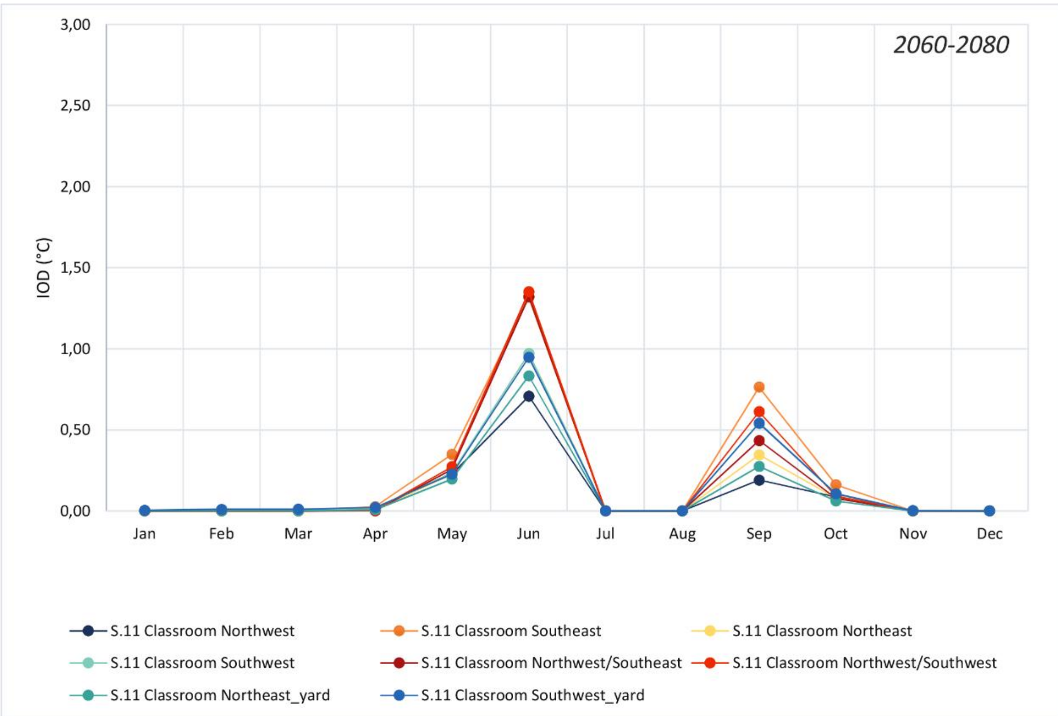


Figure 4.48. The annual solar gain for combined scenarios in the entire building

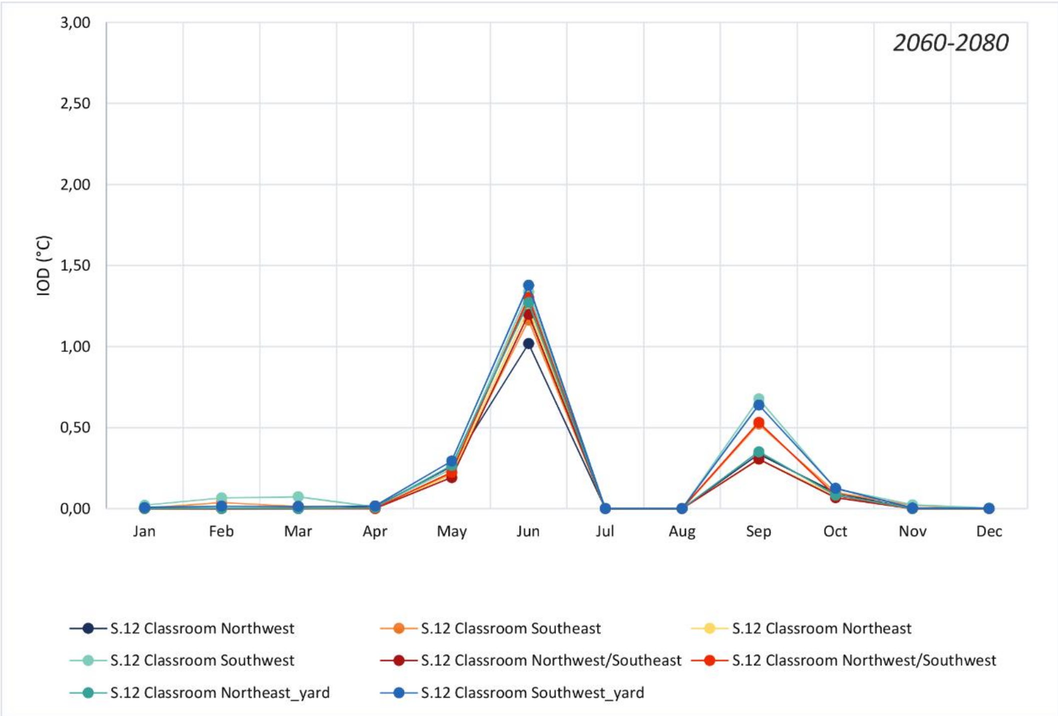
Indoor overheating degrees (IOD) of the selected zones before and after intervention are shown in Figure 4.49. The graphs reveal that the thermal performance of the school with these combined intervention scenarios was remarkably improved. The reductions of the IOD were obtained up to about 1.5 °C for all scenarios.


