

**THE REPUBLIC OF TURKEY
BAHCESEHIR UNIVERSITY**

**AN APPROACH FOR THE INTEGRATION OF ADAPTIVE
FACADE SYSTEMS TO IMPROVE ENERGY
EFFICIENCY AND INDOOR COMFORT CONDITIONS: A
DORMITORY ROOM CASE STUDY**

Master's Thesis

SONA MUHAMMEDOVA

İSTANBUL, 2019

**THE REPUBLIC OF TURKEY
BAHCESEHIR UNIVERSITY**

**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
ARCHITECTURE**

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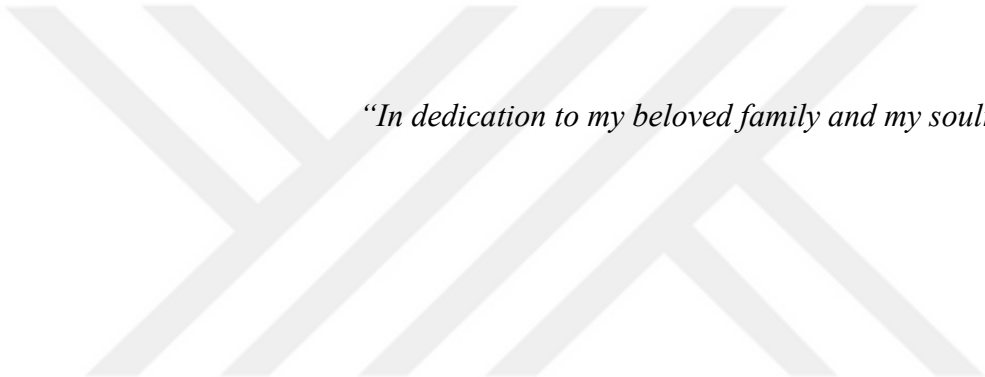
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“In dedication to my beloved family and my soulmate Mergen”

ABSTRACT

AN APPROACH FOR THE INTEGRATION OF ADAPTIVE FAÇADE SYSTEMS TO IMPROVE ENERGY EFFICIENCY AND INDOOR COMFORT CONDITIONS: A DORMITORY ROOM CASE STUDY

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The building sector ranked third place in consuming fossil energy the first and second place belongs to the agriculture and industry, energy demand is rising dramatically. For instance, according to statistics in Europe, energy expended in buildings is about 40-45% of total energy consumption. Another important reason to reduce energy consumption is related to climate issues since buildings are responsible for a huge proportion of carbon dioxide emissions due to energy use. Awareness of the above mentioned led to a considerable amount of studies, solutions are needed to curtail reducing energy consumption in buildings in order to preserve natural resources and ecological stability.

The combination of nature and technology always introduces a variety of innovative concepts to serve human beings. Building performance standards depend on a wide range of individual operational processes and also on how they behave as a consistent system to meet the needs of the inhabitants. Since most of the people living in urban areas are spending more than 90% of their time in indoor spaces, thus architects and engineers have placed emphasis not only on sustainability criteria's in buildings but also on improvements of indoor comfort conditions.

There is no doubt that the designing process of energy efficient and environmentally friendly building based on different factors need to be elaborately considered, such as orientation, materials and climate conditions of the region, thermal comfort and security levels of occupants. However, building façade plays a significant role in this process, it is a barrier between the internal space and the outside climate and has a big impact on indoor comfort quality and energy expenditure of the building.

Based on a compromise between energy efficiency and indoor comfort Adaptive Facade Systems are the best novel concept in the market, due to their capability to accommodate to inside and outside climate conditions. Moreover, this changeable behavior of adaptive facade works in tandem with intelligent controls that follow feedback from the environment. Natural resources such as solar and wind energy, daylight, water, can be used and reused by buildings efficiently since they are modulated by technological inputs.

This study will discuss the strategies and parameters in order to improve energy efficiency and indoor comfort level of buildings. The background and the concept of adaptive facades will be explored according to their types and design characteristics. The paper will analyze case study existing buildings with adaptive facades and their effect on indoor comfort quality. Finally, the paper aims to investigate how to improve energy performance and indoor comfort of a base case building through the application of adaptive facade systems.

Keywords: Energy Efficiency; Climate; Indoor Comfort; Adaptive Facade Systems



ÖZET

ENERJİ VERİMLİLİĞİ VE İÇ MEKAN KONFOR KOŞULLARINI GELİŞTİRMEK İÇİN UYARLANABİLİR CEPHE SİSTEMLERİNİN ENTEGRASYONU İÇİN BİR YAKLAŞIM: YURT ODASI VAKA ÇALIŞMASI

Sona MUHAMMEDOVA

Mimarlık

Dr. Öğr. Üyesi Yiğit YILMAZ

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Fosil enerji tüketiminde tarım ve sanayi sektörü birinci ve ikinci sırada yer alırken, üçüncü sırada yer alan yapı sektöründe enerji talebi önemli ölçüde artıyor. Örneğin, Avrupa'daki istatistiklere göre, binalarda harcanan enerji, toplam enerji tüketiminin yaklaşık %40-45'i kadardır. Binaların enerji kullanımı nedeniyle karbondioksit salınımında büyük oranda payı olmasından dolayı oluşan iklim sorunları, enerji tüketimini azaltmaktaki bir diğer önemli unsurdur. Doğal kaynakları ve ekolojik istikrarı korumak adına binalarda enerji tüketimini azaltmak için çözümler gerekmektedir.

Kentsel alanlarda yaşayan insanların çoğu zamanlarının %90'ından fazlasını kapalı alanlarda harcadığından, mimarlar ve mühendisler sadece binalarda sürdürülebilirlik kriterlerine değil, aynı zamanda iç mekan konfor koşullarının geliştirilmesine de önem vermişlerdir.

Çeşitli etkenlere dayanan enerji tasarruflu ve çevre dostu bina tasarım sürecinde, oryantasyon, malzemeler, bölgenin iklim koşulları ve bölge sakinlerinin ısı konfor ve güvenlik düzeyleri gibi durumların da özenle dikkate alınması gerektiğine şüphe yoktur. Bununla birlikte, bina cephesi bu süreçte önemli bir rol oynamaktadır, iç mekan ile dış iklim arasında bir bariyerdir ve binanın iç mekan konfor kalitesi ve enerji harcaması üzerinde büyük bir etkiye sahiptir. Enerji verimliliği ve iç mekan konforu arasındaki uzlaşmaya dayanarak Uyarlanabilir Cephe Sistemleri, iç ve dış iklim koşullarına uyum sağlama kapasitesi sayesinde piyasadaki en iyi yeni sistemdir.

Bu çalışmada, binaların enerji verimliliğini ve iç mekan konfor seviyesini artırmak için olan strateji ve parametreler tartışılacaktır. Uyarlanabilir cephelerin arka planı ve konsepti, türlerine ve tasarım özelliklerine göre incelenecektir. Tez, uyarlanabilir cephelere sahip mevcut binaları ve iç mekan konfor kalitesi üzerindeki etkilerini analiz edecektir. Son olarak tez, uyarlanabilir cephe sistemleri uygulamasıyla vaka binaların

enerji performansı ve iç mekan konforunun nasıl iyileşebileceğini araştırmayı amaçlamaktadır.

Anahtar Kelimeler: Enerji Verimliliği; İklim; İç Mekan Konforu; Uyarlanabilir Cephe Sistemleri.



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1. INTRODUCTION

1.1 OVERVIEW

The escalating concern about fossil fuel energy use continues to grow and become one of the main challenges of the 21st century. As a result of high energy consumption, we faced serious issues such as a damaging impact on the environment with the high carbon dioxide emissions, the danger of global warming and climate change. According to the statistics in Europe, building sector responsible for 40-45% of total energy consumption. (EPBD 2002) Furthermore, these figures were discovered not only in Europe but all over the world buildings hold a considerable part of the total energy consumption and responsible about 40% of total direct and indirect CO₂ emissions. (IEA 2013)

Awareness of the above mentioned led to a considerable amount of studies are being carried out over a few decades. Architects and engineers have placed emphasis on sustainability criteria's in buildings, towards improvements in energy efficiency through designing and constructing building envelopes with thermal insulation or reflective skins, in addition to the controlling of heating, ventilation, and air conditioning (HVAC) installations and lighting systems. However, this trend of the building improvements has had high requirements and need to be well-designed, examined. Building performance standards depend on a wide range of individual operational processes and also on how they behave as a consistent system to meet the needs of the inhabitants. Since most of the people living in urban areas are spending more than 90% of their time in indoor spaces, besides the energy aspect, occupants comfort level should be also considered. (Leech et al. 2002)

In fact, the high energy consumption is due to the HVAC systems propagation, which reflects the rising demand for better indoor comfort. Thus, in order to ensure appropriate energy use in buildings, first of all, it is important to enhance thermal comfort. This could be supported through building facade systems, for example, the windows and glazing systems, shading elements, etc. Today building envelopes required to be more active and adaptive to climate and inhabitants. The terms such as climate responsive, intelligent,

adaptive and energy efficient are commonly used in literature to describe those building envelopes.

Based on a compromise between energy efficiency and indoor comfort Adaptive Facade Systems (AFSs) are the best novel concept in the market, they are considered as the next stage of green building and receiving a large proportion of attention in the building sector due to combining adequate indoor comfort and reduction of energy consumption. Natural resources such as solar and wind energy, daylight, water, can be used by buildings efficiently by technological inputs. Unlike providing standard static performance, new adaptive approaches focused on optimization overall performance of building via ability react to environmental conditions. Moreover, adaptive façades could be designed to provide different performance parameters, such as insulation and thermal mass, heating and ventilation, daylighting, shading or humidity control. There are several types of implemented AFS concepts, as well as new design ideas are expected for the near future since solutions are needed to curtail reducing energy consumption in buildings in order to preserve the ecological stability.

1.2 AIM AND OBJECTIVES

This study aims to develop an approach for integration AFS in order to improve energy efficiency and enhance indoor comfort. In this respect, the main goal of this thesis is to reveal a compromise approach to reduce energy consumption and to enhance the indoor comfort level of the building. The interconnection between energy efficient parameters of the building and indoor environmental indices, need to be investigated in this framework. For this purpose, an extensive analysis of the existing AFS concepts and case studies will be given. The theoretical framework of the investigation is divided under 4: Energy; Climate; Indoor Comfort; Adaptive Facade Systems. Occasionally, there is a contradiction between energy efficiency and the required conditions of indoor comfort. Therefore, the proposed approach of this research can contribute to select the best alternatives in building facade design.

In other words, this thesis strives to (1) determine the main criteria related to climate and building facade parameters to achieve energy efficiency in buildings, (2) determine the

best renewable energy systems and passive strategies in the building sector, (3) determine the ideal thermal comfort, daylighting and indoor air quality measures, (4) study the key aspects of the Adaptive Facade System, (5) develop an approach to improve energy efficiency and indoor comfort conditions by the integration of Adaptive Facade Systems.

1.3 SCOPE OF THE THESIS

This paper develops an approach for future integrations of AFSs in buildings in order to reduce energy consumption and to improve thermal comfort. In this respect, the thesis concerns Turkey, Istanbul region. This region is known as a tempered humid climatic zone. The dormitory building was taken as a base case of the investigation, in order to propose and apply the approach. The proposed methodology can be applied in order to develop proper AFSs according to the local conditions in other climatic regions or for other building typologies.

1.4 METHODOLOGY

Firstly, it is important to designate the primary area of the study in order to investigate the climatic features of the chosen region. The following step of the developed methodology is to determine the building typology and exact base case for further examination of energy expenditure and indoor comfort requirements. Based upon on these determinations, require the case study building data which will be used as input parameters in further analysis. After that, when the data is collected it is important to compile all the information into three categories: architectural, mechanical and behavioral. According to compiled data, the normalization of parameters of the base case will be done and used as input data for energy modelling. Energy modelling of the base case building will be created and simulated using Design-Builder software. Moreover, analysis of the base case energy model in terms of energy performance and indoor comfort will be done. Then, the AFS with the consideration of base case problematic aspects will be developed and simulated. The calculation results of the proposed approach and discussion on the usefulness of the AFS in terms of energy efficiency and indoor comfort will be done in the final part.

Moreover, analysis of the energy model of base case building with all input parameters is being made. Then, Development of Adaptive facade system alternatives generated with the consideration of main aspects: reducing energy consumption and indoor comfort improvements of the base case building will be conducted. Within that, considering all above-mentioned stages of the methodology, the assessment of the results will be given. Finally, producing guidelines in order to improve energy efficiency and comfort conditions will be made.

1.5 THESIS STRUCTURE

The thesis structure consists of several stages, as represented below:

- i. A comprehensive literature review of the current energy efficiency challenges, indoor environmental conditions, the current progress of renewable energy systems in buildings, as well as the explanation of basic principles of the adaptive facade systems.
- ii. Investigation on the energy efficiency aspects of the building from different perspectives, such as climate features, orientation, main parameters of the envelope and its role in the overall performance of the building. As well as, energy efficiency requirements, that can be improved through the application of passive strategies, especially renewable energy systems. In addition to the extensive investigation of the existing case studies that represent successfully implemented building with adaptive facade systems around the world.
- iii. Adaptive Facade Systems one of the main topics in the development of the framework of this thesis. The basic principle of adaptation concept, types of AFS, determination of the design approach on both energy performance and thermal comfort quality is to be examined.
- iv. The empirical part of this study is to generate a model of Adaptive Façade System in the DesignBuilder software, for simulation different scenarios and parameters for the same case building. Thus, to establish the best model of the energy efficient and comfortable building with the application of Adaptive Facade Systems.

1.6 LITERATURE REVIEW

This chapter presents the literature review on the main aspects and current strategies towards improvements in energy performance and indoor comfort of the building, through analyzing the important components and steps of the designing process.

1.6.1 Energy and the building sector

It is a well-known fact, that with the dramatically growing population, energy demand also increases. As a result of that rise, we faced a variety of problems, starting with economic concerns up to environmental, and social threats too. Usually, a lot of energy agencies does not categorize the building sector as one of the main final energy consumption groups. The building sector comes in third 'other group' after industry and transport sector. The term 'other' is vague and incorporates various sub-sectors. However, the buildings with their numerous typologies are surely responsible for a considerable part of the consumed energy in 'other group', even it should be said that the energy expenditure in buildings has often not been well estimated. (Allouhi et al. 2015)

According to the International Energy Agency, in 2015 the public and residential sectors are responsible for about 30% of entire energy consumption in the world. (IEA 2015). In order to respond to the challenge for energy efficiency, initiatives such as Energy Performance Building Directive (EPBD 2002) 2002/91/EC were provided by the European Parliament and the council, other organizations around the world participate in this initiatives.

1.6.2 The energy demands

If no actions are taken, energy demand will increase to 50% by 2050 all around the world. This great rise in energy demand can be explained by the fast-moving growth of the construction sector and the necessary services and rising demands for an adequate level of living conditions. (IEA 2013). Due to the growing level of welfare, the requirements for comfort is increased as well, causing the rising demand for the amount of energy for indoor HVAC and lighting. However, with the consideration of these facts that we faced today, intelligent actions can be taken to prevent further degradation. For instance, the

buildings with a proper design that can provide enough natural lighting during the daylight hours, so the artificial lighting will not be in use, as a result, energy will be saved for electricity and human comfort will not be affected. (Thobaiti 2015).

1.6.3 Energy efficiency in buildings

The following criteria of actions for improving energy efficiency in buildings were categorized according to the recent publications in this topic:

- a. Building envelope refurbishments (retrofitting actions, adjusting the surface parameters such as a window glazing size and type and walls by increasing insulation and thermal mass). (Diakaki et al. 2010)
- b. Actions to reduce HVAC loads by integrating passive strategies (Synnefa et al. 2006)
- c. Utilizing renewable energy in the building (passive solar design, active solar design buildings', hybrid systems, etc.)
- d. Use of “intelligent” automatically monitoring systems, energy controlling sensors for HVAC) (Kolokotsa et al. 2005)
- e. Simultaneously improvements of the comfort condition and with minimizing energy consumption (consider the performance of mechanical and natural ventilation) (Kolokotsa et al. 2005)

1.6.4 The role of Building Envelope

As mentioned in the introduction, among various elements of the building, the envelope plays a key role in consumption energy. Since it works as a separator between outer and inner space, as well as a resistant shield to noise, heat, air, water, vapor, and light. Briefly, strategies such as envelope and active system retrofitting, application of renewable energy systems and AFSs have been developed and focused in order to achieve sustainability and desired indoor comfort. Briefly, strategies such as envelope retrofitting, application of renewable energy systems and AFSs have been developed and focused in order to achieve sustainability and desired indoor comfort. Hereby, consideration the potentials of already existing systems and the technologies will help decision makers create new methods and approaches.

1.6.5 Challenges and Trends in the field of AFS

There are various already implemented projects of Adaptive Façade Systems, however, the development and realization are still in the initial stage. It is obvious that despite new adaptive systems, appropriate testing methods and tools must be developed, as well as existing norms and regulations needed to be reviewed in order to achieve the final aim to wider application of AFS in new and existing buildings. In fact, there was a problem with the lack of knowledge transfer and cooperation between research institutions in the field of AFS. Currently, the main organization - COST ACTION TU1403 which was established in 2014 under the initiation of several research institutions- is working on this topic. In the framework of the AF network, the researches are conducted and supported by the cooperation between professionals in this field. (COST ACTION TU1403 2014)

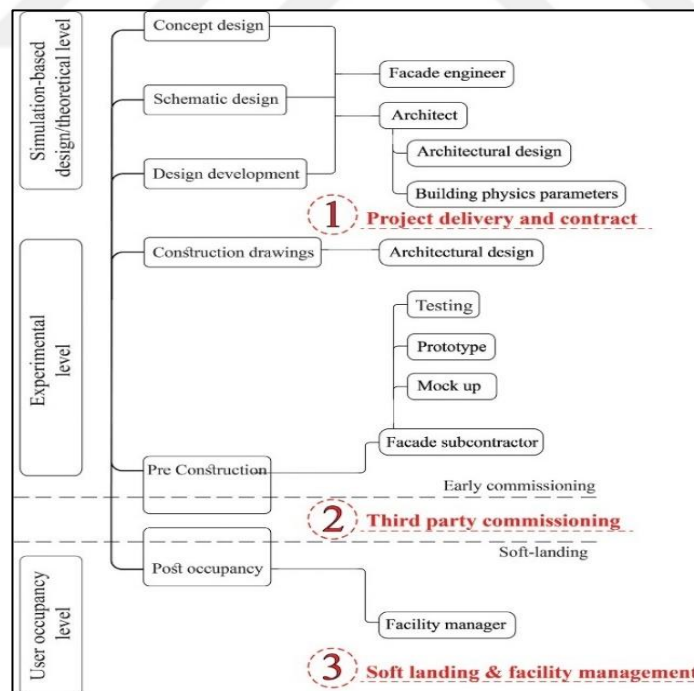
AFS requires low-tech and commercially obtainable design components such as movable shading devices, advanced glazing materials. Moreover, a lot of research has demonstrated a significant difference and benefits compared to the common models in the industry. Notwithstanding the growing progress of AFS, the concept is slightly popularized in the market.

According to Attia et al. there are two types of barriers that interfere to adoption buildings with AFS into the market: The first barrier is - impediments in the evaluation criteria of performance for building with AFS. The lack of objective efficiency parameters that have to be holistic for all systems in terms of assessment and monitoring of AFS makes the concept doubtful. In order to simplify the evaluation of buildings with AFS, scientific communities and research agencies must aim to fill this knowledge gap. Authors claim that a stable assessment has to be developed as a short-term solution, and ideally, in the long term the standard for AFS is needed. Secondly, the project delivery process of AFS requires a lot of attention from the design stage (planning, testing, mountings, and installation) execution and operation. Designing and constructing buildings with the integration of AFS means that cooperation in multiple engineering disciplines is obligatory, it is caused by the need for exchanging between all project responsible persons.

In the study of Attia et al. (2018), they developed a common process map and identified three major issues linked with AFS delivery that was done by surveying professionals during design, implementation and operating stages of the buildings with the AFS are shown in the Figure 1.1.

Thus, after the architect developed the AFS concept without any consideration for other decision-makers, the subcontractor is assigned for implementation. As a result, when the concept of AFS is already developed, the subcontractor can start the testing and implementation. Besides, the subcontractor needs to examine material options and develop suitable engineering solutions according to the material preferences of the architect. This stage includes detailed research and calculations of the façade components and elements. Hence, based on the analysis of the study, that design-bid-build method creates a dual approach and is induced several performance errors and problems, in addition to the time consumption and reduction of overall performance quality of AFSs.

Figure 1.1: Adaptive façade delivery process map and key problems.



Source: S. Attia et al. / Energy & Buildings, 2018.

The second issue according to the map that influence is commissioning the performance and quality of AFS facade. The study has shown that all the stages of development of

AFS not commissioned objectively by third-party involved. With the limitations of time and lack of an adequate method of project delivery, the subcontractors entrusting the development of AF by themselves to themselves.

The third issue belongs to the relationships of users and the operation of the façade. Soft-landing process and operation manager are must have in such a project. Providing that, soft-landing is an opportunity to customize and introducing the AF system to users. The role of facade operators here is to control the performance and meet required comfort of inhabitants, shape and orientation of the building. According to the study that soft-landing period, is a great opportunity for users, managers, architects, and subcontractors to analyze and test customization of AF operation, and to create the ideas from revealing the major problems for future projects.