2060-2080
IOD (°C)
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
S.10 Classroom Northwest
S.10 Classroom Southeast
S.10 Classroom Northeast
S.10 Classroom Southwest
S.10 Classroom Northwest/Southeast
S.10 Classroom Northwest/Southwest
S.10 Classroom Northeast_yard
S.10 Classroom Southwest_yard

(a)


2060-2080
IOD (°C)
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
S.11 Classroom Northwest
S.11 Classroom Southeast
S.11 Classroom Northeast
S.11 Classroom Southwest
S.11 Classroom Northwest/Southeast
S.11 Classroom Northwest/Southwest
S.11 Classroom Northeast_yard
S.11 Classroom Southwest_yard

(b)



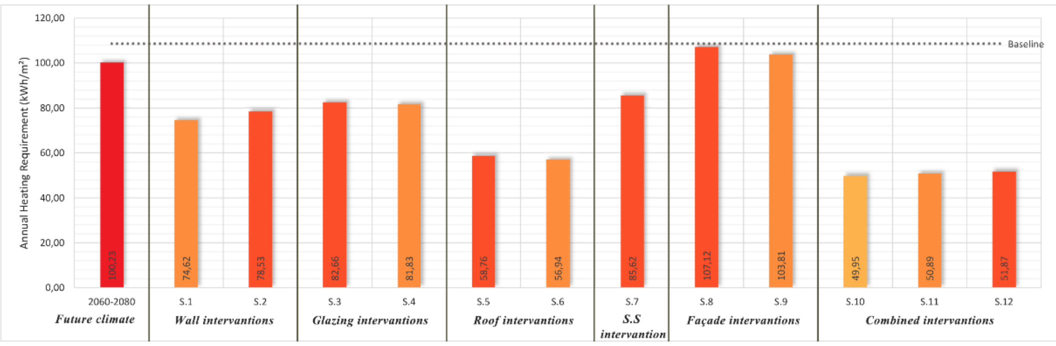
(c)

Figure 4.49. The IOD for classrooms: (a) S.10, (b) S.11, and (c) S.12

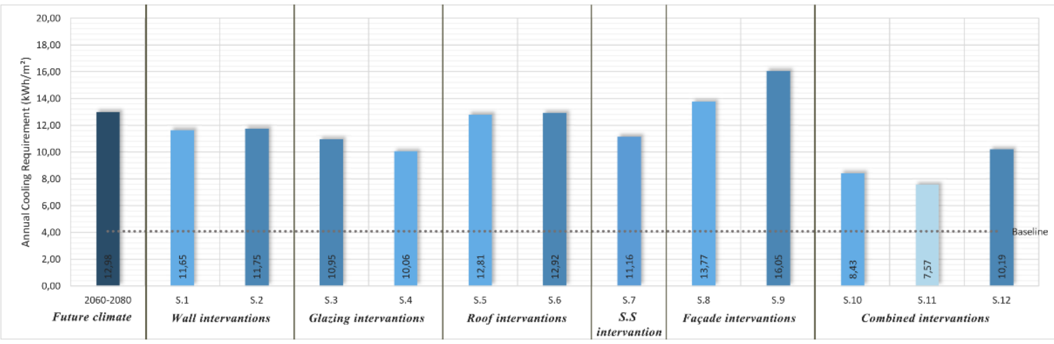
In summary, these results show that all combined interventions improve the condition of the building quite enough.

4.5. A comparative performance assessment of intervention scenarios

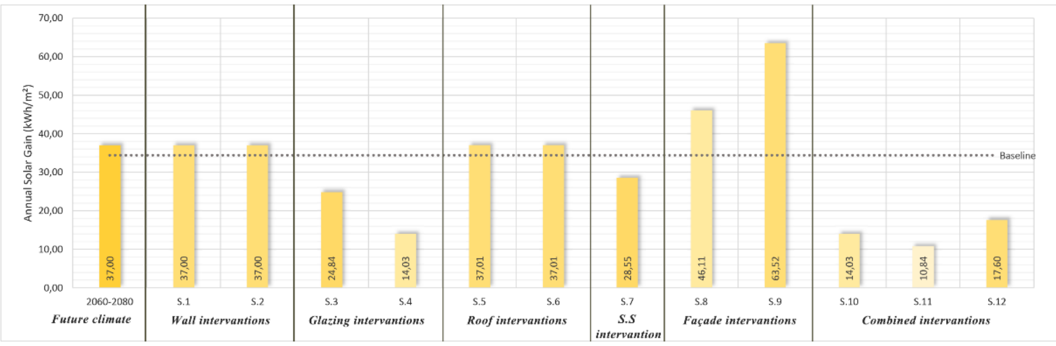
In this section, all implemented scenarios were compared and evaluated. In all cases, the improvement of energy and thermal performance was observed, except interventions related to façade configuration changes, shown as Figure 50 and Figure 51.



(a)



(b)



(c)

Figure 4.50. The annual requirement (a) heating (b) cooling, and (c) solar gain for all intervention scenarios

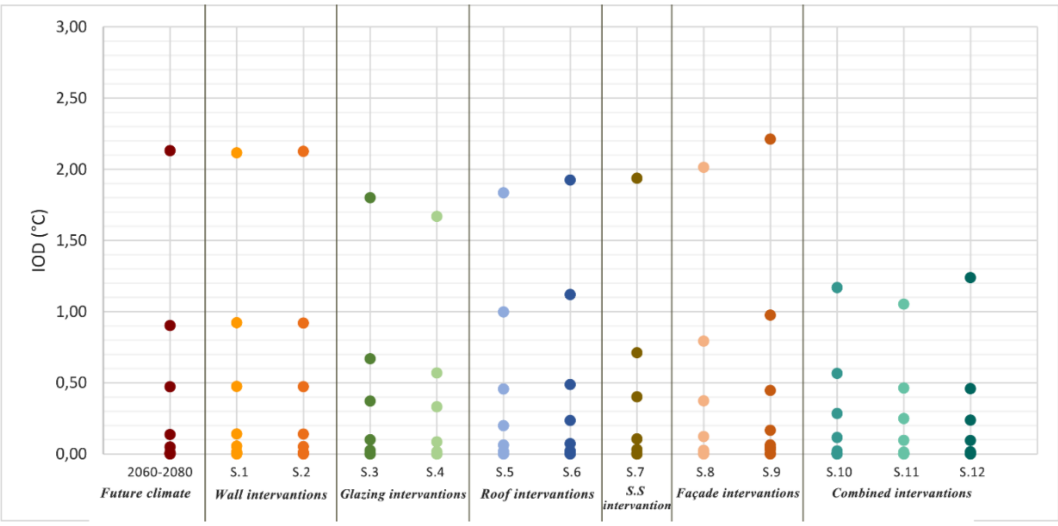


Figure 4.51. The monthly average IOD for all the implemented intervention scenarios

In the interventions through material replacement and external shading elements addition, the results are not promising compared to combined scenarios, as can be noticed in the graphs. Among the analysis by using OFAT, the best results both for energy use and thermal comfort are obtained from the scenario that the glazing performance is improved because these glazings provide efficient solar control without blocking the sun and thermal insulation. On the other hand, the most minimal changes are obtained by replacement of wall composition. The walls are uninsulated in the current situation but their thickness could provide sufficient insulation. This leads to not to achieve effective results through these interventions. Moreover, the intervention through sun shading elements addition results in a confliction between energy and thermal criteria. They reduce cooling requirement and the overheating risk due to blocking the sun but they cause an increase in heating demand.

The large window formats with sun shading elements and shelf-like frames are suggested in the intervention through façade changes. Windows are generally considered as the significant element to be correctly designed energy efficiency and comfort purposes in view of the role they play in heat exchange and solar gain processes. The findings obtained from the interventions are consistent with that of this fact. As the window area increases, heat loss increases in winter and heat gain in summer by conduction through glazing, resulting in an uncontrollable solar gain in this research. Thus, the building performs poorly and no improvement in energy and thermal performance can be achieved. However, windows have impacts on the building's heating, cooling, and lighting, as well as relating it to the natural environment in terms of access to daylight, ventilation, and views. These issues are out of scope in the thesis but it is possible that the increase in window areas provides better daylighting, natural ventilation and views.

Interventions that resulted in positive effects on the energy and thermal conditions of the building are combined together. These combinations are expected to produce higher improved performances. The IODs and requirement of heating and cooling are effectively reduced when the combinations are implemented. The largest reduction in all performance criteria is observed in S.10 that combines just improved materials for building envelope. The smallest reduction is observed in S.12 that combine new façade and improved materials with fixed sun shading elements. These results show that the combined method is more influential to provide a balance between energy performance and thermal comfort under future climatic conditions.

As a result of these improvements and analyses, although inconsistencies and conflicts are observed, this research indicates that passive design techniques through simulation model offer a viable solution to reduce energy consumption, enhance thermal comfort of the school building and help mitigate the impact of climate change and thus contribute to climate change resilience in the global and local climate.

CHAPTER 5

DISCUSSION

In this chapter, the results of the case study are discussed to propose a design guideline or method by using the proposed framework and provide an insight into the building performance within the scope of climate change mitigation and/or adaptation. The main goal of the current study was to determine the interrelationship between the design variables associated with climate change, the UHI, and building performance.

This thesis particularly concentrated on the existing educational buildings due to their high energy consumption, the higher sensitivity and vulnerability capacities of the students to climate change, and the determinative role of indoor conditions in performance, productivity, attendance, and health of students and also teachers. The impacts of climate change on the energy and thermal performance of the building are quantified by using computational methods and simulation tools. The analyses are conducted in three categories: 1) Climate 2) Performance 3) Intervention. The discussion is pursued according to the findings of these categories in the following sections.

5.1. Climate

The relationship between climate and architecture is evident and the position of architecture and architects in climate change is highlighted in previous sections. When a design approach based on climate and climate change is adopted by using simulation tools, firstly, climate analysis needs to be conducted correctly.

In this study, firstly, the future data and the UHI effects are generated. After the generations, the baseline year weather, generated future weather, and their modified data with UHI of Ankara are compared by using five different variables; monthly minimum, average, and maximum mean outdoor dry bulb temperature, heating degree days (HDD), and cooling degree days (CDD). As remarked in Section 4.3.3, the temperature tends to an increasing trend and the maximal changes are observed in the results of future weather data under the RCP8.5 emission scenario for all variables, as expected. The annual temperature increases 2.41–3.46 °C under the RCP4.5 and RCP8.5 scenarios respectively. The UHI causes a temperature shift of approximately 1-6 °C (min-max) in all weather data for selected building context. With warming temperature, HDD is to decrease by 550-700 °C-days while CDD is to increase by 134-288 °C-days.