In order to reveal all the advantages of the adaptive facades, the performance assessment framework was created in the study of Attia et al. The following categories are mostly related to key performance indicators (KPIs) of AFS.

- i. **Energy and environmental performance** - this category is about the environmental impact on the overall performance of AFS since the environment is the main factor affecting the indoor comfort and HVAC loads. There are no doubts that buildings physics in connection with energy performance envelope design are one of the main KPIs.
- ii. **Protective performance** - here the authors grouped buildings' performance indicators related to structural stability and safety. Consideration of fire resistance, structural performance, acoustics. This includes air penetration, solar radiation, and control, calculation of natural ventilation. These all are again related to building physics and material science in the design phase of AF systems.
- iii. **Building control and services** - this third category considers comfort conditions, through analyzing the interaction between HVAC systems and the AF. The authors divided this group into four types of comfort, in direct relation with building and facade operation systems. In brief, building services such as active and passive ventilation, heating and cooling and control of them towards maximum indoor comfort.

- iv. **User control and experience** - this category related to inhabitant's participation and control. Their personal perception of the indoor environment, as well as the engagement with the AFS in order to regulate their own indoor comfort.
- v. **Maintenance, durability, and lifecycle** -. The life cycle of AFS, from the operation, cleaning, and endurance and guarantee details come in this category.

In addition to all above mentioned, it is important to say that there is a need to raise advanced technologies of the adaptive facade in order to reduce buildings environmental impact and empower users.

1.6.6 The study of optimization of facade design for Energy efficiency, comfort and daylight in the early design phase.

The study of Matthias Haase et al of a single-family house in Norway region clearly show the effective strategies in order to improve the thermal comfort level. That investigation has been done by integrating an adaptive facade designed by automatically control shading devices and control strategies for natural ventilation.

The case study is a three-story building in the North Oslo, the climatic region is known for cold winters and cool summers. The spatial organization of the case study house is organized as follows: entrance and detached apartment that is used for rent, technical room and storage room is on the ground floor. In addition, a bedroom, two training rooms, and the bathroom are on the first floor. Connected with the staircase the second floor includes a living room and kitchen. (Haase and Grynning 2017) .

It has been observed the major part of heat losses is through the building envelope via windows. To continue with, two types of glazing were used in the model, one of them not openable triple-layered glass with a U-value of $0.703 \text{ W/ (m}^2 \text{ K)}$, while the second model of glass has a solar screen with the transmission. Selected for this study simulation software IDA ICE was useful for testing the appropriate strategy for the window openings of the case. Hourly illuminance levels and thermal control were also studied and calculated for each zone, the operative temperature $>27^\circ\text{C}$ Top $>27^\circ\text{C}$ was set as maximum.

According to the results of the study, it was claimed that the most problematic zone where the overheating occurs is the second floor of the house. Without applications of window shading devices, an operative temperature higher than 27°C was about 12 hours per day. Also, temperatures above 27°C are spotted in the ground floor in the detached apartment, moreover with the first type of the window 3439 hours of that temperature are captured, while with the second type if window hours of overheating reduced for 2467 hours. There is another type - openable windows, applying them reduce to 22 hours. Thus, natural ventilation via opening windows is a way more useful solution for reducing overheating, rather than an applied external screen.

The results of case studies focused on summer temperatures, overheating and daylight levels. The results confirm large amounts amount of hour when operative temperature exceed 27°C in particular zones such as rental space on the ground floor and living room on the second floor. Shading of windows with an external screen and ventilated cooling by opening windows were applied. Since the climatic features of Norway regarding cool summer outside temperatures allow cooling effect in the house by simply opening the windows. To sum up, the result of the study shown exceeding temperatures in all three stories. The application of the external screen does not give a significant impact on reducing the temperature. The best solution for the overheating issue for this particular climate is natural ventilation techniques (Haase and Grynning 2017).

According to the literature review, the main motive is to prevent the rise of energy demand in the buildings. The worldwide actions were already started by the initiative projects towards achieving near-zero energy in the buildings in the near future. The factors such as appropriate material selection, integration of renewable energy into the building play the main role here. It was observed that Adaptive Facades are has a big potential to improve energy efficiency and indoor comfort. However, since the concept is quite new there is a lack of holistic performance criteria for designing, assessment, and monitoring. This fact inhibiting the wider applications of AFS in the buildings. Indeed, with the detecting certain problems of the envelope, which cause the high energy expenditure of the building, it is possible to adjust and improve those parameters in every building.

2. ENERGY EFFICIENCY AND INDOOR COMFORT

It is obvious that climate and the environmental factors have a big impact on the comfort in any space, as well as influencing the energy systems and consumption, it is architect's responsibility to consider these environmental factors and determine the optimum values during a designing stage. In this part, the role of environmental factors and climatic features which affect indoor comfort and energy efficiency of the building will be discussed.

2.1 ENERGY EFFICIENCY AND CLIMATE

It is a well-known fact, that a climate plays a great role in building thermal performance. The tendency to study the climate and built environment was known from vernacular architecture, where sustainable and environmentally friendly buildings have been developed through understanding the features of a region.

At the very beginning, climate zoning classifications were developed to identify climate patterns related to vegetation. One of the initial examples of such classifications is the Köppen climate system that was established in 1900 and in use today. That is, climatic zones are the regions of the surface of the Earth that are classified with different climatic parameters such as average temperature, etc. Thus, according to these parameters, today we can determine standards or mandatory values for certain building characteristics for the particular climatic zone. Studying and considering climate zone features on the early design stage will help to reach energy efficiency, reduce greenhouse and as a result to decrease the change of climate.

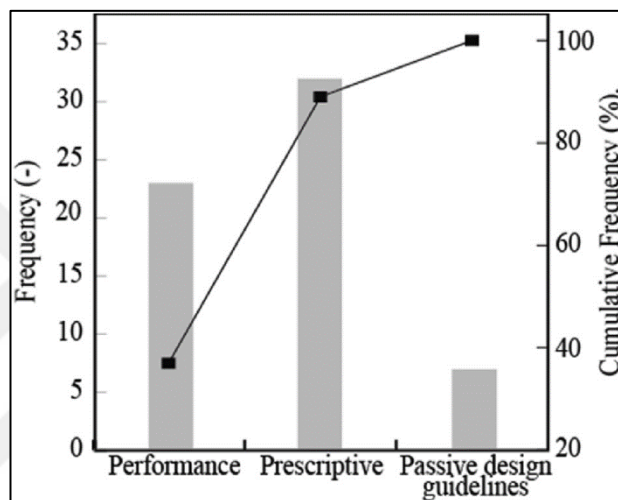
2.1.1 Purpose of Climate Zoning

As it was mentioned before, the development of climate zoning schemes was started mostly for academic or research purposes, before it came to widespread used in practice as embedded regulations and standards. Indeed, the climate zoning approach for energy efficiency differs from country to country and their building standards. However, the main criteria for climate zoning can be the same for all regions. These criteria are requirements for performance, prescriptive requirements and of course the integration of

passive design strategies. The frequencies of these three groups are indicated in Figure 2.2 (Walsh et al. 2017).

Generally, performance-based approaches concern about the building as a whole and put an emphasis on annual building energy use, indoor air quality, and thermal comfort. It is believed that this approach is more compromising and facilitate innovation in building energy efficiency programs in comparison to the second normative approach.

Figure 2.1: Frequency of climatic zoning according to their purpose.



Source: A. Walsh et al. 2017.

The prescriptive based approach is focused on the determination of optimal values for building envelope. In fact, creating the standard database that includes each parameter from the Solar Heat Gain Coefficient (SHGC), categorization for U-values, as well as the performance coefficient for HVAC operation. This approach itself became widely used in such programs since the normative is easier to apply for decision-makers.(Walsh et al. 2017)

Another climatic zoning scheme is about utilizing knowledge in the field of passive design, as a guideline for developing the facade with the passive design strategy. Mostly all the strategies are related to the early design stage period, it includes information about the appropriate orientation and shape of the building, passive heating and cooling according to the climate region. (Stevanović 2013)

2.1.2 Climate regions of Turkey

Defining the number of zones and regions are necessary to capture climatic variation plays an important role in building energy efficiency programs. Turkey is the Mediterranean country, there are five climatic regions as seen in Figure 2.2. It is obvious, that sustainable design approaches vary among climatic regions.

- i. tempered humid,
- ii. tempered dry,
- iii. hot-humid,
- iv. hot-dry,
- v. cold.

Figure 2.2: Climatic regions of Turkey.



Source: Energy efficient renovation approach in Turkey: targets, barriers, and practice. REHVA Journal, 2015.

2.2 CLIMATIC FACTORS AFFECTING ENERGY EFFICIENCY AND INDOOR COMFORT.

Climatic elements forming the climate of the outside environment are defined as environmental or climatic factors. The main climatic factors relevant to construction are those affecting human comfort:

- a. Radiation,
- b. Air temperature,
- c. Relative Humidity and Precipitation,
- d. Winds

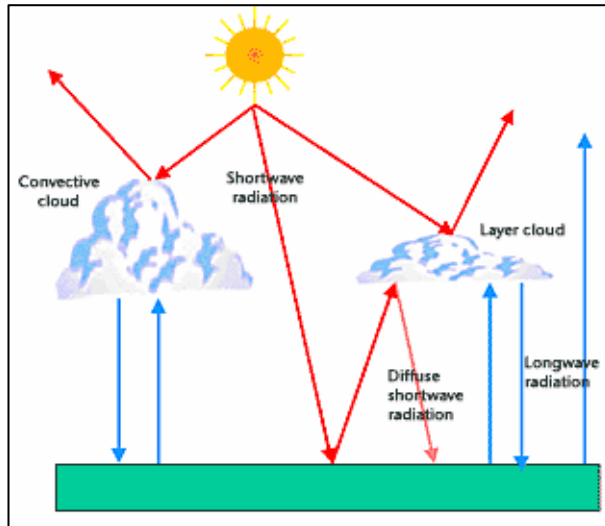
2.2.1 Radiation

There are two different types of radiation that affect the earth, shortwave solar radiation (visible light), and longwave radiation (infrared light) as shown in Figure 2.3. Shortwave radiation is radiation originating from the sun and its wavelength is between 0.3μ and 3.0μ . Longwave radiation is radiation with a wavelength greater than 3.0μ , whose temperature is equal to ambient temperature.

The shortwave solar radiation generated by the sun and emitted by electromagnetic radiation with a wavelength range from 0.3μ to 3.0μ reaches our atmosphere in the form composed of two different components, depending on various factors:

- Direct shortwave radiation reaches the surface in a direct line without any change in wavelength without any absorption by the intervening atmosphere.
- Diffuse radiation unlike the direct shortwave radiation, scattered by particles, such as dust, air molecules, and water vapor in the atmosphere, and reaches the Earth's surface as a horizontal plane. (Yılmaz 1983)

Figure 2.3: Schematic diagram of radiative processes.



Source: research.metoffice.gov.uk

Also, total shortwave solar radiation which reaches any surface with any certain inclination is a sum of direct and diffuse radiation received at a horizontal plane at the Earth's surface. In Turkey, related measurements of solar radiation and sunshine duration

are carried out by the General Directorate of State Meteorological Agency. There are several stations with bimetallic actinograph that are aimed to measure total solar radiation amounts in monthly and daily values.

The radiation which absorbs by the water vapor, CO₂ is the longwave solar radiation. The solar radiation enters the atmosphere and the surface absorbs that radiation and converts the longwave radiation to infrared rays. Stefan-Boltzmann law states the proportion of emitted longwave energy is the fourth part of emitting temperature. (Encyclopædia Britannica 2018)

2.2.2 Air temperature

Depending on the periodic change of the sun's angle of elevation, as in many other climatic elements, the outside air temperature is repeated in 24-hour periods and shows sinusoidal changes throughout the day. (Yılmaz 1983) In Turkey and other developed countries, the average daily mean of air temperature is calculated during three periods at 7.00 a.m., 2 p.m., 9 p.m. Since air temperature affects the heat transfer between man and its environment is one of the key variables that affect human comfort. (Kundakçi 2004)

2.2.3 Relative Humidity and Precipitation

The relative humidity is the amount of water vapor that can be held in the air by the evaporation of water from various moisture sources on Earth. Relative humidity depends on both the amount of humidity contained in the air and the temperature. The maximum amount of water vapor in the air at any temperature is defined as saturated air. For instance, if the relative humidity is 40%, the air contains 40 % of the water vapor it might hold at that temperature. However, increasing the temperature, the amount of water vapor the air can hold increases so that the relative humidity decreases and the opposite. Decreasing the temperature will result in 100% relative humidity, and then water vapor will begin to condense to form dew, which is called the dew point.

Precipitation is a very common phenomenon in the atmosphere of our Earth. The process of condensation of water vapor in the air in the form of water droplets and ice another falling on the ground is called precipitation. Generally, it is shaped in solid or liquid forms of water. The amount of precipitation varies from year to year and location.

2.2.4 Wind

Wind can be described as a secondary climate element caused by temperature and pressure differences in the Earth. The most effective result in the control of this climate element in terms of climatic comfort can be achieved by measures to be taken at the site planning level. (Yılmaz 1983) Since the wind one of the main climatic factors that responsible for heat gain and losses in the building, and as a result influence overall indoor comfort.

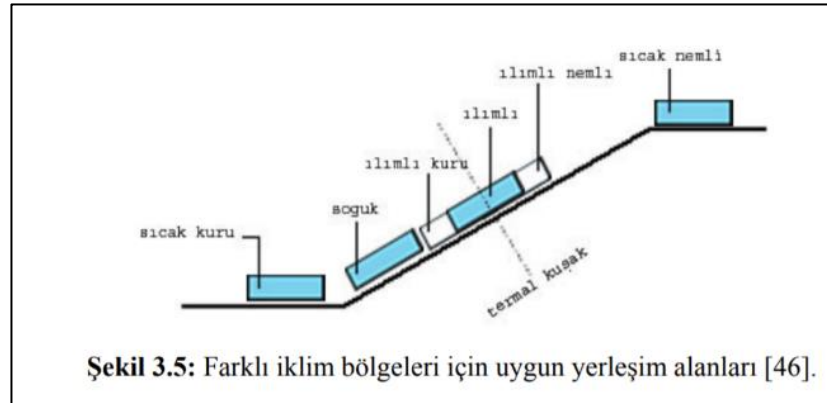
2.3 BUILDING DESIGN PARAMETERS IN TERMS OF ENERGY EFFICIENCY

Above all, in developing energy efficient building it is important to consider fundamental design guidelines and parameters, especially it is related to the question, where the building is being designed. In other words, it is crucial for decision-makers to put on emphasis on site planning, building orientation, shape, and facade design. Due to these factors, the long-term energy and environmental performance of the building are extremely important. These actions are needed to prevent further problems related to indoor comfort in all phases of building life span, in addition to the possibility to save, conserve and generate energy in the buildings.

2.3.1 Location

To begin with, thinking of the location, the main factors that must be considered while choosing the appropriate location for the building is existing surroundings on-site, for instance overshadowing and vegetation as shown in Figure 2.4. Furthermore, the analysis of topographical properties of the site is needed for the decisions for developing the energy-efficient design. The presence of slopes and hills around the building to be constructed will have an impact on the solar exposure of the building. Lack of understanding characteristics such as wind pattern of the site will be caused by high energy consumption since winter protection or summer cooling depends on the prevailing wind on site. (Bilgiç 2003)

Figure 2.4: Topographical locations in different climate regions



Source: İ.T.Ü. Mimarlık Fakültesi, İstanbul.Koca O., 2006

While deciding on the optimal location of the building, the altitude of the site will have a significant impact on the overall performance since then its effect the daylight levels, cloud cover and as a result on the probability of precipitation. This factor has to be considered by decision-makers according to the particular climate region.

However, there is another strategy such as landscaping of the existing site. This means that existing topographical characteristics of the location of the building can be improved with the consideration of the particular disadvantage of the site. Actions such as planting the trees and plants in the perimeter could make protection of building from overheating by the summer solar radiation and from cold winter winds. Especially, when the considerable part of the vegetation in the location is placed in the west and east sides of the building it guarantees a good shading in the summer period.

2.3.2 Orientation

The orientation of a building is responsible for its sunlight exposure and wind exposure understanding the main basics of solar radiation and building physics will help to define which side of the building preferable to receive direct sunlight. The building's orientation is the main aspect that controls solar heat gain due to the frequently changing conditions of the sunlight. (Aksamija 2015)

For instance, Yeang (1995) claims that building orientation has an important bearing in energy conservations, he gives tall buildings as an example since they exposed to the full impact of external temperatures and radiant heat.

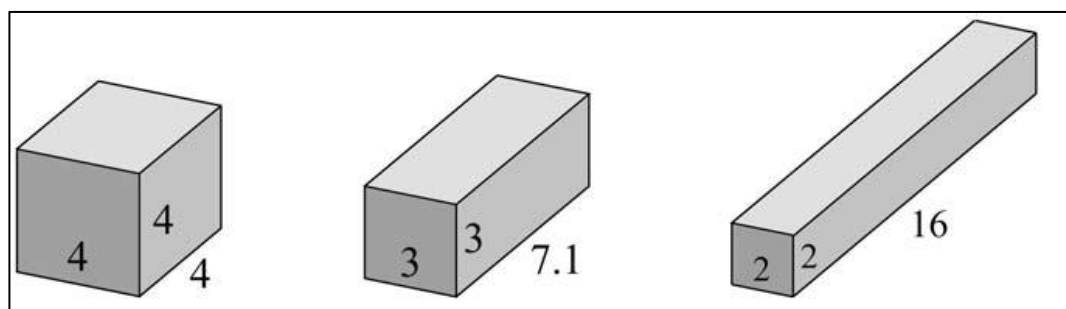
There is a wide range of strategies of planning for selecting the appropriate location and orientation of the building according to climate conditions, for example, main and broader openings facing north and south gives the greatest advantages in reducing heat insulation and will be beneficial in winter since it helps to gain solar thermal energy. As an example, in a book "Energy and Environment" as Baker and Steemers states (2003), That the maximum amount of solar radiation in winter on a vertical surface occurs in a southerly orientation. On the other hand, in climates such as the United Kingdom, east orientations are preferable for better results of heating energy and preventing overheating, because the internal gains will be made earlier in the day when a greater heating demand exists.

Thus, when it comes to high energy consumption which is directly related with the usage of the HVAC systems, by the elaborate consideration of orientation on the early design stage of the building, and with calculations of solar radiation and wind preferences, it is possible to create energy efficient building.

2.3.3 Shape

The shape of the building is defined by the length, depth and height values, as well as building roof type. Nowadays, there is a variety of building forms in the same size, but with different surface areas. The Figures 2.5 and 2.6 demonstrates configurations of the building shape with surface areas to the volume ratio change while the shape volume is the same.(Markus and Morris 1980)

Figure 2.5: Different shapes with the same volume



Source: Markus and Morris, 1980.

Figure 2.6: Types of shapes with the same volume area

Solid shape type	Surface area	Volume	Surface / Volume ratio
a	96	64	1,5
b	103,2	64	1,61
c	136	64	2,13

Source: Markus and Morris, 1980.

The compact shape has less surface area while the second and third shapes have more, and it will be reflected in the energy for the heating space.

Yılmaz, (2000) Lin (1981.) states, the building shape has a considerable impact on energy consumption. However, it is becoming a challenge to define the most appropriate combination of energy efficient form among these alternatives. Accordingly, in the climate cold regions, the large external area means heat loss, and that the more energy will be used for heating. The optimal form of energy efficient building in such climates should have a minimum external surface in the hot and temperate climates, the external surface does not play the main role in heat loss. However, it can influence the energy consumption for cooling, since the bigger external surface area and glazing it will cause the overheating.

In addition, the spatial organization of the building shape is also important for energy efficiency. For instance, the service areas, entrances, and corridors and other spaces that require lower temperatures for heating should be placed on the northern sides.

2.3.4 Envelope

There were several previously mentioned design factors that have an influence on the energy expenditure, such as climate elements, building location and orientation, however, all that energy losses occur through the building envelope. Since it is the combination of components of the building, that are works as the main buffer between external and internal space. These components are the foundation, roof, walls, doors, windows, ceiling, and their related barriers and insulation. Actually, the most influential parameters that have an impact on energy performance is the building envelope components (Aslani et al. 2019). There are standards that were introduced by the International Energy Agency, these standards consist of concepts for energy-efficient approach in the envelopes.:

- a. an advanced glass types for windows;
- b. advanced wall coverings;
- c. devices for shading and glazing;
- d. high reflectivity materials

2.4 PASSIVE DESIGN STRATEGIES

To begin with, the energy that comes from natural processes that are continually replenished is - renewable energy. Solar and wind energy, biomass, biofuels, and hydroelectricity are all renewable energy sources. The main benefits of using renewable energy are that they are environmentally friendly, sustainable, and low-priced. As a result of the integration technologies with renewable energy sources in buildings, we can get the highly efficient and aesthetically improved product. Therefore, there is a wide range of methods to reduce addiction from energy. For instance, the most popular types of renewable energy are solar power. Within the right integration of passive or active solar systems according to the site, orientation and local climatic conditions it is impossible to reduce energy consumption in the buildings.

2.4.1 Passive solar design

The passive solar design helps to reduce energy consumption due to the usage of the sun's energy for free of charge heating, cooling, and daylight. The passive design strategies include the main principles such as natural convection, conduction, and radiation. Moreover, no mechanical inputs are used in the utilization of energy resources. For instance, when solar radiation strikes an envelope that energy can be absorbed, reflect or transmit. However, solar power can be used properly if design components and materials were elaborately considered, and as a result, heating and cooling function will be achieved.

Within the understanding of the physics principles and mechanisms of heat transfer heat conduction and thermal radiation, energy efficiency can be significantly improved through passive design strategies.

2.4.2 Passive solar heating

The passive solar heating concept is aimed to absorb the solar radiation within the building elements release that heat during periods when the sun is not shining. The primary elements such as south-facing glass for the northern region and vice versa; thermal mass to absorb, store, and distribute heat in passive solar heating is strongly required. There are three different approaches of the solar heating system:

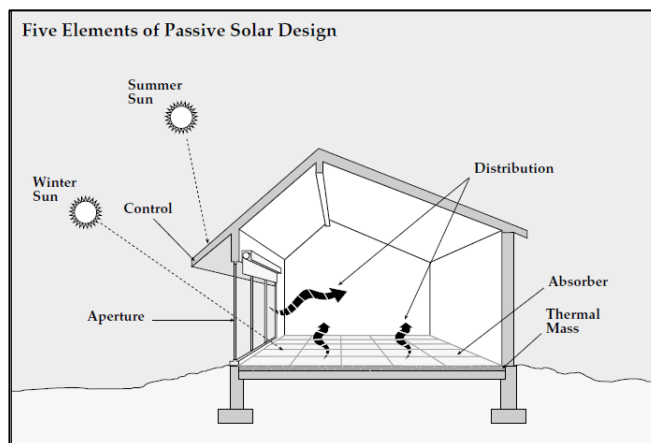
- a. direct gain;
- b. indirect gain;
- c. isolated gain.

All the above-mentioned approaches include five basic elements such as internal thermal mass, control aperture, shading device, solar radiation and distribution of heat. Within the understanding of the physics principles and mechanisms of heat transfer heat conduction and thermal radiation, energy efficiency in buildings can be significantly improved. (Chel and Kaushik 2018)

2.4.2.1 Direct gain

In this system, the house is a solar collector itself, it absorbs the heat and has its own distribution system. It is shown in Figure 2.7 the south facade transmits solar radiation directly and indirectly to the interior space and internal mass.

Figure 2.7: Direct gain principle.



Source: Chel and Kaushnik, 2018

The mass wall usually colored dark colors due to the high absorption of dark colors in comparison to white. During the night the solar radiation absorbed by the mass walls distributes heat into the room. (National Renewable Energy Laboratory 2001) It is possible to utilize 60-75 % of the sun's energy by applying the direct gain system.

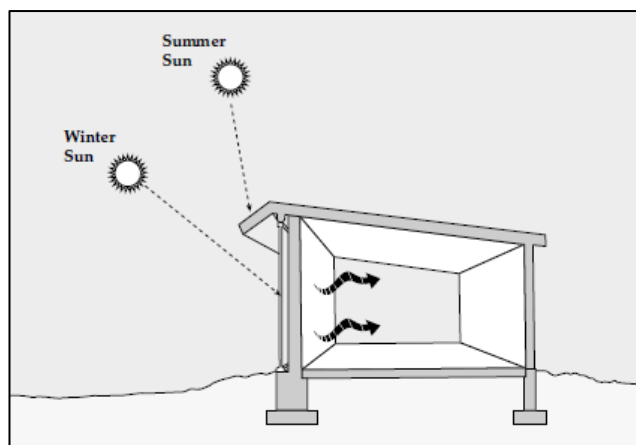
The glazing type and area and the amount of interior thermal mass are selected in response to the climate region, the shape of the building. Since the direct solar gain strategy provides solar heat directly indoor the overhangs are commonly used to avoid overheating in both summer and winter.

2.4.2.2 Indirect gain - Trombe Wall

The feature of the home with an indirect-gain system is that it has thermal storage between the south-facing surfaces. Actually, the Trombe wall is the widely used approach in indirect-gain systems. In Figure 2.8 there is an example of a Trombe wall scheme with masonry wall 8 to 16-inch-thick, and which is faced on the south side.

Heat is being absorbed by the outside surface dark side and collected in the mass of the wall, where it radiates into the living space. Thus, the received solar heat releases it inside of house over a period of several hours. This happens by heat migrating through the wall and reaching indoor space in hours when the temperature is started to below. (National Renewable Energy Laboratory 2001)

Figure 2.8: Trombe Wall.

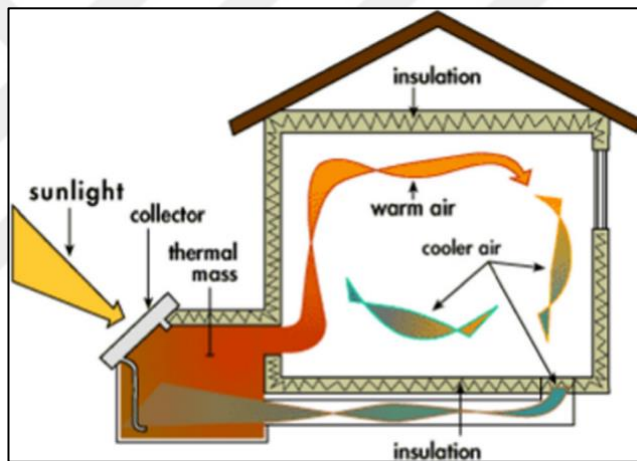


Source: Chel and Kaushnik, 2018

2.4.2.3 Isolated gain

Isolated gain systems are usually distinct from the main leaving are, they represented as a collector or storage of the solar energy. Typically, the process of transferring solar energy from the collector is by using water or air by convection as shown in Figure 2.9 Sunroom and convection are provided into the house by the flat plate device. In case if air used as the transfer convection, heated air comes from the collector to the space directed and being absorbed by the natural mass material. At night hours home is heated by the convection heat that is collected by these mass materials. Similarly, if the transfer medium is water, that heat is collected in a tank, and as hot water is introduced, cooler water is circulated to the collector. (Chel and Kaushik 2018)

Figure 2.9: Isolated heat gain



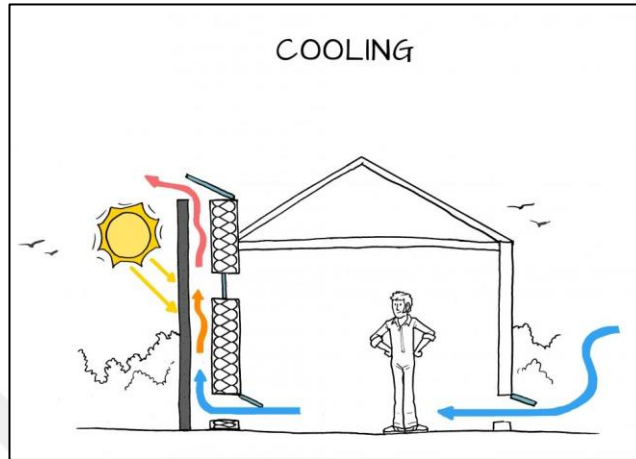
Source: Chel and Kaushnik, 2018

2.4.3 Passive solar cooling

It is possible to provide passive cooling in the building by the consideration the major parameters such as adequate shading and insulation and as well as natural ventilation. The natural ventilation can be adjusted by the right selection of glazing size and types, as well as adding vents and casement windows. Another strategy, application of vertical solid panels called wing walls situated nearby windows opposite to the wall on the building's windward side. Wing walls will hasten the natural speed of the wind due to pressure differences created by the wing wall. Generally, the thermal chimney can be described as the main mechanism of passive cooling concept, because indoor hot air can

be exhausted by ventilating the structure. (Chel and Kaushik 2018) Solar chimney removes undesirable heat from building as well as slowing heat transfer to inside in the summer period as shown in the Figure 2.10

Figure 2.10: Solar Chimney Effect



Source: academia.edu., 2018

2.4.4 Active solar design

Active solar design - is about using solar energy to heat fluid or air and directly transfer it to the inner space or to the collector. In comparison to the passive solar design, the design of the solar active collection and heating system should be separated from the structure of the building. According to Atagündüz, (1989), a liquid is heated in solar collectors and being transferred to the storage vessel, or heat and distribute air to the interior space. Thermal Solar collectors could be described as the main example of the above mentioned. Usually, they used on roofs of buildings, for both water and space heating, in some cases, the inclination of the roof is not required. Today, using active solar energy will be beneficial in both economical an environmental aspect. Since it will significantly reduce your fuel bills in the winter and as a result reduce air pollution.

2.4.4.1 Photovoltaic Systems

Photovoltaic (PV) systems is a system that converts the solar energy into the stream of electrons and generating that flow to direct current (DC) electric power which measured in Watts(W). This caused by the light striking the solar panel that consists of

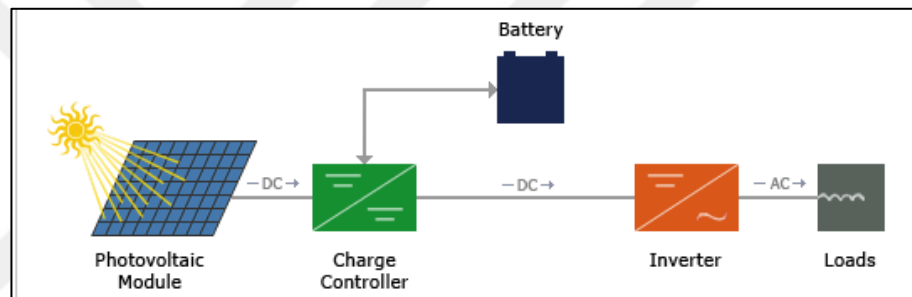
semiconductor properties. These properties allow the panel to collect the photons from the solar radiation and transform their energy into electricity. (Bilgiç 2003)

There are three types of PV systems:

- a. Stand-alone PV systems
- b. Grid-connected PV systems
- c. Hybrid systems

Stand-alone or off-grid systems are separate from the power lines and self-governing systems. These types of systems can directly distribute solar energy or charge the batteries with stored energy.

Figure 2.11: Stand-alone PV system



Source: Synergy Enviro engineers, 2016

As shown in the Figure 2.11, PV modules generate direct current (DC) electrical power and batteries are storing that generated energy. Overcharging of the battery is prevented by the charge controller device. The inverter is used as a converter of DC energy to alternative energy , the only difference in the grid-connected system is that it is connected with the utility grid, so the system components are the same, but the advantage is that power distributed by the utility grid and when the alternative energy is not insufficient the power is drawn from the PV system.

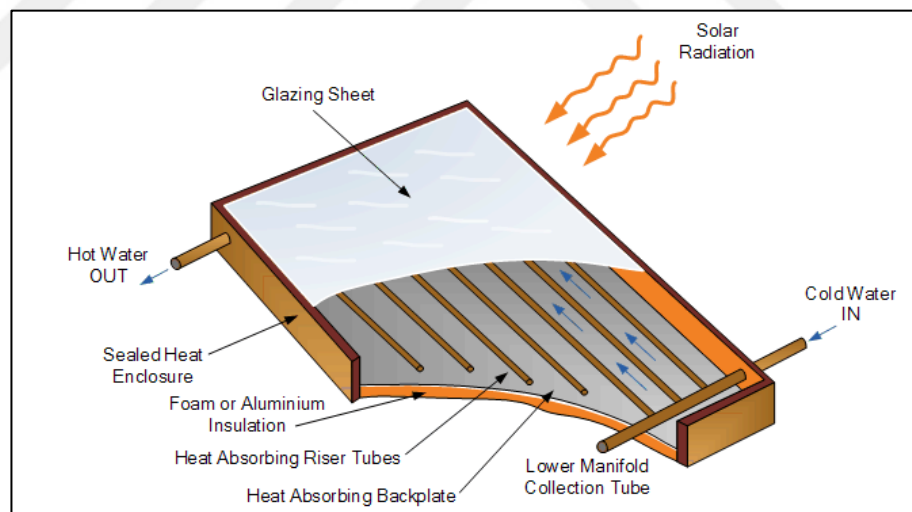
Hybrid systems - are the devices with more than one source of power, mostly the gas or diesel generator is included. The feature of the PV systems is that they could be applied in different scales, small rooftop exemplary or as a huge electricity generation facility. Indeed, there are some other advantages of PV system like quick installation, long-life utilization, no air pollution, low operating cost, etc. Despite these advantages, there are

some drawbacks too, such as high investment cost, non-efficient energy storage, decreased performance with the shadowing effect.

2.4.4.2 Flat Plate Thermosyphon Units (FPTU)

FPTU is a system represented in Figure 2.12, absorbs solar energy and converts it to heat energy use causing the greenhouse effect. The captured heat energy used to provide hot water for bathing and heating. The application of solar flat plate collectors is a very common practice for residential buildings, due to the simple design and installation and of course relatively low cost. In general, the system consists of an aluminum plate due to the good conductivity the plate is usually colored in dark colors for effective absorption. The dark layer surface includes several copper tubes and pipes that transfer water. How hot the circulating water gets. FPTU systems are usually small in size and provide from 100-200 liters of heated water per day. (Chel and Kaushik 2018)

Figure 2.12: Typical Flat Plate Collector



Source: Alternative energy tutorials, 2015

2.4.4.3 Solar Collectors with colored absorbers

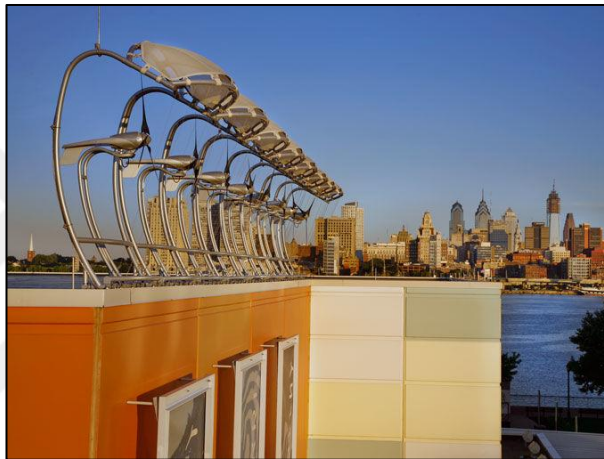
Another alternative type of solar collector is absorber with different colors, apart from the typical black colored collector this could be a unique solution for the application. Indeed, the colored collector has lower performance, but the design can be the reason for the wider usage of renewables since its interesting solution for architects. However, it is

claimed in order to get performance as in the black covered solar panel increasing the collector area for about 20% is needed.

2.4.4.4 Building integrated wind systems

The most appropriate applications of wind turbines are the location with high wind velocity, they usually installed on buildings roofs. The size of the wind turbines and their placement order depends on the building size and shape. The systems are efficient for hotels and residential places where the decentralized application of electricity is provided.

Figure 2.13: Wind Turbines.



Source: Photo by: Jeff Titcomb

Mostly, the blades of WT are made from thin and lightweight materials in order to make the turbines more reactive for small air movements. There are wind turbines of vertical (VAWT) axis and horizontal (HAWT) wind concentrators. Building wind energy systems have great potential as RES since they can be combined with photovoltaic systems.

2.5 INDOOR COMFORT

The term indoor comfort includes several aspects such as thermal comfort, indoor air quality, acoustics. According to the Cambridge Dictionary, comfort is a state of mind the pleasant feeling and being relaxed, the absence of discomfort. There is no doubt that inappropriate indoor comfort can diminish not only the productivity of the occupants but also their health. Thereupon, heating, ventilating and air-conditioning (HVAC) systems play a vital role in buildings, to provide a highly sufficient comfortable indoor climate to the occupants. However, these high requirements for the HVAC system reflect a huge

energy usage in the building. Indeed, a determination and evaluation of the adequate thermal comfort and indoor air level are important since it will help to use the HVAC system efficiency and as a result, reduce energy consumption at the same time. (Atthajariyakul and Leephakpreeda 2004)

Above all, if the inhabitants of a building are experiencing discomfort in significant periods of time, architectural delight will not have any sense.

According to (Baker and Steemers 2000) predefined indoor temperatures is not the guarantee of comfort at all. They claim that comfort is a more holistic experience, and it depends on environmental factors and the options that the environment offers, and it becomes valuable when the occupants can determine these options for themselves. As an example, they give a passive building, where the main requirements again related to the outdoor conditions, rather than the control system. (Markus and Morris 1980)

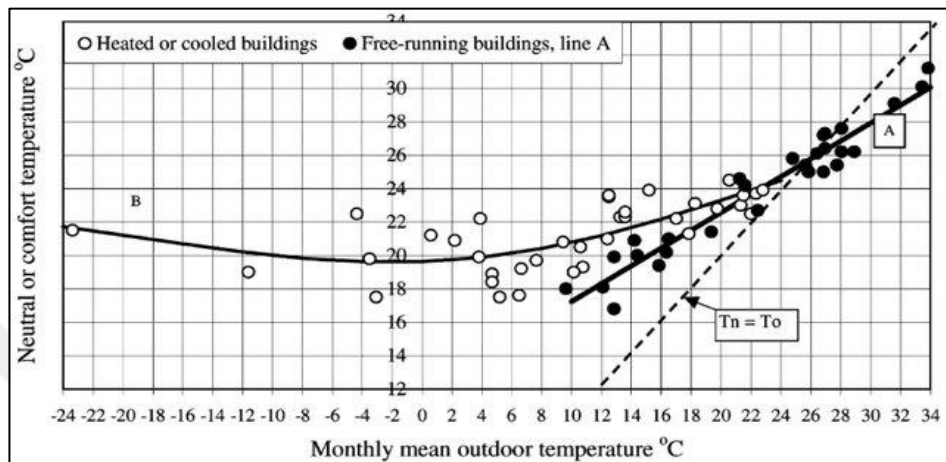
2.5.1 Thermal comfort

The ASHRAE describes thermal comfort as a subjective evaluation of a person of the thermal environment. Despite this modern definition, at the very beginning, thermal comfort was adjusted according to a predetermined temperature, which may not be necessary to make occupant comfortable. Thereafter, a lot of studies has been done many about comfort-based control, as a result of these researches, predicted mean vote (PMV) was proposed to use as the comfort index at the comfort range scale. PMV index consists of six thermal variables that indicate the satisfaction of thermal comfort: human activity level, clothing insulation, mean radiant temperature, humidity, temperature and velocity of indoor air. In brief, there are two types of perception the thermal comfort. Well known PMV or so-called static approach that was established by the study of Fanger in 1970, but the lack of interim conditions and neglecting the important cultural, climatic and the real-life scenarios, make this scheme imperfective especially today.

Whereas the second one is a dynamic method, it is theory initiated by (Humphreys and Nicol 1998) adaptive model that described as: as: “if a change occurs that produces discomfort, people will tend to act to restore their comfort”. It is important to say that, this approach was developed and tested in real buildings, during real environmental conditions, without any trivialized human activities and pragmatic predictions. Research

carried out showed that occupants comfort temperature depends on externally monthly average temperature, and as presented in Figure 2.14 the range of comfort indices is wider than in Fanger's PMV.

Figure 2.14: Changes in temperature with external monthly mean temperatures.



Source: Humphreys and Nicol, 1998

First and foremost, the level of comfort and satisfaction occurs through appropriate adaptation to the indoor climatic environment. There are three crucial categories of thermal comfort adaptation (Folk 1974, 1981, Goldsmith 1974, Prosser 1958, Clark and Edholm 1985.)

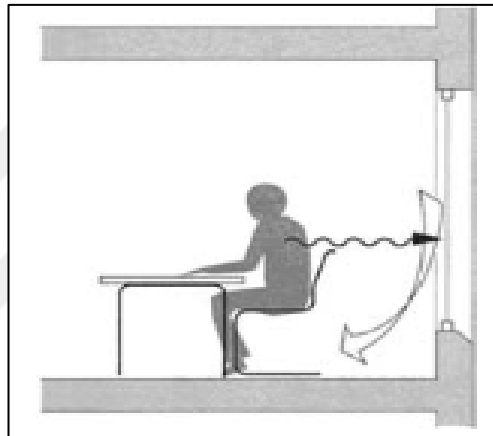
- a) Behavioral adjustment- that means all consciously or unconsciously actions made by a person in order to control or to regulate the body's thermal balance. For example, removing an item of clothing, turning on an air conditioner, etc.)
- b) Physiological adjustment - includes changes in the physiological responses that result from exposure to thermal environmental factors, such as acclimatization and genetic adaptation.
- c) Psychological adjustment - The psychological dimension of thermal adaptation refers to an altered perception of, and reaction to, sensory information due to past experience and expectations. (Dear et al. 1997)

There are some aspects that need to be considered in order to overcome the conflicts between passive and low-energy measures and comfort.

For instance, avoid overheating the space in relation to the occupant's level of activity and clothing; avoid local radiant heat loss and down-draughts due to the large surfaces of glazing, by using multiple glazing and careful positioning of heat emitters that shown in Figure 2.15;

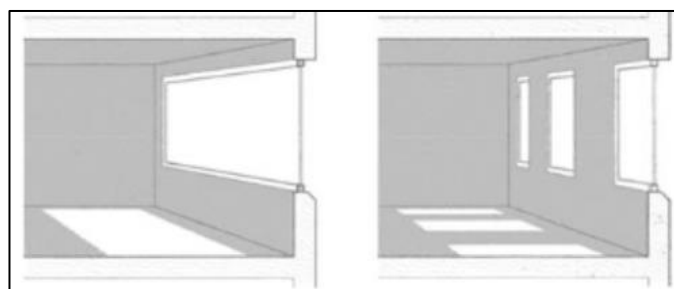
Avoid local overheating of occupants by the direct sun providing shaded areas as shown Figure 2.16. Local overheating is a common mistake, caused by a desire to get benefits from solar radiation and to maximize thermal comfort and daylighting. (Baker and Steemers 2000)

Figure 2.15: Radiant heat loss and cold down-draughts



Source: Baker and Steemers, 2000.