These findings in this study broadly support the work of other studies in this area (e.g. Şen, 2013; Cities of the future, 2019). In Şen's report (2013), it is predicted that temperatures in Ankara will increase throughout the year and will be drier in the spring and summer for the period 2071-2099. The temperature rise in summer will be much higher than in winter (Şen, 2013). The research of "cities of the future" conducted in the Crowther Laboratory (2019) shows that the annual temperature of Ankara will increase 2.9°C in 2050 (Cities of the future, 2019).

If the global temperature rose beyond 1.5°C, the consequences would be devastating and according to the results of this study, the temperature of Ankara will rise far above the 1.5°C. Therefore, these findings and the previous research help to understand the climate change impacts on temperature and the urgency of this issue.

5.2. Performance

A comprehensive evaluation of energy use and thermal comfort between the baseline year and the 2060-2080 projection is conducted. Primary data is obtained through modeling and simulation according to heating, cooling, total energy requirements, total solar gain, and indoor overheating degree (IOD). As a result of increased temperature, cooling requirement and total solar gain are expected to increase while heating and total energy requirement are expected to decrease in the future.

Many of zones in the building provide cooling with natural ventilation, only 24 of the building's 119 rooms have air-conditioning, resulting in a minimal increase in cooling requirements. Moreover, warming temperature and increasing total solar gain reduce the requirement for heating. As a consequence of these, the total energy requirement is on the decline of 13.83%. The use of much less energy for heating in the climate of Ankara and the decrease in total energy consumption may be perceived as a positive result, but the increase in temperature and solar gain in spring and summer affects the thermal comfort negatively and dramatically. As expected, for the zones with air-conditioning, negligible IOD values are obtained. However, in the classrooms, students experience significantly higher overheating risk. As stated several times, thermal discomfort negatively affects health, performance, and productivity. In order to prevent these kinds of consequences, the demand for air-conditioning is predicted to increase in the future if an improvement in building thermal performance is not achieved. This implies that a considerable amount of energy consumption and CO_2 emissions is expected to rise. Thus, these comparative analyses provide to understand how the changing climate affects the energy and thermal performance of the building.

5.3. Interventions

In accordance with the analysis of climate and performance, the number of intervention scenarios is determined by adopting passive design techniques. They are classified into 3 main categories: intervention through material replacement, through external sun shading elements addition, and through a façade configuration change. The simulation results show that passive design strategies could decrease energy consumption and enhance thermal comfort but sometimes they could conflict with each other. To be able to obtain better results and to prevent conflicts, scenarios with the positive results are combined.

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In the interventions through material replacement, when evaluated individually, the results are not effective to provide better thermal comfort inside the building and reducing energy consumption in this study, as stated in Section 4.5. However, when the materials that give better results are combined together, the improvement of the case building performance is achieved. In line with these findings, the impact of the materials on buildings performance is undeniable. Each material offers distinctive characteristics and attributes in terms of energy and thermal performance of buildings while at the same time, presenting an envelope of constraints in terms of shape, property characteristics, and processing capabilities. In addition, the whole life cycle of buildings depends on materials and for this reason, it is an essential step of the architectural design for climate change that thermal properties, the durability, recyclability, and environmental impacts of the materials are needed to be defined and evaluated. Therefore, taking into account all of these, it is possible to improve the performance of the building and to discover new design possibilities by including materials selection in the design process.

In the intervention through fixed external shading elements addition, the results by using OFAT are observed to decrease for cooling, solar gain, and IOD but the results for heating are not satisfactory due to blocking the sun, as explained previously. However, when the shading elements are implemented together with intervention through material replacements, it is noticed that the sun shading elements play a significant role to improve the performance of the building. In accordance with the results of this study, the use of sun shading elements or devices is an efficient way to control the sun, to reduce energy consumption, and to provide a comfortable environment inside of buildings. In other words, it is possible to greatly reduce the impacts of climate change and the need for mechanical heating and cooling by controlling heat gain through openings with the proper design of sun shading considering the orientation of openings, seasonal variation in the sun path and changing climatic conditions.

Finally, the results for the intervention through façade configuration changes show that the goals of reducing energy requirements and improving thermal comfort are not accomplished in this study. However, when the façade change with proposed sun shading elements are combined with improved envelope materials, the results are promising. As stated before, the façade configuration change is categorized as deep intervention. The performance and environmental impacts of buildings can progressed much more with deep interventions that offer more possibilities both in terms of addressing the problems of buildings and architectural design.

As it is seen in this study, the interventions applied by using one factor at a time method do not give much beneficial results in terms of the improvement of building performance and mitigating impacts on climate change. But when the intervention scenarios are combined in the right ways, energy requirement decreases up to 70% and overheating risk decreases up to 1.5°C. In line with these, unique combinations of intervention scenarios are required for each building, depending on the individual requirements of the building. Therefore, it is critical to fully understand problematic parts of the building performance and its systems and to solve these problems with design approaches that focus on climate and climate change.