Figure 2.16: Continuous glazing and intermittent glazing.



Source: Baker and Steemers, 2000.

2.5.2 Indoor air quality

Likewise, to the thermal comfort, indoor air quality is also was one of the most important concerns of the decision-makers. Carbon dioxide concentration is used as an indicator of air quality In the HVAC system since it is the main fluid waste that excels by occupants.

Carbon dioxide concentration is used as an indicator of air quality since it is the main fluid waste that excels by occupants and HVAC systems. The levels of indoor CO₂ concentrations are:

- a. 350-1,000 ppm – standard concentration of space with good indoor air quality.
- b. 1,000-2,000 ppm- the concentration with drowsiness and poor air.
- c. 2,000-5,000 ppm – the unpleasant concentration that can have an impact on health.

It is used to think that air pollution is could be only the outdoor, however, the air in your house or office could also be polluted. There is a wide range of indoor pollution sources have appeared. Mainly, they come from household appliances, cleaning materials, plastic furnishings, etc. It is believed that the outdoor conditions are not in the competence of the designer, but to be aware of these factors is important while choosing fresh air inlets, for both the natural or mechanical ventilation (Baker and Steemers 2000).

On the other hand, there is no guarantee that a particular system will be satisfactory high, both of the ventilation systems are based on the approximate estimates. Furthermore, in order to find a compromise among air quality and energy concerns, it is important to pay attention to the seasonal use of windows and appropriate design of the openings.

2.5.3 Daylighting

Providing daylight is directly related to the spatial and architectural design. Besides, the elements of daylight such as windows and other surfaces are playing a significant role in the visual expression of the architect's design. In addition to that, daylighting design has an influence on both energy use and indoor comfort of the building. The energy use of buildings can be reduced by the proper design of fenestration that will provide natural light and will not require extra artificial lighting. For instance, a typical office shallow-plan with depths not greater than 15m that is occupied for standard working hours can obtain 70% of daylight (Baker and Steemers 2000). The factors that influence the intensity and distribution of daylight are the room surfaces, the shape of the room, and the detailed design of openings.

According to EN 17037, sufficient natural illumination for building users is considered a minimum 100lux and maximum as 300 lux. For artificial lighting, it depends on the type

of activity, for instance in the classrooms the values are 300 lux, dining areas are about 150 lux, kitchens 500 lux, bathrooms average are 200 lux.

2.5.4 Thermal Comfort Standards

In fact, thermal standards are aimed to define classifications, parameters, and conditions for providing adequate conditions for the comfort of inhabitants. Nowadays, the indoor comfort of occupant's standards is identified in two primary documents such as EN 15251 ASHRAE 55 and EN 15251, they both related to the residential and commercial buildings. These standards consist of mandatory requirements and predetermined measurements for HVAC system designers in order to meet the needs of inhabitants and provide sufficient indoor thermal comfort level.

It should be said, that with the EPBD initiation the importance of these standards is significantly raised. The abbreviation EPBD means "The Energy Performance of Buildings Directive", the document is aimed to refine the energy efficiency of buildings. Initiated in 2002, the Directive began with the adoption of the Kyoto Protocol where the EU countries are assigned to reduce CO₂ emissions and to diminish climate change.

The standard EN 15251 was mounted with European Standardization Organization (CEN) initiation and became a part of the EPBD implementation. EN 15251 aimed to identify, the design properties of the indoor comfort. To clarify, the standard addressing the inputs of design and assessment of energy performance parameters for:

- a. thermal environment;
- b. indoor air quality;
- c. lighting;
- d. acoustics;

The standard is set four categories of buildings shown in Table 2.1 that include the expectations and perception of the comfort of occupants and as well as the recommended design criteria of comfort.

Table 2.1: Description of the applicability of the categories used.

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like sick, very young children and elderly persons
II	The normal level of expectations and should be used for buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories.

Source: BS EN 15251:2007 2007

PMV (predicted mean vote) and PPD (predicted percentage dissatisfied, operative temperature) are accepted as two indicators of general thermal comfort parameters in this standard. PMV- is the average vote of a large group of people on the seven-point thermal sensation from hot to cold. PPD is related to PMV, it is an index that predicts the percentage of thermally dissatisfied people. Thus, recommended categories for the design of mechanical heated and cooled buildings are split into three categories:

- a. $PPD < 6\%$ ($-0.2 < PMV < +0.2$),
- b. $PPD < 10\%$ ($-0.5 < PMV < +0.5$),
- c. $PPD < 15\%$ ($-0.7 < PMV < +0.7$)

Specifically, to the thermal comfort parameters, the Figure 2.17 shows the operative temperature ranges for hourly calculation of cooling and heating energy divided into three categories and different type of the building. However, the factors like local custom or desire for energy saving could have an effect on the mean design temperature. (BS EN 15251:2007 2007)

Figure 2.17: Temperature ranges for hourly calculation of cooling and heating energy

Type of building or space	Category	Temperature range for heating, °C	Temperature range for cooling, °C
		Clothing ~ 1,0 clo	Clothing ~ 0,5 clo
Residential buildings, living spaces (bed room's living rooms etc.) Sedentary activity ~1,2 met	I	21,0 -25,0	23,5 - 25,5
	II	20,0-25,0	23,0 - 26,0
	III	18,0- 25,0	22,0 - 27,0
Residential buildings, other spaces (kitchens, storages etc.) Standing-walking activity ~1,5 met	I	18,0-25,0	
	II	16,0-25,0	
	III	14,0-25,0	
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, class rooms, Sedentary activity ~1,2 met	I	21,0 – 23,0	23,5 - 25,5
	II	20,0 – 24,0	23,0 - 26,0
	III	19,0 – 25,0	22,0 - 27,0
Kindergarten Standing-walking activity ~1,4 met	I	19,0 – 21,0	22,5 - 24,5
	II	17,5 – 22,5	21,5 – 25,5
	III	16,5 – 23,5	21,0 - 26,0
Department store Standing-walking activity ~1,6 met	I	17,5 – 20,5	22,0 - 24,0
	II	16,0 – 22,0	21,0– 25,0
	III	15,0 – 23,0	20,0 - 26,0

Source: BS EN 15251:2007 2007

2.5.4.1 ASHRAE 55: Thermal Environmental Conditions for Human Occupancy

It is claimed that the approach of the standard is to identify the right values for indoor thermal comfort of occupants. The indoor environmental factors such as temperature, thermal radiation, humidity, and airspeed are addressed within the scope of the standard. Hence, it is intended that all parameters in the standard be applied together since indoor comfort is complex and needed the interaction of all above-mentioned factors.

Again as a scope, ASHRAE 55 identify thermal comfort conditions, that acceptable for people health at atmospheric pressure equivalent to altitudes up to 3000 m indoor spaces designated for human occupancy for periods not less than 15 minutes (American National Standard 2010). The difference between the ASHRAE standard and BS 15251 is that ASHRAE excludes the non-thermal environmental factors as air quality, acoustics as illumination.

Accordingly, there are six primary factors that need to be addressed in order to define conditions for thermal comfort. These are:

- a. Metabolic rate
- b. clothing insulation
- c. Air temperature
- d. Radiant temperature
- e. Airspeed
- f. Humidity

As in EN 15251, ASHRAE 55 uses the operative and effective temperatures to specify the acceptable thermal environmental conditions. In addition, the standard defines measuring thermal environment parameters as well as provides calculation algorithms.

2.6 CASE STUDIES

Over several decades, our world is facing massive environmental challenges, these challenges changed our requirements for the building envelope. Today building envelope tends to be more adaptive and interactive with the outdoor and indoor environment. In respect to this, adaptive facades are considered as a next step upgrade in both energy efficiency and indoor environmental comfort.

There are wide a range of successfully implemented projects with the integration of adaptive facade systems to the buildings. The following part will be conducted by an overview of selected case study projects of existing adaptive facade buildings.

2.6.1 Al Bahar Towers

The project represents two 25 story towers in Abu Dhabi (Figure 2.18). It was intended to create a symbiosis of an outstanding landmark that reflects the region's heritage and modern design using technologies.

Figure 2.18: Al Bahar Towers



Source: S. Attia Evaluation of adaptive facades: The case study of Al Bahr Towers, 2018

The design was done by Abulmajid Karanouh (Aedas) architects, two circular 150- meter towers with a curtain wall with an adaptive folding shading system shown in Figure 2.19. The traditional concept of Mashrabiya was commonly used in Islamic architecture for providing better privacy, solar control, and natural ventilation. The most appropriate material in terms of performance of the concept was wood.

**Figure 2.19: Adaptive folding shading system
of Al Bahar Towers**



*Source: S. Attia Evaluation of adaptive facades:
The case study of Al Bahr Towers, 2018*

The building represents one of the most significant computerized facades in the world, this was achieved by algorithms and parametric methods of modeling. More than 1000 Mashrabiya units placed for east and west, and react according to the outside conditions and predefined commands.

In fact, the adaptation to the environmental conditions was the primary goal of the project, due to the climate region of Abu Dhabi with the humid and hot climate where the peak temperatures in summer reach about 49 °C with the maximum humidity level.

Shown in the Figure 2.20, system applied in the envelope is a curtain wall that consists of panels with a height of 4200mm and 900–120 mm width. The shading mashrabiya is separated from the curtain wall, this approach allows to dynamic systems to operate independently from the main structure (Attia 2017).

The origami umbrellas are the main association of the dynamic systems, due to the triangular forms of each unit. They designed to create movement in response to the angles of solar radiation by folding and unfolding approach (Attia 2017).

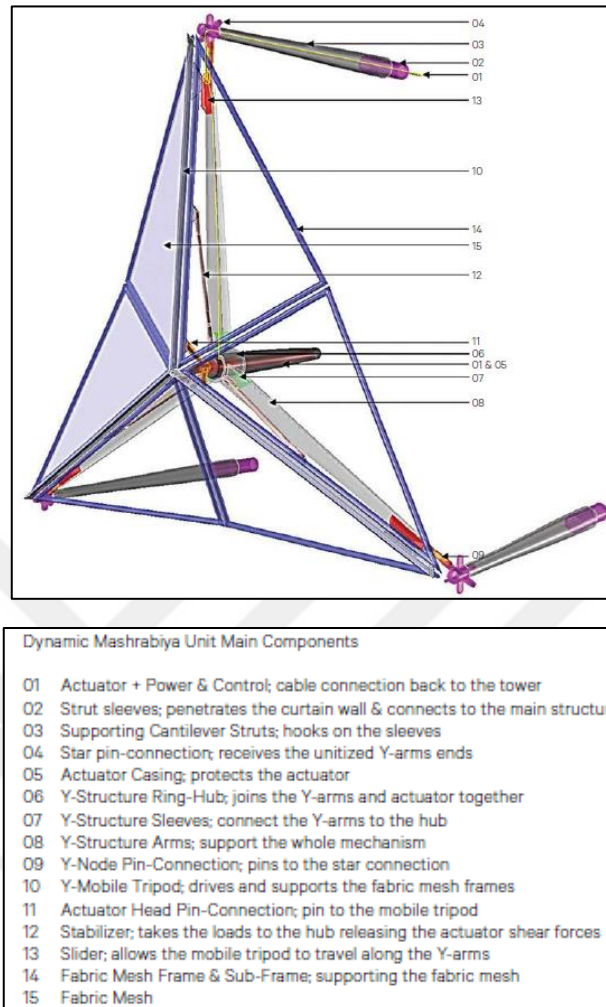
Figure 2.20: A close view of the mashrabiya and curtain wall



Source: S. Attia Evaluation of adaptive facades: The case study of Al Bahr Towers, 2018

The detailed 3D model of components of the shading system is shown in Figure 2.21, the system is made by supporting framed stainless steel, aluminium active frames, as well as glass wool mesh infill and other elements.

Figure 2.21: 3D model of an individual shading device.



Source: Interactive Architecture: Adaptive World. Fox, 2016.

The 1049 units are each automatically controlled by a central Building Management System (BMS), Siemens technology runs a system within pre-set automated control following the sun's path during the year.

The dynamic mashrabiya solar screen of the Al Bahar Towers may represent a new benchmark in the field of adaptive building systems. Just as with other technologies, the more popular and common this system becomes, the more its reliability and affordability will increase (Fox 2016).

To sum up, the main benefits of the project are improved user comfort, a 20% reduction in carbon emission and energy savings. As well as the unique architectural design, representing the local heritage of the region.

2.6.2 Kfw Westarkade

Located in Frankfurt, The KfW Westarkade is one of the greatest examples of eco-building and being one of the greenest office structures in the world. The 14-story building was designed as an extension for completing an existing KfW's headquarters buildings from the last four decades. (Figure 2.22) Streamlined form aimed to integrate into the urban context and to exploit the prevailing winds for natural ventilation.

The KfW Westarkade Tower is an example of highly efficient design the building's skin and the structure that meet all environmental, and human conditions. The high technology of the active building skin has a counterpoint in the atmospheric use of color, which adds the layer of chromatic variation as one moves along the street. (Figure 2.23)(Fox 2016)

The aerodynamic form is oriented to the predominant wind direction and with the application of the double-layered, wind-pressurized facade makes this building ecologically considered.

Figure 2.22: KfW Westarkade, Frankfurt



Source: Fox, 2016. Interactive Architecture: Adaptive World.

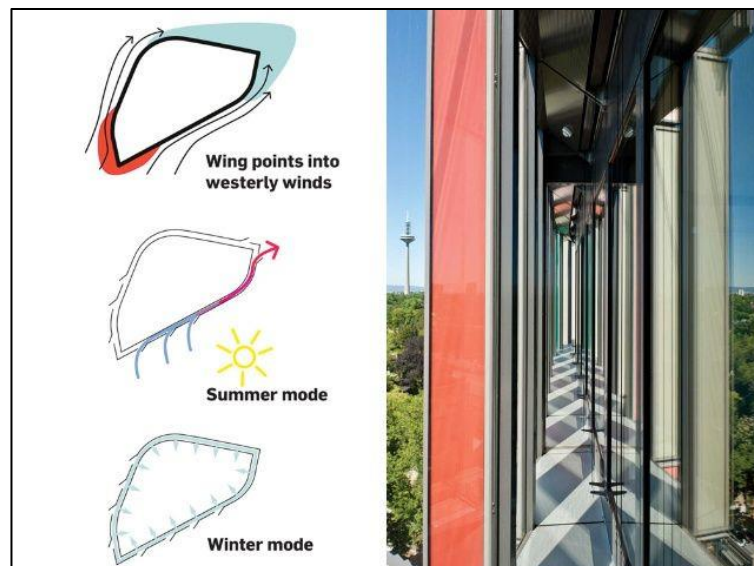
Figure 2.23: Facade detail. KfW Westarkade, Frankfurt.



Source: Fox, 2016. Interactive Architecture: Adaptive World.

As shown in Figure 2.24, the building skin consists of two layers: the double-glazed facade of the offices, with normal, operable windows, is enclosed within a second single layer of glazing and an air buffer between the two layers. This creates a “pressure ring” around the inner windows, protecting them from turbulent weather conditions that otherwise prevent their being opened at such heights (Fox 2016).

Figure 2.24: Performative qualities of the "Pressure Ring" in plan.



Source: Fox, 2016. Interactive Architecture: Adaptive World.

This unique system of protected window opening provides natural ventilation for offices throughout 8 months of the year and creates independence from outdoor weather conditions without drafts or unwanted heat loss.

The deep floor plan of the buildings is shown in Figure 2.25 includes the single, double, and group of offices with perfect circulation and views of the surroundings and the Frankfurt skyline access is provided by the curved and diversified spaces of the corridors. These corridors are accompanied with exterior windows for natural lighting and view.

Figure 2.25: Plan of the third floor. KfW Westarkade, Frankfurt



Source: Fox, 2016. Interactive Architecture: Adaptive World.

Consequently, the principle of the double façade of the building works as a passive thermal solar collector and prevents heat loss and conserve energy. The outer skin of the double façade can be opened completely in order to avoid overheating of the building in summer.

2.6.3 AGC GLASS BUILDING

Figure 2.26 shows the AGC Glass Building head office located Louvain-la-Neuve, 25 km to the south of Brussels. Nearly zero energy building was designed by Philippe SAMYN and PARTNERS as a highly efficient modern workplace for over 500 employees.

Figure 2.26: AGC Glass Building.

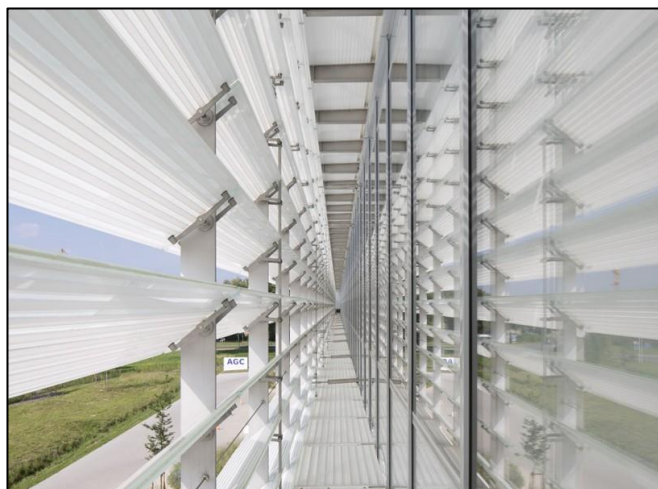


Source: Fox, 2016. Interactive Architecture: Adaptive World.

It is stated that the requirements for HVAC and artificial lighting are minimal for the scale of building and offset by the reliance on renewable energy such as photovoltaic panels on the roof and heat drawn from ground heat pumps.

The building designed with a double outside skin of glass, where the first layer is inside and has double glazing extra-clear glass with high insulation. Whereas, the second skin which is outside is unique itself since it made up from dynamic louvers of screen-printed glass with alternating white stripes on either side. The louvers represented in Figure 2.27 have an automatically follow to the sun's movement with providing the maximum amount of natural light and protecting occupants from overheating.

Figure 2.27: The double skin façade with its glass louvers. AGC Glass Building.



Source: Fox, 2016. Interactive Architecture: Adaptive World.

The compromise between compact type for energy performance and spatial organization for better comfort in workplaces made the project plan divided into four wings as it is shown in Figure 2.28. The two large courtyards are directly obtaining the wind and sun. Most of the workplaces arranged in less than 4 m distance from the wall but still have a perfect visual outside view.

Figure 2.28: First floor plan. AGC Glass Building.



Source: Fox, 2016. Interactive Architecture: Adaptive World.

It is obvious that all the case studies with Adaptive Facade Systems are improving energy efficiency and provide better indoor comfort. However, there is a big difference in the design and operation between all of them. For instance, in the case of Al Bahar Towers, the design reflects the region, there are elements of Islamic architecture such as wooden shading elements. While in the project KfW Westarkade that is in Frankfurt, the main components of the skin are glass and colors. The Al Bahar Towers are designed to get benefit from the solar radiation, in contrast to KfW Westarkade where the main element is wind

It is observed that spatial organization, the facade components, control, and operation are varied among these projects. However, the main factor is integrated passive and active strategies to the building that gets benefit from solar and wind energy and as a result, improve energy efficiency and indoor comfort.

3. STRATEGIES AND PRINCIPLES TO DEVELOP ADAPTIVE FAÇADE SYSTEM

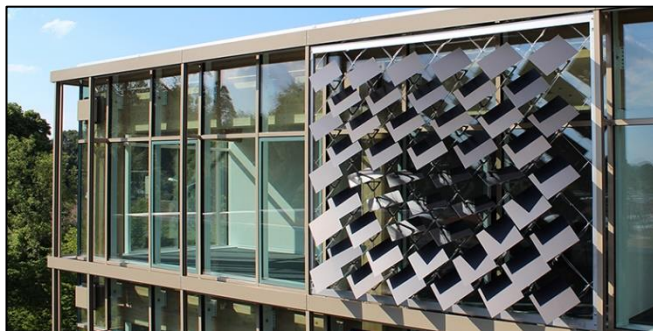
Façade has to act as a protective screen for indoor environments from outdoor conditions. Moreover, the modern envelope needs to perform for energy efficiency, provide adequate daylighting and fine indoor air quality. As a matter of fact, many strategies of building's façade have been developed throughout history, however, today the best example that demonstrates all the importance of the filtered envelope concept is adaptive facade systems. This chapter will discuss the basic principle and existing types of AFS, as well as key parameters and methods for developing such a system.

3.1 ADAPTIVE FAÇADE SYSTEMS

To begin with, the basic principle of adaptive architecture is to design elements that can be created façade geometry which is responsive to environmental conditions and applied to build's façade and makes it sustainable, one of the examples of AFS concepts are given in the Figure 3.1.

Adaptive facades systems (AFS) are building envelopes that are able to react and adapt to changing boundary conditions within the kind of short-run weather fluctuations, diurnal cycles or seasonal patterns. The term adaptation here means that facades capable to react to, or benefit from, changes in outside climatic conditions and dynamic inhabitant requirements (Loonen et al. 2013).

Figure 3.1: Adaptive solar façade.



Source: ETH Zurich

The basic principle of the concept can be described as an adaptation approach, which is usually associated with living organisms in nature. For example, human behavior can be given, how people can adapt their behavior according to outdoor weather with adjusting clothes the same principle has an AFS.

The scope of AFS is wide, the facade has great potential that can be applied in modern new buildings as well as for retrofitting approaches in existing. The envelope with adjustable insulation, ventilation, humidity, solar and heat control makes AFS unique and promising.

AFS strategy is aimed to improve energy efficiency and enhance indoor comfort. In this respect, in the scope of near-zero energy building (nZEB), where all the buildings have to consume zero energy and be interactive, AFS can be a great contribution to these reforms. Problems with climate change cause the demand to adapt play an important role in the buildings today, making AFS the best alternative solution.

3.1 TYPE OF AFS

These systems have different names, but the main principle of design is adaptable performance. The design strategies are also varied, some of them differ with automatically based control or technological features.

3.2.1 Active facades

The feature of the active facade that they have technological inputs in the concept, it means that the envelope can change particular facade components according to indoor and outdoor conditions as shown in Figure 3.2, and with reducing energy consumption and achieving human comfort. This technology can be driven both manually and automatically.

Figure 3.2: Active Façade Nordic Embassy in Berlin.



Source: Wikipedia

3.2.2 Intelligent Façade

The idea and research about new building skin technologies assisting in the evolution of responsive buildings were set out by Michael Wigginton in 1985s. The idea itself was not new, it had been already highlighted by architects and engineers. However, Wigginton with the assistance of distinguished engineers started to evaluate the studies intensively.

In 1995 it was 10 step program called “Intelligent Façade” intended to investigate the feasibility of façade which will collaborate with the technologically controlled mechanism itself and provide indoor comfort conditions, although the outdoor conditions will differ. The concept of the intelligent building is based on the integration of good passive design in the variable building types and as a result, decreases the expenditure on building active systems and improve the energy efficiency of the building (Wigginton 2002).

In fact, facades need to respond and adopt any conditions and perform functions that can be contrasted to each other: daylighting versus energy efficiency, ventilation versus views and energy generation (Kensek and Hansanuwat 2011). Intelligent facade features are responsible for dynamic capabilities, facade’s movement based on timescale changes and taking into account the environmental aspects for improving building energy efficiency.

3.2.3 Kinetic Façade

Kinetic or adaptive systems are engaged in generating the surfaces and inextricably linked to digital architecture and computational fabrication design. The Figure 3.3 demonstrates that the system consists of three-dimensional layers which are operated the two-dimensional skin elements, however, these layers are embedded in the skin and attached to the material system used. (Maragkoudaki, 2013)

Figure 3.3: Kinetic façade. Kiefer Technic Showroom, Bad Gleichenberg.



Source: Arch Daily by Irina Vinnitskaya.

This kinetic adaptive concept is responsive for any flow energy, natural and artificial, and that feature affects the performance of the building in terms of climate and user. The façade technological solutions designed to increase control comfort inside the building, and it is a good alternative for application in different climate regions, locations, and building types since the design concepts for such systems have no boundaries. Parametric design is the key factor of kinetic systems, the envelope operation is provided by automatically system and actuation mechanism that creates the movement.

3.2.4 Interactive Façade

The meaning of the word 'interactive' is commonly used in the computer-based platforms and other technological fields and rarely used in architecture. Nevertheless, the interactive meaning of facade comes from the idea of human participation in building performance. However, they could also use an automated building management system. The aim of interactive envelopes is again optimization of energy and ensuring the comfort of the inhabitant by themselves.

Figure 3.4: Interactive Façade. SolPix, New York.



Source: Arch Daily 2008

3.2.5 Responsive Façade

Responsive facade comes in the same meaning as adaptive and interactive, since this type of facade includes three interaction: with occupants, space where they dwell, and the environment. Devices for managing natural ventilation in combination with mechanical ventilation systems are the main strategies in this type. The comprehensive system is comprising similar functions and performance characteristics as in kinetic and Intelligent Façade such as real-time automatization and other technical aspects as well included as in other types of AFS. In fact, the responsive facade is the system that can have an impact on indoor space by taking advantage form environmental conditions such as radiation, ventilation, and temperature.

3.3 MAIN DESIGN PARAMETERS OF AFS

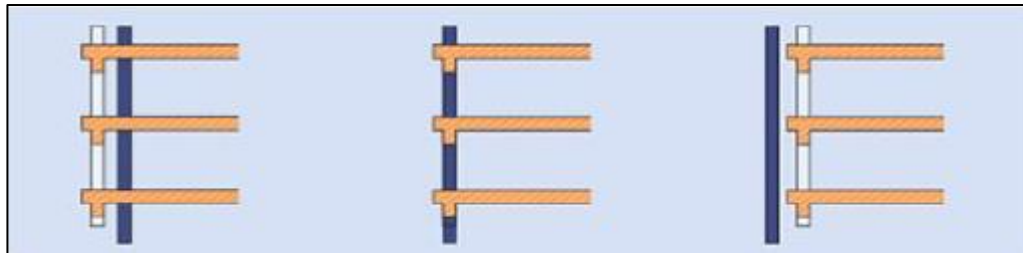
Nevertheless, the design and concepts of the AFS can differ, there are some common design steps that exist in all of the systems. These are the determination of structural placements, selection of mechanical movement systems and flexibility of AFS, etc.

3.3.1 Determination of structural placement of AFS

As shown in Figure 3.5, the very first action for designing AFS is the decision on the exact structural integration into building. The common application of such a system is

usually placing in the outer facade of the structure. This alternative is considered as most protective from solar radiation, but there are major risks related to decreased lifespan due to the damages that may occur, as well as high installation cost.

Figure 3.5: Position of AFS: 1. front, 2. in the skin; 3. behind.



Source: Sommer, 2010.

The common approach is conceived double-skin facade is the second alternative, where the AFS integrated directly inside the envelope. In comparison to front placement, this alternative will not reduce the performance of building active systems.

The third option is inside placement is rarely used in AFS design, however, no risks of defects are existing. however, the most noticeable disadvantage of this alternative is that it will decrease the interior zone space.

3.3.2 Mechanisms of AFS

The active movements of AFS depend on two main classes. The first is a macro scale and is responsible for changes in the largest components of AFS. For instance, the changes of shading devices, panels or even whole shell element, movement such as sliding, rolling and expanding. The second class is the micro level movement which means the adjustment of material properties such as changing of opaque and transparent AFS elements. These are often associated with changes on the surface level such as temperature, radiation and, lights.

3.3.3 Adaptability, Multi-ability, and Evolvability of AFS

There are three aspects of flexibility, during the life span of the building with AFS. According to the statement of (Ferguson et al. 2007), **adaptability** is the ability of a

system to deliver planned functions considering multiple criteria under changeable conditions through the changing physical values of the design elements during the time.

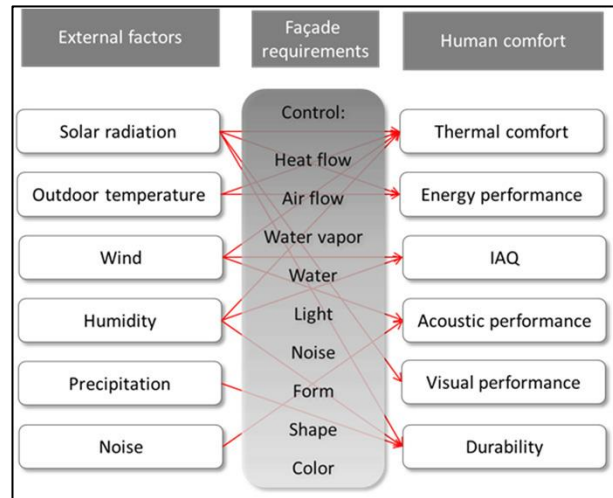
Multi-ability is related to non-simultaneous performance requirements. Non-simultaneous means that the façades are able to play different roles over time. In comparison to the ‘adaptability’, multi-ability refers to the carry out of multiple objectives consistently instead of concurrently.

While adaptability and multi-ability are emphasized on short term targets variations, **evolvability** is the long-term handling flexibility. Evolvability means the ability to react to changes in the future, even uncertain events, it can be employed to deal with changing environmental conditions. All the aspects will help for the operation of AFS as it was intended, without any unpredicted changes and uncertain factors.

3.3.4 Adaptability and External Factors.

One of the main considerations while developing AFS is the environmental conditions, it means the determination of the climate region is crucial. In other words, outdoor climate factors such as solar radiation, outdoor temperature, wind, humidity, precipitation, and noise are needed to be analyzed for certain region. The Figure 3.6 from the studies of Aelenei et al., demonstrates the schematic role of adaptive façade in terms of external conditions and human comfort.

Figure 3.6: Schematic role of adaptive façade.



Source: Aelenei et al. 2015

Firstly, solar radiation is a major outdoor factor related to the performance of the building, as seen in Figure 3.6, thermal comfort and visual performance such as a sufficient level of lighting are depending on sunlight. Thus, AFS should be designed for providing adequate lighting in the room without overheating. Moreover, solar radiation is responsible for energy efficiency, if the proper passive strategies are applied the solar gain can decrease the need for heating systems.

Humidity and Outside Temperatures are the conditions of weather that are changing hourly, daily, seasonally. Thus, with the proper evaluation and prediction scenarios for each period of these changes, it is possible to integrate a passive heating-cooling system in AFS and provide thermal comfort with a sustainable solution.

Another characteristic of indoor comfort - air quality, is also impacted by outdoor humidity.

In order to achieve an adequate level of comfort by designing AFS, the wind must be also considered, because it directly affects the amount of natural ventilation of the building. The level of Precipitation should be included in the analysis to provide protection through the building envelope. The noise from outdoor is a common issue in conventional buildings, the way to improve the acoustic performance is to put emphasis on sound design as another important parameter of AFS design.

3.3.5 The timescale in relation to AFS performance

As it was mentioned before, buildings are influenced by a variety of environmental factors, however, these impacts occur at different orders of time. The most dominant time scales in relation to AFS could be explained as follows:

- a. Seconds- the short-term fluctuations which influence the building envelope, wind direction and wind speed can be given as an example of it.
- b. The second changing condition is - minutes. In practice, all AFS are aimed to reduce energy consumption with the application from solar radiation and shading, these all calculated via the rate of change in minutes (Marysse 2015).
- c. Hours is another time indicator of the changeable outdoor conditions. The sun's path typically measured in hours.
- d. Daily alterations are present as a result of the occupants' behavior in the building and meteorological boundary conditions. Some of the AFS is designed to take advantage of a fixed 24 h scheme.
- e. Seasonal changes are the last group of the timescale category. The different seasons' such as winter, summer, spring, and autumn have different climate conditions (Loonen et al., 2013).

3.3.6 Control systems of AFS

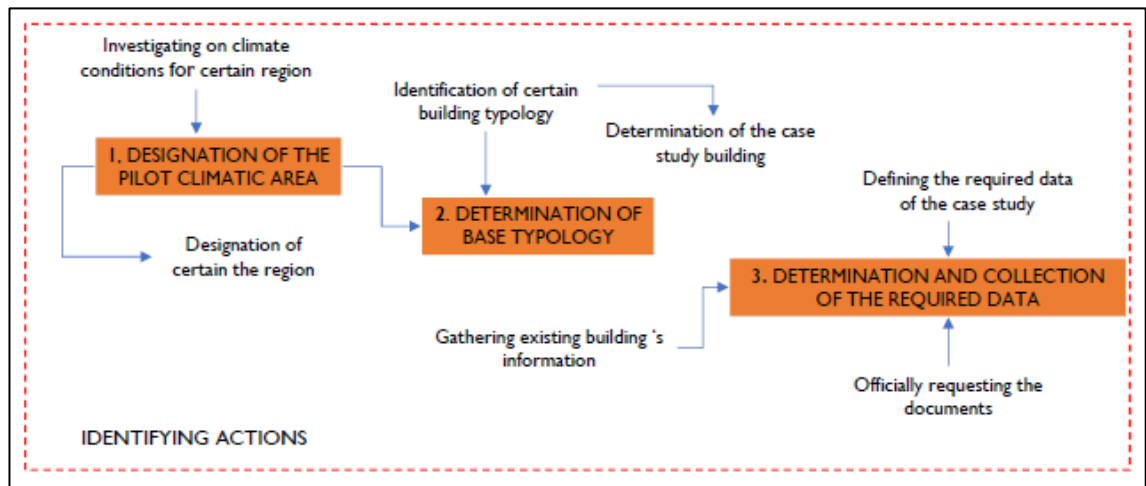
Another important performance parameter of AFS is - control. It is stated that there are only two major types, extrinsic or intrinsic. The extrinsic control strategy works according to required performance; thus, it transfers the feedback from outdoor conditions and activates the appropriate adaptation. The aforementioned kinetic systems that operate via actuators and sensors are the best example of extrinsic control. Managing can be done on both local and centralized level.

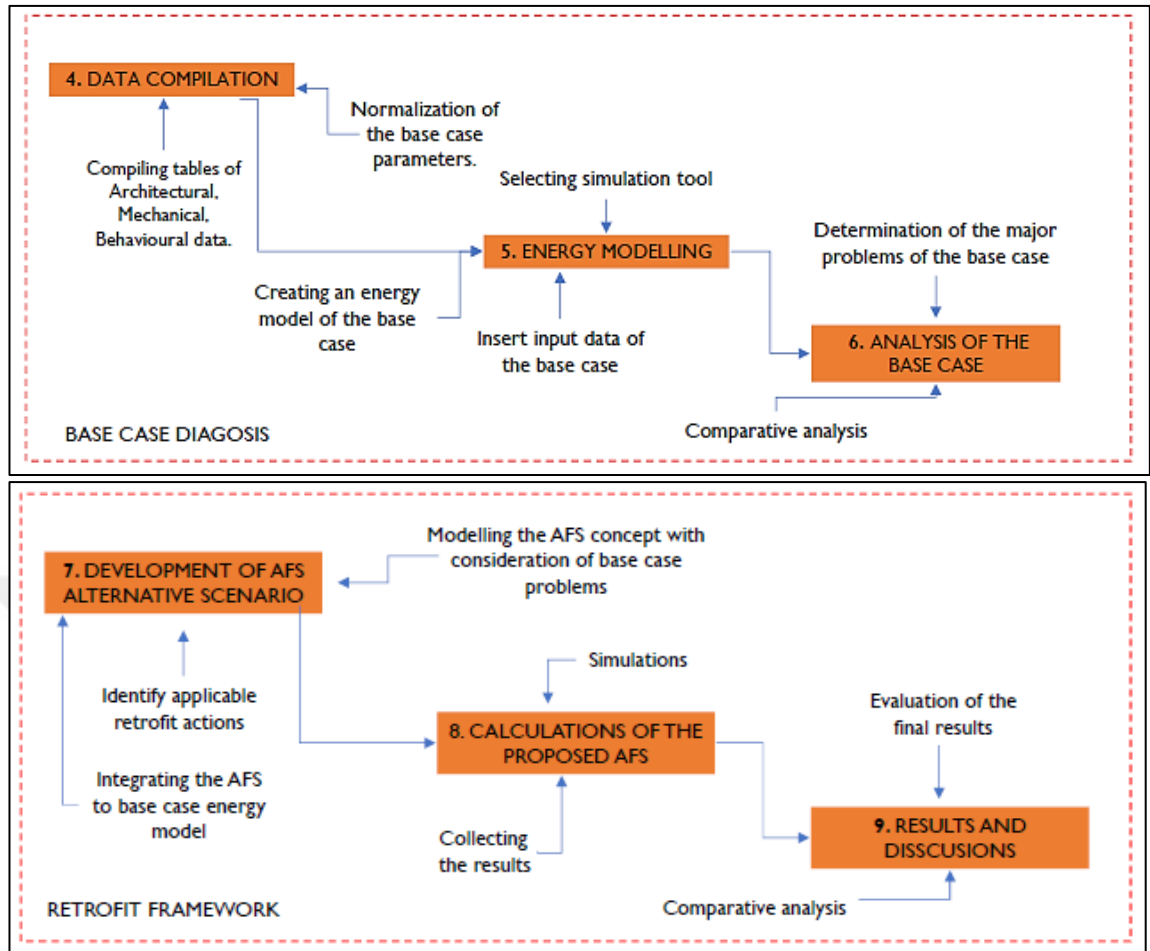
In contrast to extrinsic, the decision of intrinsic control is made by transforming environmental impacts such as wind pressure, solar radiation is activating the adaption of the facade. In this system control sensors and actuators are working simultaneously. The beneficial side of intrinsic controlling is that it not requires any energy to operate, but the main drawback is limited in adjustment configurations, so if unpredicted environmental conditions will occur the system will not adapt.

4. METHODOLOGY

Firstly, it is important to designate the primary area of the study in order to investigate the climatic features of the chosen region. The following step of the developed methodology is to determine the building typology and exact base case for further examination of energy expenditure and indoor comfort requirements. Based upon on these determinations, require the case study building data which will be used as input parameters in further analysis. After that, when the data is collected it is important to compile all the information into three categories: architectural, mechanical and behavioral. According to compiled data, the normalization of parameters of the base case will be done and used as input data for energy modelling. Energy modelling of the base case building will be created and simulated using Design-Builder software. Moreover, analysis of the base case energy model in terms of energy performance and indoor comfort will be done. Then, the AFS with the consideration of base case problematic aspects will be developed and simulated. The calculation results of the proposed approach and discussion on the usefulness of the AFS in terms of energy efficiency and indoor comfort will be done in the final part.

Figure 4.1: Methodology of the research.





4.1 DETERMINATION OF PILOT CLIMATE REGION

Determination of the region's climate plays a key role in the developed methodology. Firstly, it is important to investigate and understand the features of the local climate, this will give a clear insight to further action in designing new or retrofitting approaches in the existing buildings. With the understanding about particular climate conditions we can ensure or improve the indoor comfort and as the main purpose, the human comfort level. Furthermore, we can decrease energy consumption, by adopting new passive approaches which are directly related to weather and climate. One of the best examples of implementing the knowledge of the climate in the building design is vernacular architecture, where the local climate and materials, and cultural conditions are interconnected in building design.

In order to achieve the maximum indoor comfort decision- makers must investigate the climate features of the region, especially pay attention to these four primary characteristics:

- a. air temperature;
- b. air movement,
- c. radiation;
- d. humidity.

It is necessary to accurately determine that characteristics and climate scenarios that have or will have a significant impact on the building. In addition, a particular region can have several climate zones, that vary mostly by temperature and humidity level.

The statistical weather data about, the extreme and normal climate conditions throughout a year, the seasonal variations of temperature, predominant wind directions and other specific information need to be defined according to the particular region. The aim is to get a picture of typical weather fluctuations at different seasons. Actually, all these details are collected and published by meteorological stations of the region and open to access.

The climate features in developed methodology are also important to define the problems related to the comfort of occupants, even if this term is subjective, yet there are some well-known established standards. Indoor comfort conditions are linked with outdoor conditions, and frequently with the lack of proper attention to the climatic features of a particular region on the early design stage, it has resulted on insufficient thermal comfort of the building. Moreover, the energy performance of the building is also affected by climate conditions, the lack of climate considered design causes the high energy consumption of the building.

Fortunately, decision- makers today can solve such problems in different ways, through integrating climate adaptive facades, passive strategies and retrofitting scenarios.

For instance, with the considerations of all above-mentioned climate criteria, it is possible to remain indoor temperature cold while hot temperatures outside, and warm in cold days, with minimum external energy.

Climate analysis is required part in developed methodology since it gives information for both defining the indoor comfort and problems and developing adaptive facade concept.

Rarely, there is a slight difference between the regional climate data from meteorological stations and the actual site climate. Accordingly, the decision-makers should be aware of the possible pros and cons of the particular site.

4.2 DETERMINATION OF BASE TYPOLOGY

Identification of the certain building typology in the meaning of its function and form is the second major aspect in this methodology. Since with the classification of the building, decision-makers can understand what sort of improvements are needed in particular case.

Moreover, the clarifying all typological parameters means that the requirements for the case building in terms of lighting, HVAC systems, indoor comfort indices, occupant behavior and energy demand will be identified.

The classification of the building type in terms of function is crucial. As well as the defined building type. As it was mentioned before, the exact functional purpose of the building will help to understand the information related to the HVAC systems, lighting requirements, user behavior, thermal and energy performance according to the international building standards. Depend upon the character, density of occupancy, the type of use the buildings can be classified into different categories such as residential, educational, assembly and other.

The overall building geometry is also included in part of the determination of building typology. For instance, does the building plan belongs to the common type of building in this category, as well as the height and shape parameters. As a result of these determinations, the decision-maker will have an overall representation of the building. For instance, while deciding about the type of facade that will be appropriate for the school or residential building, the building performance requirements that are in privilege in that particular case.

4.2.1 Determination of case study

After the determination of the pilot climate area and the type of the building, decision-maker should select and define the base case building for further examination. Mostly, the base case is chosen from problematic building categories such as historical heritage, buildings that are not suitable for living and in need of refurbishment, high densely occupied buildings such as schools, etc. The availability of data related to the building is one of the most important requirements while choosing the case study.

Furthermore, while deciding on a case study it is necessary to consider the usefulness of the applying approach on that particular building.