In light of the whole analysis processes, firstly, the effects of climate change and the UHI effect on the Ankara climate were determined by the analyses. It is supported that climate change is a critical, vital and urgent problem by the findings. It has been clearly established that existing designs have already started to perform poorly and they will not perform effectively in the future. It was supported by the results obtained from a simulation model that architecture should take responsibility in this regard. In line with these, it is concluded that architectural design needs a new approach including the role of the built and natural environments, weather, climate, and human activity, behavior, and needs for both newly designed and existing buildings.

In recent years, buildings with the same typology have been designed and constructed in similar ways. The studies show that 57 percent of architects copy and paste the specifications of projects from a previous one (Murray, 2019). There is a widespread artificial understanding of contemporary architecture based on façade with large and plenty of windows, aesthetic concerns being at the forefront, and loss of importance of all other architectural elements in the face of form searching. These similarly designed buildings perform poorly in similar ways such as problems in overheating, cooling, and ventilation and so on. The solutions used to deal with these problems contribute to carbon emissions again and thus, the interaction between climate change and the building goes round in circles. In order to be able to avoid this feedback loop, the architectural design and architectural profession need to be reconsidered its value systems, what is considered good and what bad, in a radical and critical way. In other words, the architectural design requires a paradigm shift, a new approach. This new design approach should not be perceived as just a technical fix, photovoltaic insertion or finding the most accurate the HVAC method. Impacts and problems of local climate and the changing climate on buildings are generally tried to be solved with engineering solutions after the design process is completed. In point of fact, it should rather be integrated into architecture and be one of the fundamental elements of the design. All components of a building included form, function, material, façade elements, thermal, visual, and acoustic comfort, indoor air quality, and all systems should be considered holistically in the early design stage and the contribution of the built environment to climate change should be reduced to a minimum. It is necessary to be realized that the activities of architecture today are all about the future. The designers need to understand the dimension of time and how it affects the design components in the context of climate change mitigation and adaptation. The proposed method in this study can create insight to designers on this issue. Although the method is proposed in the framework of various intervention scenarios for an existing building, it is applicable for various design proposals in the early stage of the design process. It can contribute to the assessment of the design alternatives under the current and future climatic conditions and to determine the best option or options to balance between comfort, energy requirements, predicted climate conditions, and contextual situations. Furthermore, the change in the performance of the building can be monitored over a lifetime of building with this method.

As mentioned earlier, newly designed buildings that constitute 1-3% are not enough to deal with the climate change crisis. The existing building stock must be mitigated and adapted. The method proposed in this study can be a guide in this subject. Unlike the other methods explained in the literature review, this method aims to reach the most accurate climate data by incorporating the UHI effect and it is very important to work with the accurate data in order to reach to the point and accurate solutions in this climate change mitigation and adaptation process. In the proposed method, the most important step is to identify the problems by collecting detailed information about the building and analyzing the performance of the building with the most accurate climate data. When problems are correctly identified, it is possible to identify and implement the interventions in an easy and quick way. In addition to these, the general recommendations in the literature and in practice do not show the expected impacts at any time. As an example, common design knowledge indicates that the sun shading prevents the heat gain during hot weather and greatly reduce the need for mechanical heating and cooling to maintain thermal comfort inside buildings, by controlling heat gain through openings. In this study, however, when the fixed sun shading elements has applied the model, heating demand results in an increase and they do not provide efficient thermal comfort inside the school. However, in the combined intervention scenario, they play a significant role to reduce overheating risk. This implies that the design variables exhibit very complex and dynamic interactions and nonlinear effects on the performance of a building.

In the context of climate change mitigation and adaptation, the intervention and design approach need to be unique for each building due to two reasons. The first reason is that although impacts of climate change have started to be observed all around the world, it affects every region, every country and every city in different ways depending on climate, density, industrial activities, land use, and so on. Secondly, factors included the typology, orientation, geometry, envelope shape, contextual elements, and user profile cause various specific problems in the building systems. In order to achieve the most effective results, the design process needs to be fully addressed to these problems. The proposed method allows a unique approach to each building to be adopted.

In conclusion, the proposed framework can be a guide to understand and analyze the interaction between design variables and to develop the most effective design approach in terms of building energy use and thermal comfort.

CHAPTER 6

CONCLUSION

Within the scope of the thesis, it is mainly aimed to develop a framework of the design process can help architects during the design processes of climate change adaptation and mitigation of existing buildings. This research is based on a systematic methodology that is underpinned by building performance analysis through quantitative simulation. The concepts of climate change, urban heat island effect, and building performance are explored in architectural design by means of energy simulation tools and methods. A viable design method that can support design activities for climate change adaptation and mitigation in existing buildings is investigated and based on the findings whole research processes and discussion, the following conclusions have been reached:

- The climate and architecture are always in a complex interaction and in a dynamic dialogue with the changing climate, re-establishing the dialogue of architecture with the climate is a necessity.
- Existing building performance need to be addressed carefully, taking into account adaptations in human perception of thermal comfort/discomfort.
- The interventions play an important role in ensuring building performance in the long term and thus have a significant impact on the adaptation of buildings to climate change.
- The design variables exhibit very complex and dynamic interactions and nonlinear effects on the performance of a building. It is not possible to determine the ‘best' design solution without gathering the essential information and analyzing the performance.
- In the context of climate change mitigation and adaptation, the intervention and design approach need to be unique for each building.