4.3 DETERMINATION AND COLLECTION OF THE REQUIRED DATA

Respectively, after choosing a specific case study building, all required data could be divided into three major categories such as architectural properties of the base case, mechanical systems of and third is occupant behavior. The list of required data will be classified according to the framework of the study and the simulation program and after requested from responsible authorities. The technical data that are required such as CAD drawings of the project is required for the experimental part.

There is no doubt that in order to reveal the problems of the building performance the decision-makers should evaluate the situation from different perspectives. That is why it is recommended to make a survey of occupants, this will help to understand their overall perception and level of satisfaction from different aspects of building performance. For instance, how they satisfied with the thermal performance or indoor air quality, does the natural lighting is sufficiently distributed in the rooms.

Secondly, with the interviews, the information about the occupancy schedule can also be collected, this is an important point that will affect the analysis. The questionnaire will reveal the typical number of hours when the room is occupied, how many hours inhabitants use artificial lights, how many hours they open the window per day etc. The results of such a survey can give a strong understanding of what are the primary objectives in further improvements.

4.4 DATA COMPILATION

After collecting all the information and documents about the project, these raw data must be compiled. Compilation could be achieved by dividing into respective parts and segments. In order to better evaluate the validity of the gathered information, compiling data should be represented in the table and graph figures. In the framework of the methodology, the compiling groups are divided as follows: architectural, mechanical and behavioral. Compiling of architectural data should consist of all design parameters and a list of materials of the representative buildings. While the compilation of mechanical systems for the base case includes the general tables such as heating, cooling, ventilation, and lighting schedules. While the compilation of mechanical systems for the base case includes the details about heating, cooling, ventilation, and lighting system and operation schedules as represented below:

Heating

- a. type and capacity of the boiler;
- b. type and parameters of radiators;
- c. duration of operation in hours/ days and days/ year;
- d. details about control system (automatic/ manual, number);
- e. Setpoint temperatures.

Cooling

- a. type of AC system;
- b. number of AC;
- c. duration of operation in hours/ days and days/ year;
- d. details about control system (automatic/ manual, number);
- e. Setpoint temperatures.

Mechanical Ventilation

- a. type of air exhaust;
- b. number of air exhaust;
- c. number of air flush per day;
- d. quantity of air exhausted per flush;

Natural Ventilation

- a. number of windows;
- b. size of windows;
- c. sash size of the window.

Lighting

- a. type of lighting;
- b. number of lighting bulbs;
- c. details about control system (automatic/ manual);
- d. duration of operation in hours/ days.

4.4.1 Normalization of the base case parameters

Following the collection and compilation of data, decision-makers should put an emphasis on the normalization of the base case parameters, it is an important stage before the modeling. The decision-maker should define and normalize all the minor and major details here, starting from the main design parameters (room dimensions, orientation, etc.), working hours and occupancy schedules up to lighting operation hours, etc.

Firstly, it is important to designate the parameters of the representative building, the scale of further examination, normalization in a scale of building or room, afterward the detailed dimensions, location, orientation and envelope properties.

In order to get coherent information about the HVAC and lighting systems that exist in the building, as well as operation schedule data, it is recommended to interview facility managers.

4.5 ENERGY MODELLING

Since this methodology is focusing on the integration of adaptive facade systems, the thermal comfort, and energy performance are prior aspects of improvements in the building. This is why the experimental part of the methodology starts with the developing base case building energy model.

Regarding the energy model, the model could be static or dynamic. Static modelling specifies the structure of the objects that exist in the problem statement, it includes class and objects, its time independent. While the dynamic model shows the object interactions during runtime (activity flows, sequence). Thus, choosing the appropriate simulation tool is should be done by consideration of these facts. The most common software in creating the energy model of the building that is used today is TRNSYS, Energy Plus, Design-Builder, and DOE-2 (Sousa 2006). The majority of simulation tools are focusing on

assessing thermal and energy performance such as Design-Builder. However, software as TRNSYS can equally well be used to model other dynamic systems. It is necessary to clarify and compile all the parameters before starting the actual energy model.

The aforementioned compiled architectural, mechanical and behavioral data can be used in each certain category of energy modelling. To begin with, architectural modelling starts with entering all the physical properties of the case, dimensions, the opening areas, materials of the wall and other exterior and interior elements. Besides, the input parameters from collected data such as heating and cooling working schedule are defined in active systems modelling stage. Occupancy fraction is entered in detail during user and operation part.

The advantages of energy modelling are that decision-makers can create a particular building model with all input parameters and simulate it in a particular climate region. In other words, after correctly creating the energy model, the decision-maker can get the proper results from one certain building parameter (thermal performance, air quality, lighting) or from the whole base case performance. Moreover, the simulations can be run for any period of time, daily, monthly, annually.

As an example, the decision-maker can create an energy model of the base case building, run required simulations and get the report of the overall building performance. Within the framework, the further analysis of the results from the energy model, the drawbacks of the current base case building will be revealed. It could be the high energy consumption due to the lack of proper heating systems or low-quality materials or insufficient fresh air inside etc.

After the simulation results of the existing building and detailed analysis of problems, the decision-maker endeavor to solve a number of problems. The possibility to test all the alternatives to the energy model makes the process efficient.

Software such as Design-Builder and Energy Plus are very useful and reliable instruments that include all the appropriate data for decision-makers like international building standards, and extensive material library. Energy models are easy can be created from the data of the real buildings, the reliability of the energy model completely depends on the decision-maker.

4.6 ANALYSIS OF THE BASE CASE

As aforementioned, with the framework of the methodology, the results from energy calculations of the base case are collected by the decision-maker and the comprehensive analysis starts. First of all, analysis in terms of the current problems in the base case. Understanding the problems of the building is a time-consuming process, however, not only understanding but also finding the origin of the problem is strongly important. Maybe they related to the mistakes at the early design stage like an inappropriate layout or construction material. These sorts of complex problems will require more efforts than retrofitting approach.

This methodology is focusing on the analysis in terms of energy performance and thermal comfort of the representative building. First of all, it is important to examine the results for annual energy consumption for:

- a. heating;
- b. cooling;
- c. lighting.

These values from the energy consumption of the base case should be checked according to the standard energy consumption rate for that type and size of the building.

The monthly indoor temperature fluctuations together with the comparison with outside temperatures should be gathered. The indoor comfort temperatures need to be evaluated according to international standards such as ASHRAE 55 and BS EN 15251:2007. Human comfort can be estimated by well-known Fanger PMV and PPD levels.

The comparative analysis between the results from the base problematic case and above-mentioned standards will give an opportunity for decision-makers to develop a strategy for the base case by applying appropriate solutions for the particular parts that need improvements.

4.7 DEVELOPMENT OF AFS ALTERNATIVES

Improving energy efficiency and indoor comfort conditions with the integration of adaptive facade systems are the main objectives of the developed methodology.

Following the comprehensive analysis of the existing base case and identifying key problems, the actors start to seek for applicable solutions.

The process of developing AFS itself requires an operation of multiple engineering disciplines to be involved, as well as testing, assessment, and monitoring. There is a wide range of existing AFS concepts in the market and this creates unlimited alternatives and configurations for decision-makers. Over the last decades, the low energy buildings have divided into two large groups passive and active design strategies, thus in the designing stage of AFS, the determination of the main strategy is required. For instance, a dynamic movable facade that will react on outside weather conditions like solar radiation and temperature fluctuations and as a result improve overall building performance.

Regarding the methodology of the suggested approach, it is possible to integrate or make improvements to the existing facade. Since the AFS is not a device that needs to be applied, it is a flexible concept of the building envelope that is developed and aimed to improve overall building performance.

The methodology suggests that development AFS alternative with consideration of the energy performance of the building needs to include passive solar design strategies in order to decrease the energy consumption on heating. However, indoor comfort is also the factor that comes with energy performance, it is important to develop a concept that will provide adequate thermal comfort and indoor air quality throughout a year. Within the framework of this methodology, it is said that indoor comfort could be improved by the application of flexible shading devices, that will prevent overheating in summer and heat loss in winter. The indoor air quality can be controlled by vents and windows. Thus, with the adjustments on building surface level (materials, glazing, shading) it is possible to develop AFS alternatives according to a particular issue.

4.8 CALCULATIONS OF THE PROPOSED AFS.

Calculations on the energy model with developed AFS system is an imperative part of the work. Since the facade concept has to be tested in terms of defined performance criteria. This process requires careful observations by the decision-maker since he/she will face a lot of errors during the calculations, this is the most challenging part. Modifications and

testing of AFS are continued until the decision-maker will establish and prove the final result.

All the final calculations must be presented in a schematic way (graphs, tables). Respectively to the developed methodology, the results of the base case with integrated AFS should include annual energy consumption of HVAC and lighting systems, monthly operative temperature, outputs of zone sensible heating and cooling, interior gains, the natural and mechanical ventilation. The results of the developed concept should also depict the weak and strong points of the concepts.

4.9 DISCUSSION OF RESULTS

As the final purpose of the framework, it is necessary to adequately evaluate the final results. Firstly, a detailed description of the applied approach together with the results of the simulations from the energy model has to be given in values and graphs.

Secondly, the simulation results of the existing base case need to be compared with the results of the proposed approach. In this respect, the assessment of results requires a comparative analysis between both models. It is important to highlight the results of energy performance and indoor comfort indices from both cases. The assessment of the results should include totals as energy consumption rate, monthly indoor temperature values and the amount of fresh air.

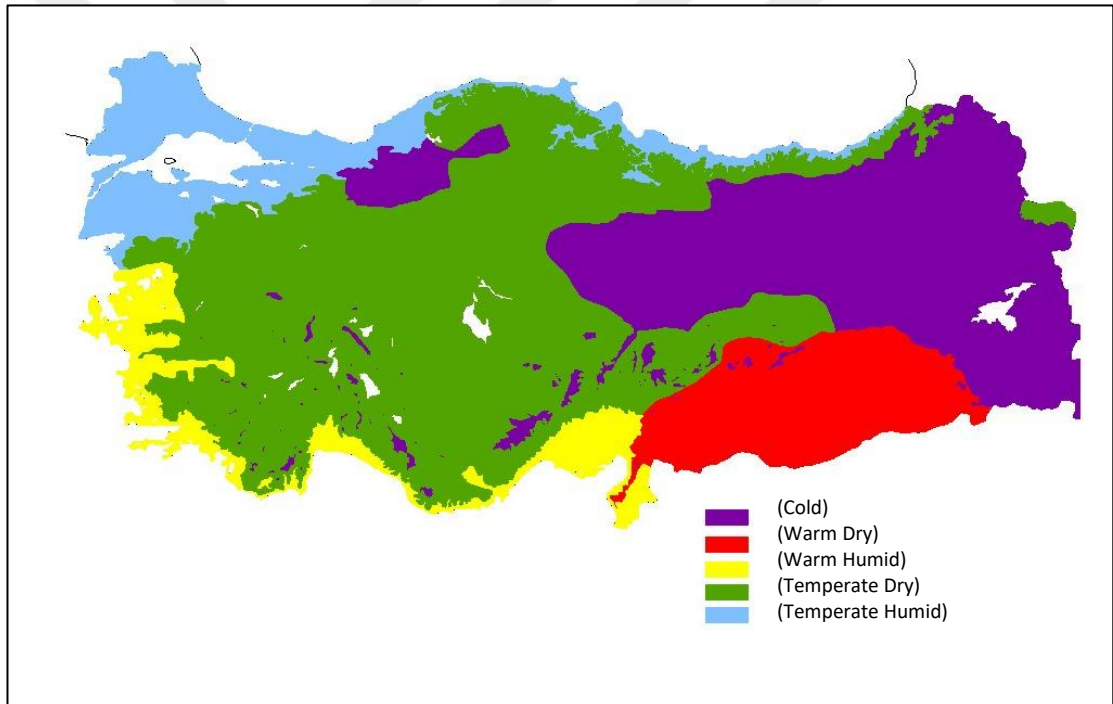
Since the concept itself is new, in order to fill this gap between the knowledge and the implementation, it is crucial to discuss all the work done to develop the AFS. Discussion in terms of the accomplishments of the thesis objectives is also significant and needs to be represented. Moreover, a discussion of the usefulness and potential of the developed concept has to be given. Suggestions about developing AFS will make assistance to other decision-makers and professionals in this particular field of AFS.

5. IMPLEMENTATION

5.1 DETERMINATION OF PILOT CLIMATE REGION

As aforementioned, the most important part of the retrofitting buildings is the process of climate considerations. Moreover, since this thesis aims to improve energy performance and indoor comfort level the climate characteristics are essential in this regard. The climate map shown in Figure 5.1, shows determined pilot climate area in this research is the largest climatic region of Turkey, Istanbul which has a temperate climate. As well as it is the most populated region and critical in terms of energy demand.

Figure 5.1: Turkey Climate zone map.



Source: Zeren, L., 1959. Mimarlık Fakültesi, İstanbul.

As shown in the map Figure 5.1, Istanbul has the temperate dry climate zone, and belongs to Marmara Region, with a transitional climate between Oceanic and humid subtropical climate. The moderately dry and warm to hot summers and wet cold winters. The City itself has a diverse topography due to its size and two coastlines from north and south this creates multiple microclimates. However, the climate in the populated areas to the south of the city is defined as tempered humid. According to the Turkish State Meteorological

Service, during the summer the average temperature in Istanbul is 14.4°C and high temperatures average around 29 °C, July is the warmest month with an average 23.3°C. January is the coolest month in Winter with an average temperature of 5.6°C and low temperatures averaging 1–4 °C. The precipitation annual average is 130 days, which amounts to 810 millimetres per year.

It is important to mention that, ASHRAE classification of climate zones developed together with the International Energy Conservation Code (IECC) is more useful in retrofitting projects rather than Köppen Climate Classification.

According to the ASHRAE classification, Turkey categorized as a mixed-climate, and the Marmara region is referred to a mixed-humid climatic zone. In the following chapters, the required actions for improving energy efficiency and indoor comfort in buildings suitable in the mixed-humid climates are represented.

5.2 DETERMINATION OF BASE TYPOLOGY

Since this study focuses on integrating AFS in order to improve energy efficiency and indoor comfort, initially educational and residential buildings were considered due to the potential and usefulness of retrofitting.

As a result of the investigation of certain building types in that field, dormitory buildings were selected as a primary building type for the base case. The dormitory belongs to the education (residential) type of buildings. The Dormitories usually is densely occupied and definitely, it is reflected in high energy consumption rates, this was one of the main arguments in choosing this type. On the other hand, another argument in terms of occupant comfort is essential for residential spaces. They are in use all day and even in the summer due to the summer and night schools. Thus, the further application of the approach of this thesis in terms of improving energy and comfort with the selected dormitory building type was useful and reasonable.

Regarding spatial organizations of this typology, most of the dormitories in Turkey are low-rise buildings approximately four-five floors, with several separated blocks. The significant feature of studied plans is that rooms organized in a linear way accessed from the corridors. The spatial organization of the dormitory is also made sense for the

application AFS since they can be developed accordingly to the layout of the building. Corridor and shallow plan buildings have greater opportunities in involving passive strategies, however, there are possible disadvantages such as installation and high façade costs. According to the orientation to South or North, the facade will perform differently.

The bedroom dimension varies from case to case and depends on the number of occupants in each. Important criteria of the dormitory are a sufficient level of lighting and thermal comfort. Again, the selection dormitory type is an appropriate choice since it is possible to apply AFS strategies to the existing facades, with the aim to reduce energy consumption and improve indoor comfort.

5.2.1 Determination of Case study

The selected case study is 'Ataturk Student Dormitory' located in Istanbul in the Zeytinburnu district. It is located at a latitude of 41.013236 North and a longitude of 28.913074. The choice of the case study building was based on two major factors that 'Ataturk Student Dormitory' is the largest student complex in Turkey and the availability of data and documentation for a building. The dormitory shown in the Figure 5.2 was reconstructed in 2013, with a total bed capacity of 3555. The complex represents 5 blocks of 7-story buildings, in a total more than 110 thousand square met of living area.

Figure 5.2: Atatürk Dormitory in Zeytinburnu.

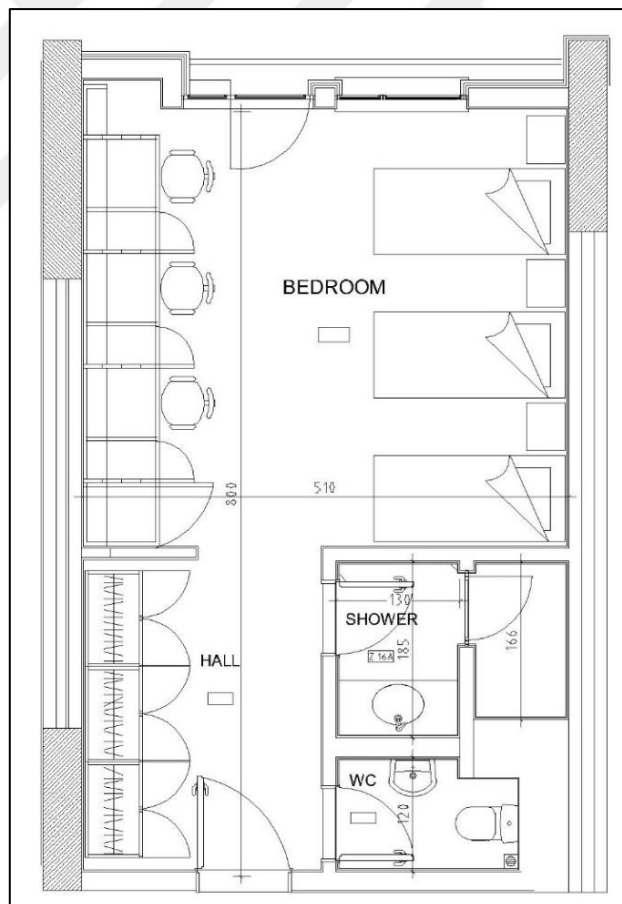


Source:(IPKB)

The dimensions of each room are 44 square meters, the maximum amount of the occupant per room is 3. Each room can be accessed through the card-pass system and includes a private bathroom and space for working and recreation. The dormitory has one type of room, the spatial organization is the same for each just some of the rooms have a balcony, and some are only with window openings. The south and north orientated rooms are connected with a long corridor.

The selected case study room shown in Figure 5.3 is occupied by three people. The dimensions of the room are 8.0 x 5.1 m with a height of 3.5 m, two windows and one door in the south wall facade. The base case is designed as a concrete frame structure and has a rectangular shape in plan. The size of the windows 1.40 x 1.30 m, and the door 1.40 x 2.20 m.

Figure 5.3: Plan of the selected base case room.



Source: (IPKB)

5.3 DETERMINATION AND COLLECTION OF THE REQUIRED DATA

After selecting the base case project and defining the room as the main case study, the official documents were required for the further experimental part of the thesis. The list given below represents data of the base case project that were determined as necessary in the framework of this research.

Architectural CAD drawings:

- a. floor plans;
- b. elevations;
- c. sections;
- d. detailed drawings of walls;
- e. detailed drawings of facade elements.

Mechanical Data of Building:

- a. heating;
- b. cooling;
- c. ventilation;
- d. lighting.

Behavioral Data:

- a. occupancy density;
- b. occupancy schedule;

The data were requested and as the result received from the project responsible organizations - İstanbul Project Coordination Unit (IPCU) and PROCON Engineering.

5.4 DATA COMPILATION

5.4.1 Compiling architectural data

The base case facade facing the south side and has a 15% window to wall ratio (WWR). All the materials and components of the base case were obtained from the technical drawings of the construction project. The glazing properties are given in the table 5.1, it

is double glazing with outer generic pure clear (3mm) air space (13mm) and inner generic clear layer (3 mm), thermal and optical properties are given in the table below.

Table 5.1: Base case room window thermal and optical properties.

Transparent Component	U-value (W/m ² K)	Solar heat gain coefficient	Visible transmittance
Exterior Window	1.96	0.74	0.82

Source: By author.

The walls are brick 23 cm thick, the floors are made from reinforced concrete beams and slabs, the ceilings from the gypsum board. Detailed information about opaque components of the base case is summarized in the Table 5.2

Table 5.2: Base case room opaque materials thermal properties.

Opaque Component	Material	Thickness (m)	Conductivity (W/mK)
Exterior Wall	Silicone Base Granulated covering	0,0200 (thermal resistance 0.15 m ²) K/W	0,3000
	XPS Extruded Polystyrene	0,1000	0,0340
	Brick	0,1050	0,7200
	Gypsum Plaster	0,0130	0,4000
Internal Partitions	Gypsum Plasterboard	0,0250	0,2500
	Air Gap	0,1000	0,3000
	Gypsum Plasterboard	0,0250	0,2500
Ground Floor	Reinforced Concrete	0,1500	2,5000
	Floor Screed	0,0700	0,4100
	Marble Covering	0,0300	3,5000
Internal Floor	Floor Screed	0,0700	0,4100
	Cast Concrete	0,1000	1,4000
	Gypsum Plaster	0,0130	0,4000
Flat Roof	Clay Tile	0.0250	1.0000
	Asphalt	0,0100	0,7000
	MW glass Wool	0,1000	0,0400
	Plasterboard	0,0130	0,2500

5.4.2 Compiling Mechanical Data

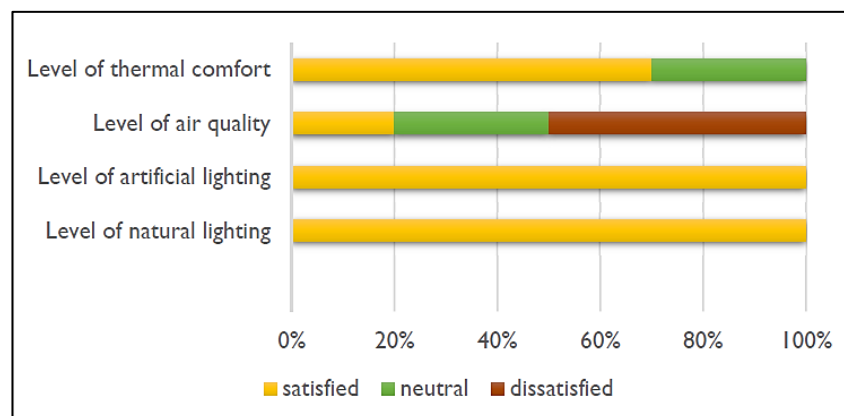
Within the framework of the survey of the base case facility manager, data about active systems of the building were collected. The heating system is automatically controlled according to schedule and assigned setpoint temperatures. The standard heating system works by supplying hot water to radiators through pipes. The heating setpoint temperature for the room is 21 °C.