- There is a need to conduct more climate change impact studies, to cover a wider range of building types, configurations and systems and further climate scenarios for additional locations.

As a conclusion, rethinking the design, construction, and operation of buildings in order to mitigate climate change and increase resilience toward its effects is needed to be the most important issue in architectural agenda. Architecture must change with the climate and must change now.

Limitations and further studies

This thesis focused only on the building scale and the framework based on the mitigation and adaptation of building performance was developed. The improvement of microclimatic conditions in urban areas can play a fundamental role to mitigate the combined effects of climate change and UHI effects and to improve buildings' performance. Urban design strategies for climate adaptation measure such as solar control, green and blue infrastructure, natural ventilation, and replacement or selection of cool urban materials and their impacts on buildings' performance can be investigated in future studies.

The proposed framework in this research does not include active design techniques. Passive techniques, however, alone cannot be always sufficient to achieve the goal of building performance improvement and a combination with active techniques can be required. Moreover, in the majority of educational buildings, it might not be very practicable to rely only on passive strategies. Consequently, the measures included both active and passive strategies can be explored in the next researches. Furthermore, the role of building materials and sun shading elements were examined in a limited vision. Some common materials, sun shading and their impact analysis on building performance were investigated. In practice, they can play a greater role in governing the quality of indoor environments and energy consumption and also in the reduction of environmental impacts of a building. More detailed material and sun shading varieties can be researched in further studies.

The proposed method does not include the model calibration. Calibrated energy performance models enable a baseline representation of existing building performance patterns, accuracy in identification of problematic zones, operation, and energy conservation measures. A calibration study can be carried out in further studies in order to facilitate performance predictions with high accuracy.

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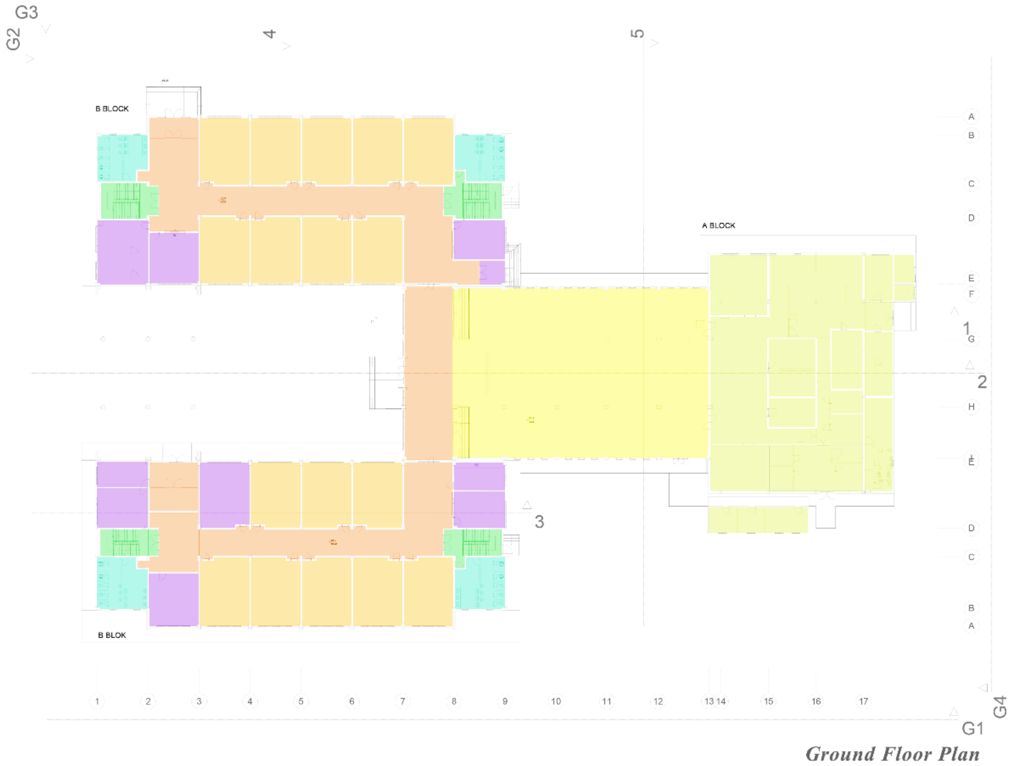
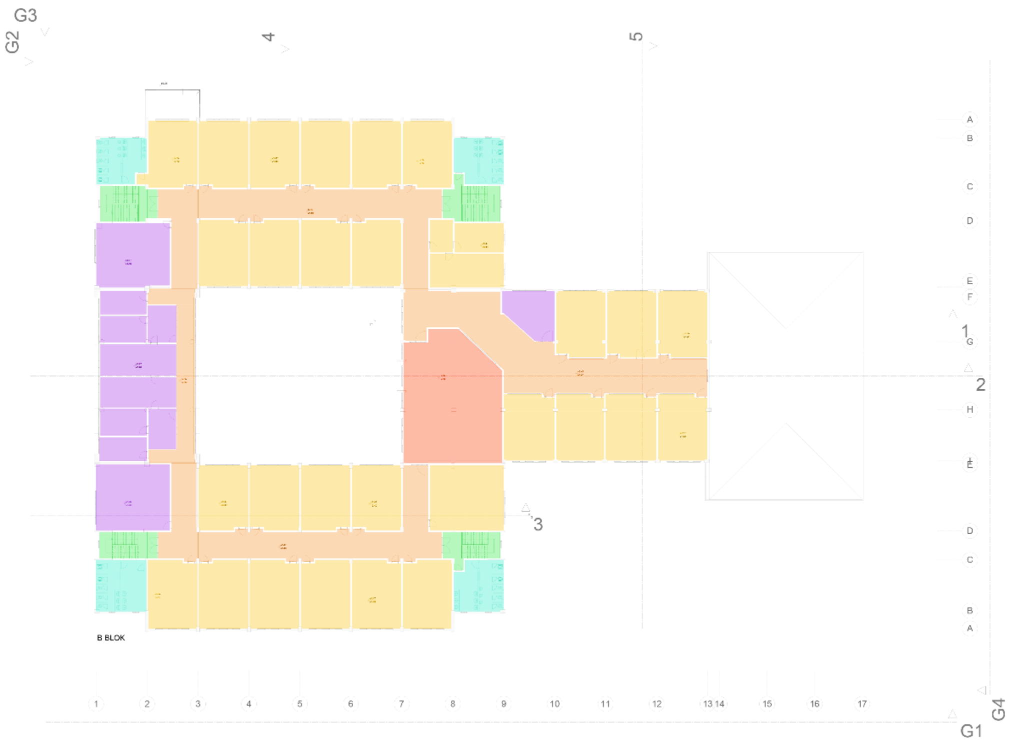
APPENDICES