There is no cooling and mechanical ventilation in the building. The fresh air distribution is only provided by natural ventilation, controlled with the opening of the windows.

The artificial lighting in the room provided by 3 suspended LED lamps with an average of 2.50W/m² lighting power density. Lighting system operation controlled automatically by the card system. According to the questionnaires, the lighting system is turned off during the daytime when the level of natural light is sufficient.

Moreover, a questionnaire related to the level of satisfaction of indoor comfort was also done. This was done in order to define the performance of the active system in the base case and have an idea where the improvements are needed. The graph given in Figure 5.4, demonstrates winter period satisfaction level of occupants according to the thermal comfort, air quality, artificial and natural lighting.

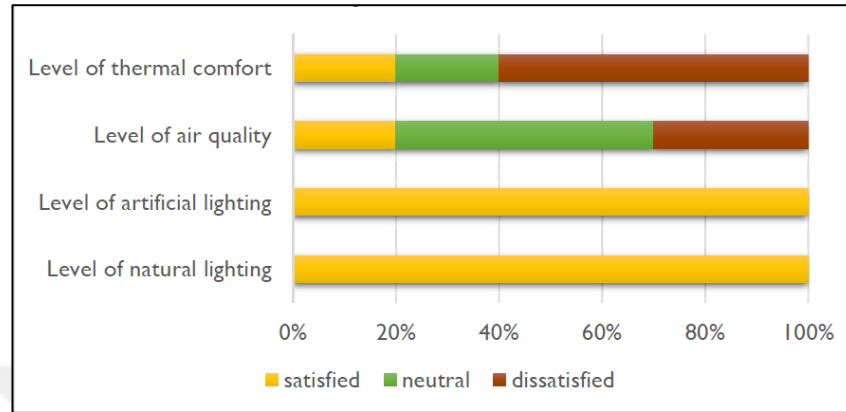
Figure 5.4: Winter period occupants' satisfaction



The graphs indicate that the level of artificial and natural lighting in the representative room is sufficient. However, when it comes to thermal comfort as aforementioned, there are no cooling systems in the room. According to the summer period survey that shown

in Figure 5.5, some occupants, it is very hot in the rooms during the summer period, thus most of the complaints are related to the lack of cooling system.

Figure 5.5: Summer period occupants' satisfaction.



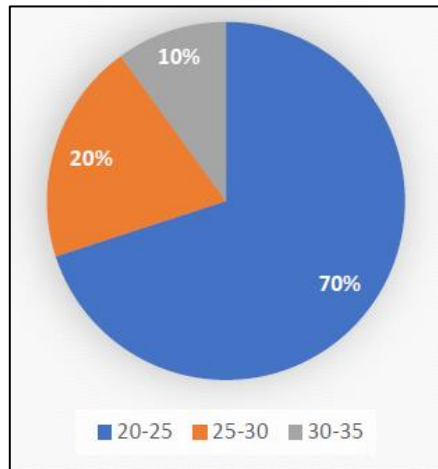
Another issue is related to indoor air quality during the winter period, it was explained by the interviews that due to the low temperatures during the winter occupants are opening the windows rarely and only for a short period of time. This causes a low level of fresh air in the room. This significant issue again related to the lack of mechanical ventilation in the base case.

5.4.3 Compiling Behavioral Data

The representative base case is a dormitory for girls. With the permission of authorities of the dormitory, as a part of the framework of the thesis, the survey of the occupants was done, in order to get a clear image of their schedule and behavioral patterns.

As shown in the Figure 5.6 the occupants' age range is varied from 20 to 35 years old. The major group is 20-25 years old girls. Half of the questioned are students in the fourth year, 30 percent in the third year, and minority second and fifth year group.

Figure 5.6: Occupants age range



Although while selecting building type of dormitory, it was debatable in terms of the reliability of the results. Since the concept of a university dormitory intends that on a particular period of time such as holidays and summer vacation when the students absent the mechanical systems are not in use and its effect on major results of consumption. There were arguments that enhancing indoor comfort is unreasonable since the room can be unoccupied for a significant period of times during the classes. However, with the taken survey it was clarified that some of the students have morning and evening courses, thus the schedule difference of occupants means that the hours when the room is unoccupied, not significant.

Figure 5.7: Percentage of students in two different courses.

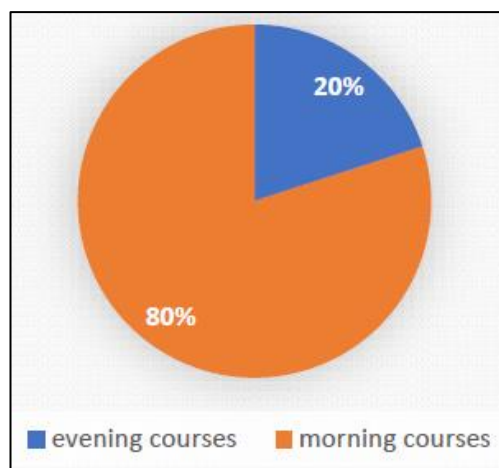
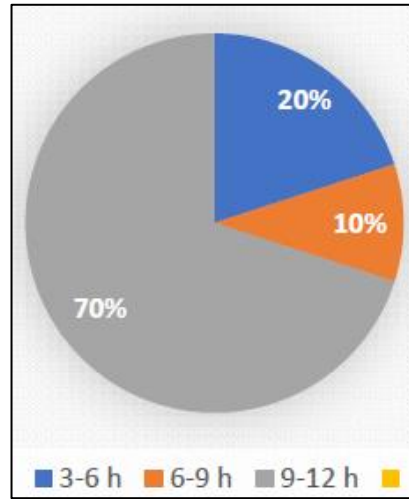


Figure 5.8: Percentage of hours spent in the room



Figures 5.7 and 5.8 represent the percentage of students in two different courses and the daily average of the hours they spend in the room. In Figure 5.8 it is clear that most of the occupants usually spend from 9 to 12 hours daily.

The base case room is fully occupied from mid-September until the end of June. According to the survey during the weekdays from 8 pm until 10 a.m. all three occupants are in the room. From 2 p.m. to 5 p.m. there is only one user in the room. In the weekends there is a tendency that the room is unoccupied from 4 p.m. to 21 p.m.

5.4.4 Normalization of the base case parameters

After gathering all the project data and compiling the important aspects, it is necessary to normalize all the input parameters for the energy model. The primary normalization parameters of the base case should include information about the HVAC and lighting system operation. Secondly, behavioral data such as occupancy schedules should be normalized as input data to the future energy model.

5.4.4.1 Heating

Normalized input parameters for the heating system given in the table 5.3 include information about the type, assigned setpoint temperature, the operation schedule obtained from the facility manager.

Table 5.3: Base case heating parameters.

Type of heating system	Type of Boiler	Operation	Setpoint Temperature °C.
Central heating radiators (Convective)	Gas-fired condensing boiler	Thermostat (automatically)	21 °C.

Source: By author.

According to the collected information, heating operated seasonally, according to the schedules. Heating schedule table shows the period of the year when the heating is on. The value 1 in schedule means that heating is activated in that period of time and 0 when it switched off.

Table 5.4: Base case heating parameters.

Through	Operation	Operation time
3 May	1	24/7
25 September	0	24/7
31 December	1	24/7

5.4.4.2 Natural Ventilation

As aforementioned, the natural ventilation (NV) is only obtained by the opening windows. Thus, the schedule of NV was created by the questionnaires of occupants. The window opening schedule further will be used as an input parameter for NV.

According to the window opening schedule given in Table 5.5, in the winter period from January to the end of April the maximum amount of opening is 4 times per day for a maximum of 30 minutes.

Table 5.5: Base Case Natural Ventilation schedule.

Through: 30 April	Window Operation (1- opened; 0-closed)
Until: 10:00	0
Until: 10:30	1
Until: 13:00	0
Until: 13:30	1

Until: 17:00	0
Until: 17:30	1
Until: 20:00	0
Until: 20:30	1
Until: 24:00	0
Through: 15 May	Window operation (1- opened; 0-closed)
Until: 12:00	0
Until: 16:00	1
Until: 24:00	0
Through: 15 October	Window operation (1- opened; 0-closed)
Through: 31 December	Window operation (1- opened; 0-closed)
Until: 10:00	0
Until: 10:30	1
Until: 13:00	0
Until: 13:30	1
Until: 17:00	0
Until: 17:30	1
Until: 20:00	0
Until: 20:30	1
Until: 24:00	0

* natural ventilation is on in accordance with the schedule when the min indoor temperature is 20°C

5.4.4.3 Occupancy schedule

The metabolic rate for the man and woman has different values, for male, it is 1.00 and for women is 0.85. For instance, in the case when the average is equal to 0.90 that means that space is occupied with both. However, in this case, study, the average value is 0.85 since there are three female students living in the room. The typical activities in the

examined room described as standing/walking, resting/sleeping. The values of metabolic rate and activity are important for the calculation of CO₂ generation.

Table 5.6: Case Study Room Occupancy.

Number of occupants	3
Occupied floor area	53.5
Density (people/m ²)	0,0127
Metabolic rate	0.85

The given table 5.7 demonstrates the schedule of occupancy for weekdays and weekends. The occupancy given in the fraction values, the fraction maximum is 1 and it means that all of the three occupants are in the room. The minimum fraction is 0 means that on that period of time the room is unoccupied.

Table 5.7: Occupancy schedule.

Through: 31 December	Fraction for: Weekdays	Fraction for: Weekends and Holidays
Until: 10:00	1	-
Until: 12:00	-	1
Until: 14:00	0.25	-
Until: 16:00	-	0.75
Until: 17:00	0	-
Until: 20:00	0.75	-
Until: 21:00	-	0
Until: 22:00	-	0.25
Until: 23:00	-	0.75
Until: 24:00	1	1

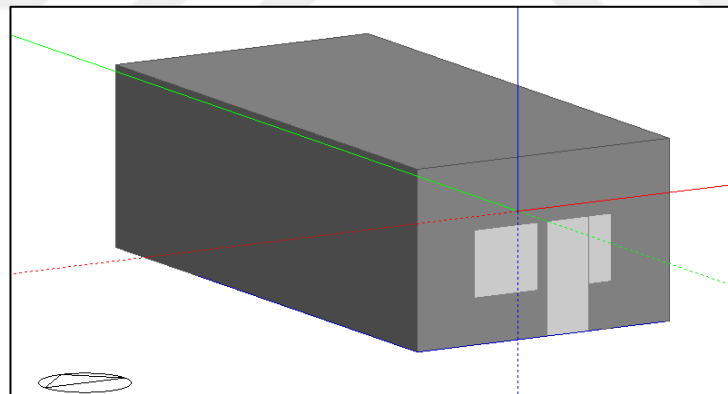
5.5 ENERGY MODELLING

As the starting of the experimental part of this thesis, the energy model of the representative room was created. It was decided to apply the simulation method in this study using DesignBuilder software. Since DesignBuilder the most appropriate tool for analyzing the performance of the base case and carry out the approach of the thesis for energy efficiency and enhancing indoor comfort. As aforementioned, the oriented to the south room was selected for retrofitting.

5.5.1 Architectural modelling part

The process of creating the energy model of the room was started by drawing perimeter and putting data of spatial dimensions. Then, the base case predefined input parameter of the envelope such as glazing, and opaque surfaces were applied to the energy model. A three-dimensional view of the base case room is given in the Figure 5.9.

Figure 5.9: 3D model of the base case.



5.5.2 Active Systems of the model

After the entered parameters of the envelope, prepared data about HVAC systems of the base case were defined in the model. All the operation schedules of active systems in the building were stabilized in the energy model. The heating system of the energy model

was defined as and modelled in detail in EnergyPlus, in addition, normalized heating operation data was established in the representative energy model. The conduction transfer function method was used as a general solution algorithm with four-time steps per hour. 6-TARP "Detailed" Inside convection algorithm was used for base case simulation. Since the selected base case is only one room, in order to get the adequate calculations of energy consumption and thermal comfort it was necessary to define the adjacency of the walls as adiabatic.

The NV calculations method of the energy model were defined as calculated, this means that ventilation rate is obtained by the results, opening size and operation schedule. The airtightness value of the envelope in the representative room was set as excellent with a constant rate of 0.700 (ac/h). The base case model has an opening for the left opening position, with the glazing area opens for 30%. The indoor minimum temperature control for NV is 20 °C, this means that ventilation operates from that temperature value. As an input schedule for window opening, the base case window opening schedule that was normalized in the previous part of the study was settled.

5.5.3 Occupancy schedule

The schedules for occupancy of the base case were set according to the normalized data from the questionnaire, the number of occupants is defined by fraction range. The energy model of the base case was created as a reference model to assess the results of energy and indoor comfort in the existing case and as a result to compare with the results of the thesis approach for improving energy efficiency and indoor comfort.

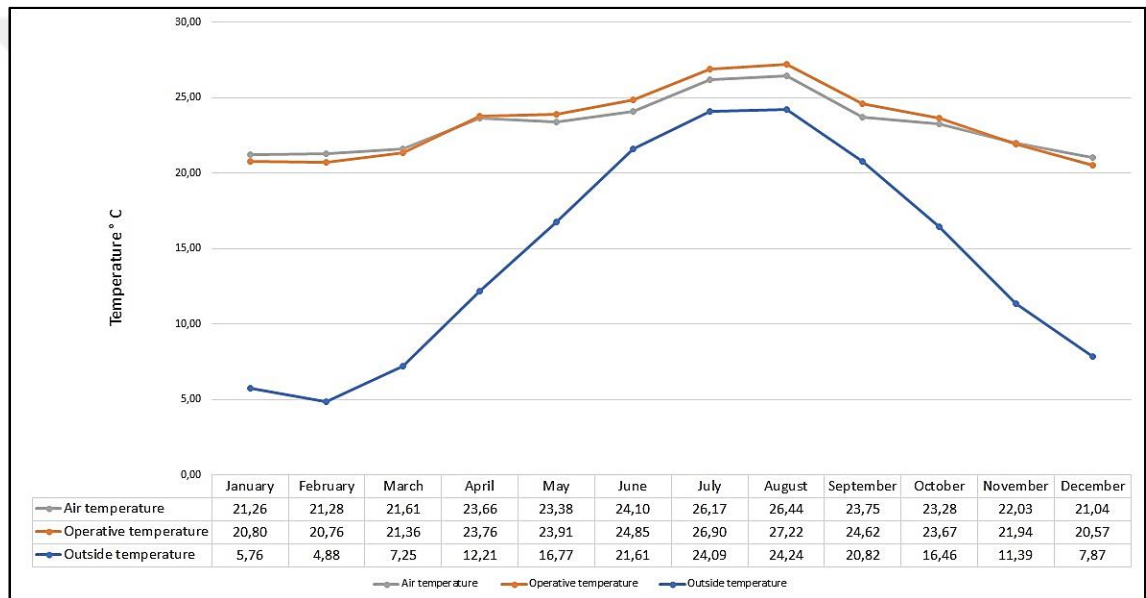
5.6 ANALYSIS OF THE BASE CASE

Finally, when all necessary input data of the base case is adjusted and fixed the simulation part was started. Within the calculations of the energy model, the main objective was to get the results from the base case in terms of energy, such as energy consumption for HVAC and internal gains (including solar). Comfort aspects were also included in the calculations and analysis. In terms of comfort thermal performance of the building such as indoor temperature range was also examined by the ASHRAE 55 standard and Fanger thermal comfort index. Moreover, the amount of fresh air in the base case room was

analyzed by internal and external air total range. All the results for each determination were obtained in monthly and annual reports.

First of all, the calculations of the indoor and outdoor temperatures were collected in order to investigate the monthly range of comfort temperatures in the base case. The analysis given in Figure 5.10 shows that the average temperature in winter months is between 20°C - 21°C, while the minimum comfort temperature in winter according to ASHRAE 55 is 20.3°C. Thus, the temperature in the room in the winter period is accepted as adequate for human comfort.

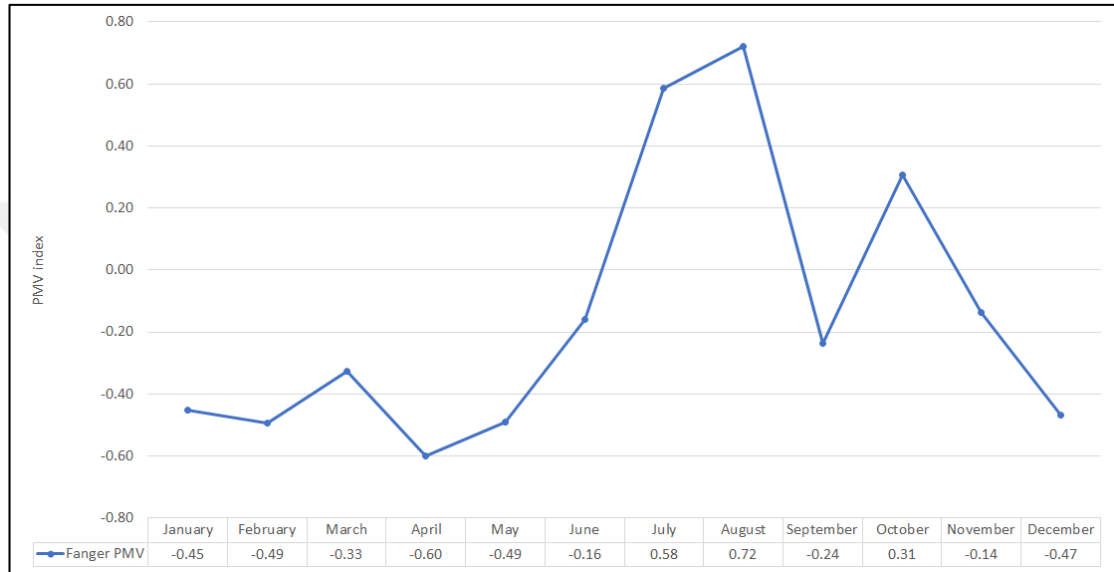
Figure 5.10: Average monthly indoor and outdoor temperatures of the base case.



As stated by ASHRAE standard 55, the maximum comfort temperature in summer is equal to 26.7 °C. However, the temperature in the summer period in the base case exceeds the maximum range, on July 26.9 °C and August is 27.2°C when the outside temperature is about 24 °C, the difference for the temperature to reach the comfort level is between 0.2 and 1°C. (Figure 46). It is stated that the overall comfort temperature in the winter period met the defined standard, however, there is overheating in summer months in the base case.

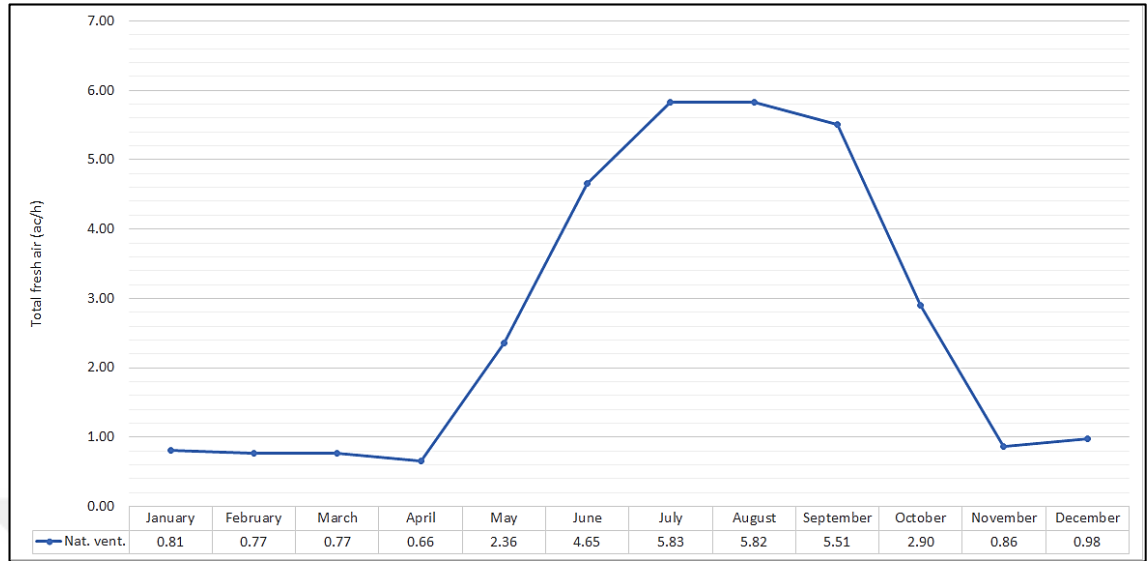
The PMV index calculation of base case was done for analyzing the overall human comfort. The Figure 5.11 represents the average monthly values evaluated by Fanger analysis that includes human activity level, clothing insulation, mean radiant temperature, humidity, temperature and velocity of indoor air. The PMV values that are ranging between $(-0.5 < \text{PMV} < +0.5)$ are considered acceptable.