A. DETAILS OF THE CASE BUILDING

I. The Floor Plan Drawings

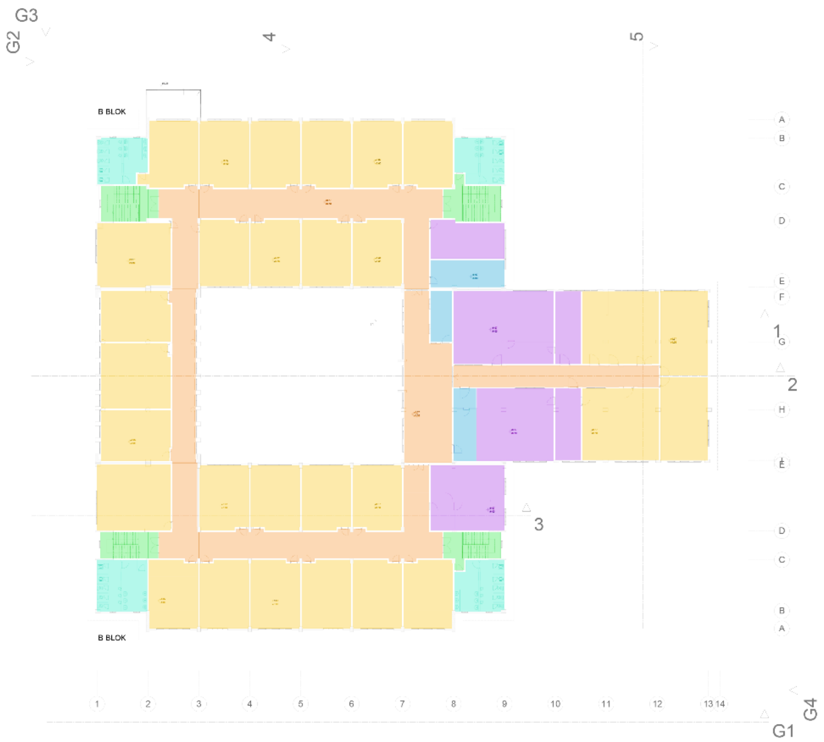


: Classroom : Office and Teachers' room : Cafeteria : Kitchen : Library : WC : Corridor : Staircase



First Floor Plan

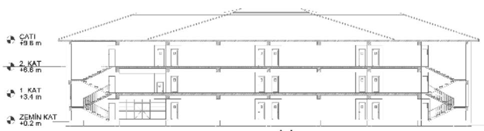
: Classroom : Office and Teachers' room : Cafeteria : Kitchen : Library : WC : Corridor : Staircase



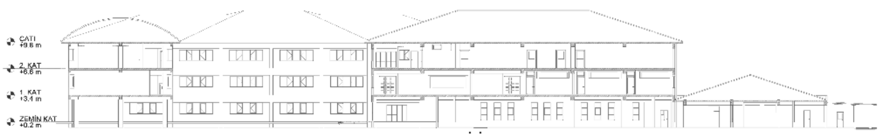
Second Floor Plan

: Classroom : Office and Teachers' room : Cafeteria : Kitchen : Library : WC : Corridor : Staircase

II. The Section Drawings



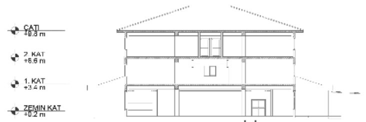
1-1 KESİTİ



2-2 KESİTİ

3-3 KESİTİ

4-4 KESİTİ



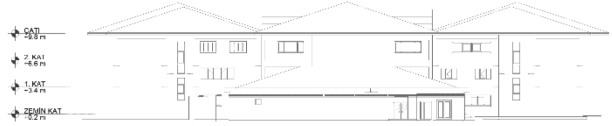
5-5 KESİTİ

III. The Elevation Drawings

G1-G1 GÖRÜNÜŞÜ- Ö:1/100

G2-G2 GÖRÜNÜŞÜ - Ö:1/100

G3-G3 GÖRÜNÜŞÜ - Ö:1/100



G4-G4 GÖRÜNÜŞÜ - Ö:1/100

The Table of Zone Information*

Zone_ID	Zone_type	Orientation	Zone_floor	Zone area	Air-conditioned	Occupant number
Z1	Classroom	Northwest	First	261,19	No	24
Z2	Classroom	Northwest	First	255,04	No	24
Z3	Classroom	Southeast	First	250,12	No	24
Z4	Classroom	Southeast	Second	562,54	No	72
Z5	Classroom	Northeast	Ground	757,74	No	120
Z6	Classroom	Northeast	First	757,75	No	120
Z7	Classroom	Northeast	First	595,82	No	96
Z8	Classroom	Northeast	Second	897,54	No	144
Z9	Classroom	Northeast	Second	345,84	No	24
Z10	Classroom	Northeast	Second	283,18	No	24
Z11	Classroom	Southwest	Ground	717,66	No	120
Z12	Classroom	Southwest	First	849,23	No	144
Z13	Classroom	Southwest	First	192,9	No	24
Z14	Classroom	Southwest	First	191,76	No	24
Z15	Classroom	Southwest	Second	713,3	No	120
Z16	Classroom	Southwest	Second	353,74	No	24
Z17	Classroom	Southwest	Second	280,84	No	24
Z18	Classroom	Northeast/Southeast	Second	218,48	No	24
Z19	Classroom	Northeast/Southewest	Second	218,48	No	24
Z20	Classroom	Northeast_yard	Ground	580,12	No	96
Z21	Classroom	Northeast_yard	First	573,52	No	96
Z22	Classroom	Northeast_yard	Second	181,92	No	24
Z23	Classroom	Northeast_yard	Second	311,72	No	48
Z24	Classroom	Southwest_yard	Ground	593,77	No	96
Z25	Classroom	Southwest_yard	First	587,02	No	96
Z26	Classroom	Southwest_yard	Second	587,02	No	96
Z27	Classroom	Southeast	Second	258,73	No	24
Z28	Classroom	Southeast	Second	252,58	No	24
Z29	Office	Northwest	Ground	131,1	Yes	1
Z30	Office	Northwest	Ground	192,5	Yes	2
Z31	Office	Southeast	Ground	184,12	Yes	1
Z32	Office	Southeast	Ground	188,77	Yes	2
Z33	Office	Southeast	First	567,45	Yes	7
Z34	Office	Northeast	Ground	158	Yes	1
Z35	Office	Northeast	First	193,88	Yes	1
Z36	Office	Southewest	First	128,32	Yes	1
Z37	Office	Southewest	First	183,82	Yes	1
Z38	Office	Southewest	Second	186,15	Yes	1
Z39	Office	Northeast_yard	Ground	153,72	Yes	1
Z40	Teacher's Room	Northwest	Second	170,15	Yes	15
Z41	Teacher's Room	Northwest	Second	261,2	Yes	17
Z42	Teacher's Room	Southeast	First	256,25	Yes	15
Z43	Teacher's Room	Northeast	Second	133,75	Yes	15
Z44	Teacher's Room	Southewest	Second	135,05	Yes	15
Z45	Teacher's Room	Northeast_yard	Second	179,72	Yes	17

*This table includes only examined zones that are classrooms, offices, and teachers' room. The other zones were excluded from the table.

B. CRITERIONS OF SIMULATION TOOL SELECTION

In this study, *Ladybug Tools* are used. They are collection of open source computer applications that include Ladybug, Honeybee, Dragonfly, and Butterfly. Furthermore, these software are plugins for Rhino/Grasshopper to support designers to create an environmentally conscious architectural design in practice and education. In point of fact, there are a number of environmental plugins such as Diva, Geco, Gerilla, and Heliotrope developed for Grasshopper used in this study. Besides all the factors mentioned above, among all the accessible software packages related to environmental design, Ladybug is the most compact and satisfying tool that meets the requirements for a 3D Computer-Aided Design (CAD) engine (Roudsari, 2013) (Table B.1).

Table B.1. *Comparison of the existing environmental analysis tools for Rhino/Grasshopper*

PROCESSES		ANALYSIS TOOLS				
		Ladybug	Heliotrope	Geco	Gerilla	Diva
Climate Analysis	Analysis	✓				
	Visualization	✓	✓			
Massing/Orientation Study		✓		✓		✓
Daylight Study		✓		✓		✓
Energy Modelling		✓			✓	✓

The reasoning criterion for the selection of the Ladybug Tools as the main modeling tool, depend on the features and distinctive characteristics of the software, which can be listed as;

- Being architect-friendly; in the mean of graphical user interface,
- Having a complete simulation and feedback work with few inputs,
- Ability to support parametric analysis,
- Having support for the comparison of multiple alternatives,
- Inoperability of building modeling,
- Capability of assumption and limitations for the model,

- Being an open source tool for easy access,
- Having specific requirements for in-situ data,
- Compatibility with other tools; Excel and etc.,
- Giving the results in a form that is open for manipulating or processing via various tools; Excel, MATLAB and etc.,
- Compatibility with databases and other models for pre and post-processes.