Figure 5.11: Fanger's PMV results of the base case



Another important aspect that was observed via the base case analysis once again related to indoor comfort. As shown in the Figure 5.12, the fresh air indices in the winter period from January to April are low in comparison to other months.

Figure 5.12: Natural Ventilation and Infiltration of the base case.



Since the air penetrates into the room only by opening the windows, this effects on the insufficient level of indoor air quality during the winter when the windows opened at a short period of time. These results were proved the aforementioned statements of occupants, about the air quality.

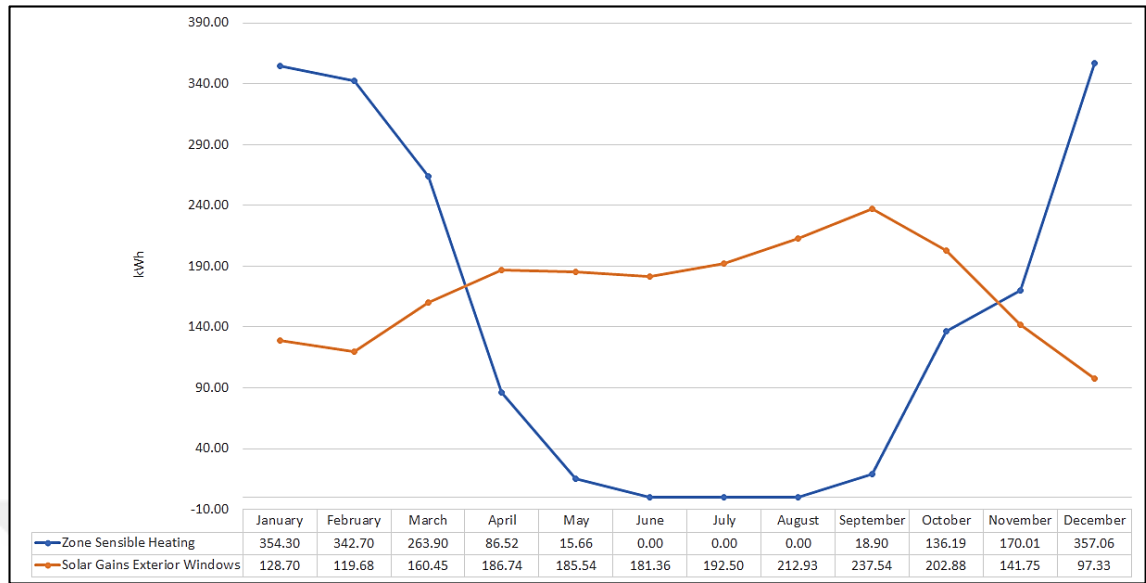
In order to better evaluate the results of the base case simulation in terms of energy. The totals of energy consumption per area of the building were taken and given in the Figure 5.13. The existing annual energy consumption results will be compared to the retrofitting base case model results later

Figure 5.13: Annual energy consumption of the base case.



The internal gains of the base case were also analysed in terms of solar gain of exterior windows and total zone sensible heating and given in a detailed graph in Figure 5.14. It is clear that the solar gain of exterior windows in the summer period considerable increases and as a result causes of overheating in July and August due to the high solar radiation in that period.

Figure 5.14: Internal gains of the base case.



5.7 DEVELOPMENT OF AFS ALTERNATIVE SCENARIO

In the framework of the experimental part of this study, the survey and an energy model analysis of the base case were needed in order to examine and reveal the weak sides. To deliberately understand all the energy and comfort performance criteria. Moreover, to develop the strategy of the facade that will improve these performance criteria.

In the results of examining the base case the following major problems of the building performance were revealed:

- The overheating of the base case room in the summer period.
- The insufficient level of indoor air in the winter period.

The development process of the AFS concept was aimed to improve these two particular issues as well as improving the energy performance of the base case.

During the process of sketching and searching for an appropriate strategy, one of the proposed alternatives to solve the indoor overheating of the base case was the application of shading devices to the windows. Since it is a common and useful practice to reduce high temperatures inside. As a solution alternative for the insufficient amount of air, the

additional vent installation was proposed. With this kind of improvements, the aforementioned performance issues can be solved.

Moreover, it was decided to choose the concept of the Trombe wall as a solution for improving the energy efficiency of the base case as well as the capability of the facade to utilize the aforementioned parameters. However, the proposed Adaptive Facade System should meet not only indoor comfort but the reduce energy consumption as well.

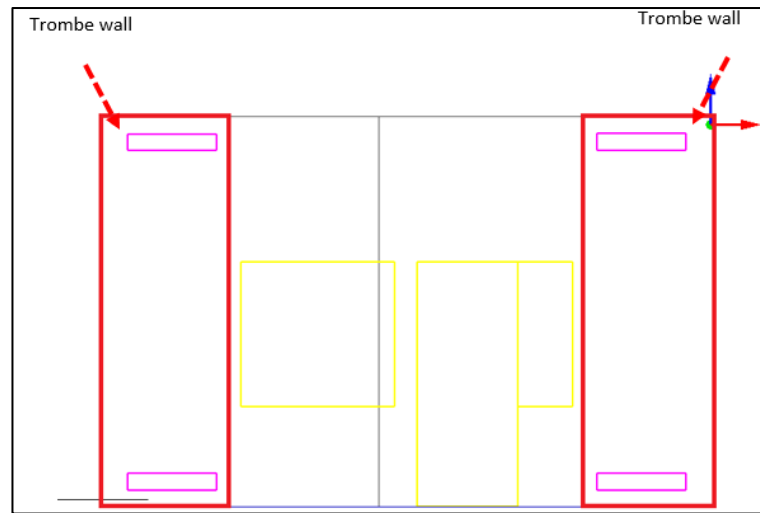
5.7.1 Proposed AFS alternative scenario

As a result of the investigation for most appropriate AFS alternative - the concept of Ventilated Trombe Wall was chosen. According to the study of Chel and Kaushik and Dabaieh and Elbably, the Trombe wall is the best passive heating and cooling system, from the perspective of energy efficiency.

Another influential factor to the decision was that there are a lot of configurations can be applied to the facade with a Trombe wall such as previously mentioned shading devices.

All the parameters of the design and the AFS itself were applied to the previously developed energy model of the base case room. The proposed AFS was applied in the south facade of the base case. The dimensions of the facade are 5.50 m x 3.50 m, the existing base case windows were kept and included in the overall concept. Two Trombe wall systems were developed in the right and the left side of the façade as shown in Figure 5.15.

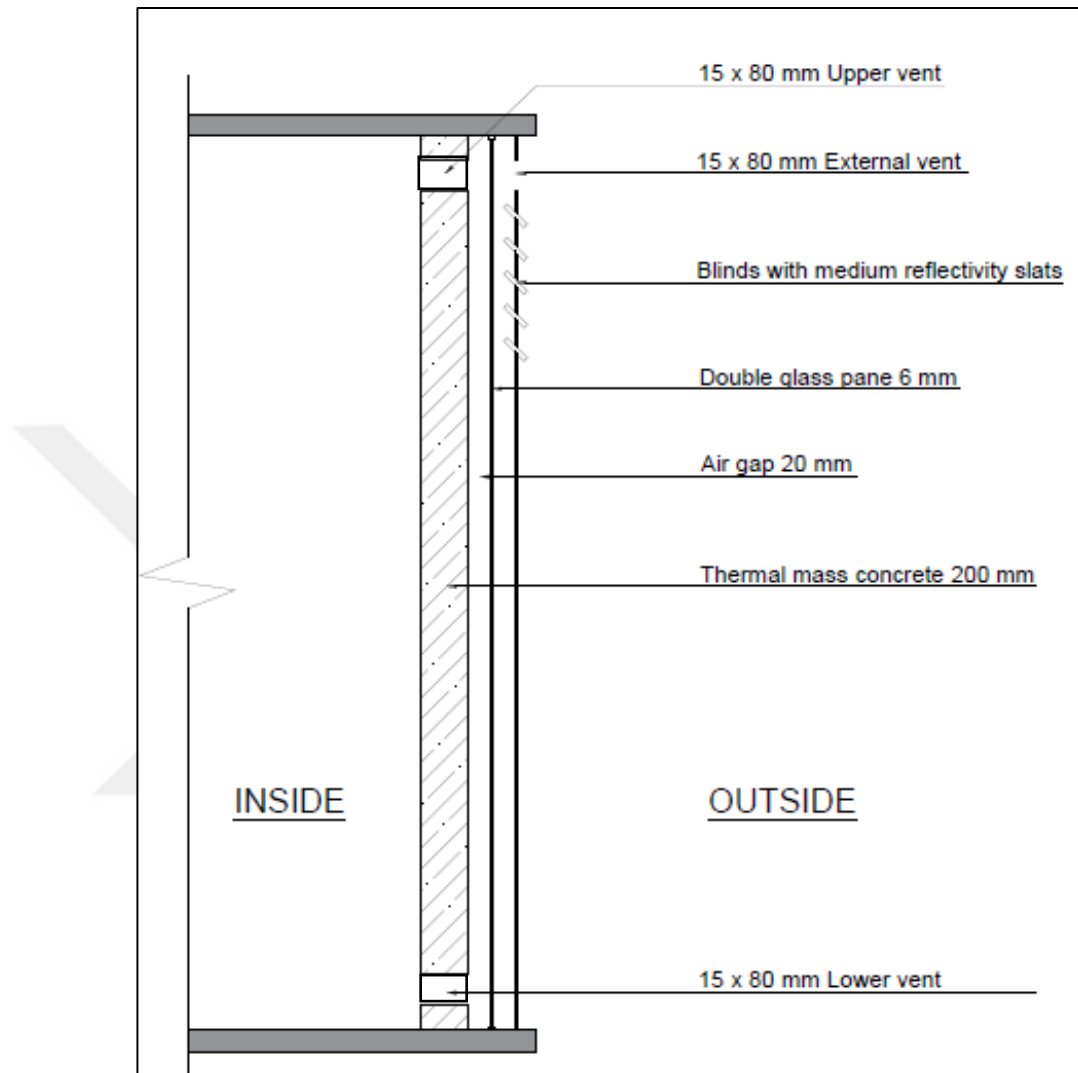
Figure 5.15: Front facade view of facade base case with AFS.



The dimension of each Trombe Wall is 1.15 width to 3.50 height. The design parameters of the façade were done by following from the classic Trombe Wall concept. Presented schematic drawing in Figure 5.16 shows the layers in the proposed Trombe Wall. The four main components are:

- a. Thick mass wall;
- b. Air gap;
- c. High transmissivity glass pane;
- d. Outside horizontal shutters with medium reflectivity slats;

Figure 5.16: Schematic section of Trombe wall.



This passive solar system designed for thermal storage and delivery, this is why the material of the absorptive wall is important, for this approach. Trombe wall shading elements are the must-have element it is applied to decrease sun exposure in the summer when heating is not required, it is assumed that shutters will be closed during the daytime in summer. External glass pane type should cover nearly all of the wall area and be high transmissivity and low reflectance. This is why Trombe Walls are mostly faced to the South for maximum sun exposure.

It was observed that the application of the external top vent is a useful strategy to enhance the ventilation in the summer period since it works as a solar chimney and move the air upwards withdrawing undesirable heat from indoor space.

5.7.1.1 Modelling Parameters of proposed AFS

The process of integrating AFS to the base was started by drawing a narrow zone and attaching it to the existing facade surface. In this respect, the thickness of the AF corresponds to the air gap size, in the developed facade air space is 20 cm. As the thermal mass wall of the wall, the black colored concrete wall with 20cm thickness is chosen. External glass pane type is the 'Best Practice' Double glazing that defined from DesignBuilder material library as the best alternative for Trombe Wall. The louvers placed on the outside layer of the Trombe wall are chosen as horizontal, medium reflective steel slats.

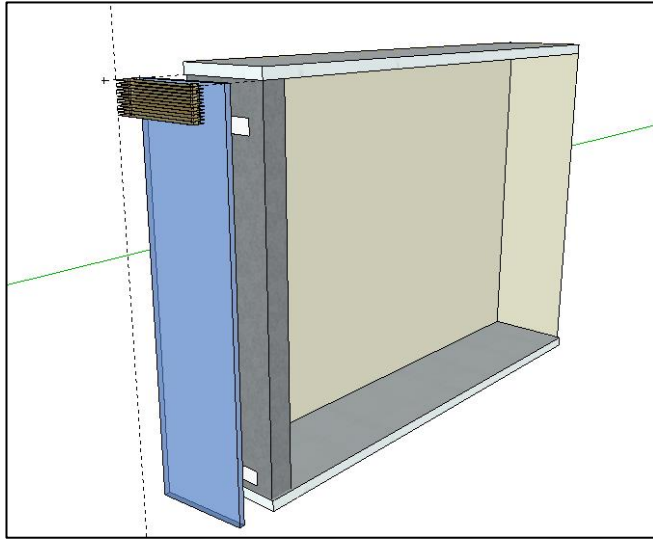
The difference between the proposed alternative and conventional Trombe wall is that the classic wall is sealed and unvented, and it works only for absorbing and distributing heat. While the proposed approach is assumed to operate for both passive heating and cooling. This achieved through installing the internal vents on top and below the mass wall and in addition adding the external vents on an external wall creating the chimney effect for cooling and shading as well.

In order to get adequate and correct results from the calculations of developed AFS, it is important to follow the simulation guide parameters for Trombe Wall in DesignBuilder. Thus, the narrow zone was set as unoccupied, no HVAC activity in a defined zone. In order to model the air space (cavity zone) in the Trombe Wall for correct calculations, the internal convection algorithm is set as 5-Cavity.

5.7.1.2 Basic Principle

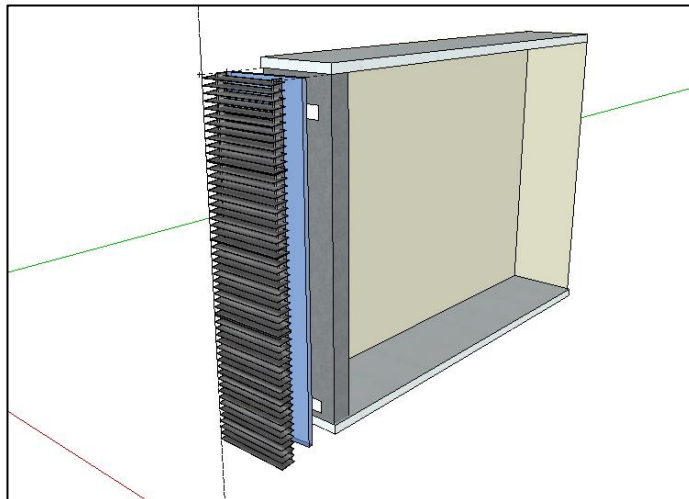
Natural convection and solar radiation are the main work factors of the developed AFS. It is assumed that shutters are not used during the day in the winter period as shown in Figure 5.17, so the maximum amount of solar gain will be obtained, and during the night hours when the absorbed heat gain is distributed to the room the shutters will be closed and as a result, keep the heat inside.

Figure 5.17: Sketch of proposed AFS scenario for winter period.



As shown in the Figure 5.18, in contrast to shutter operation in Winter, in the Summer period, the shutters will be used during the whole day preventing the direct sunlight to the room and as result reduce overheating issue of the base case.

Figure 5.18: Sketch of proposed AFS scenario for summer period.



However, there is a need for fresh air in the Winter period, this issue assumed to be solved by the internal and external vents that were applied. They will operate according to the defined schedule, so in the period from January to April vents will be opened during the daytime for approximately 6-7 hours and transmit fresh air inside in the adequate amount without decreasing the comfort temperatures and will be totally closed in the evening hours. The lack of a cooling system in the base case was also assumed to compensate with natural ventilation and air convection.

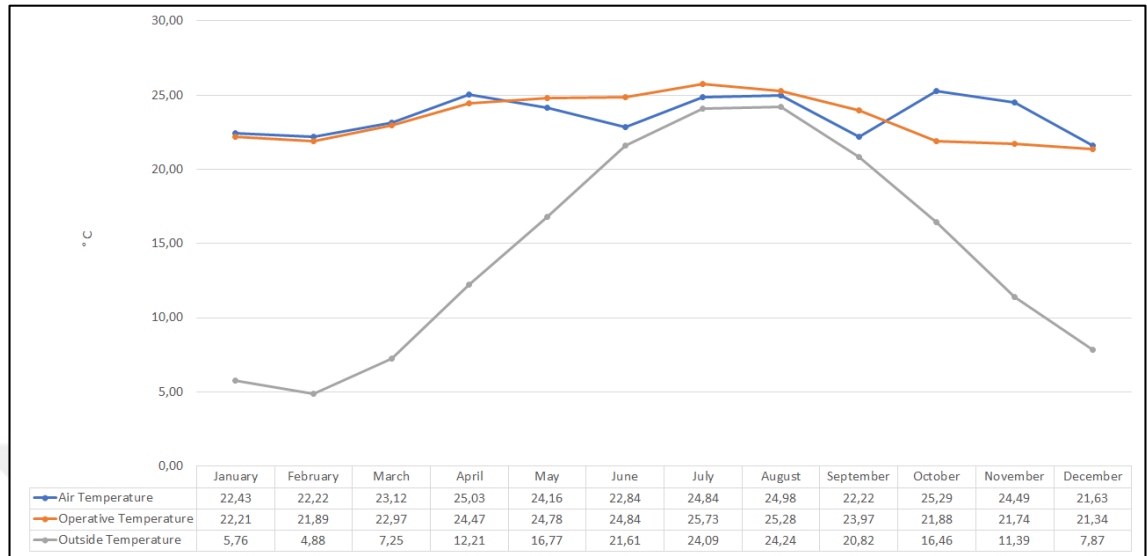
It was assumed that the combination of closed shading shutters and opened vents will be a solution for overheating challenge. Moreover, the existing exterior windows of the base case were also modified by adding shading blinds with the same schedule as for Trombe wall shutters. This was done again to prevent an overheating in summer. The minimum indoor setpoint temperature for NV in the Trombe wall is 21 °C. It is assumed that the vents are opened from that temperature value.

5.8 CALCULATION OF THE PROPOSED AFS

After defining all the design parameters of the proposed AF concept to the existing base case model. In the calculations of the model with AFS, all the material parameters, HVAC systems, and occupancy schedules data are kept as in the conventional base case energy model. Just with adding the developed AFS with its parameters and material properties.

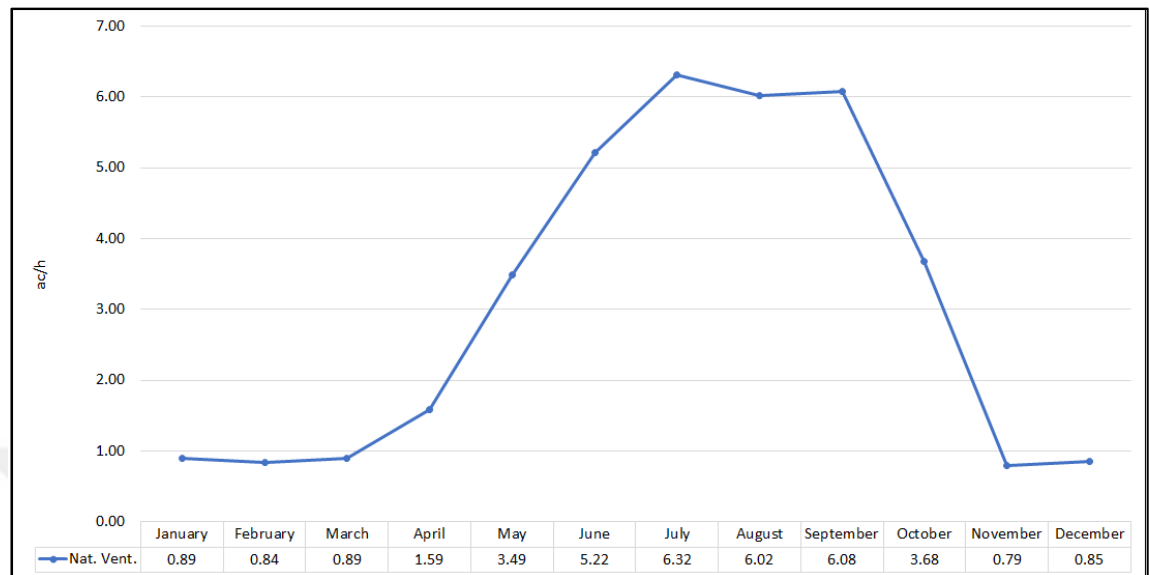
The model with AFS will be calculated the same as in the base case model calculations. The compulsory calculations for indoor and outdoor temperature ranges with the improved model. As well as the natural ventilation monthly outcomes. And the most valuable results for the developed approach the internal gains and totals for zone heating.

Figure 5.19: Average monthly indoor and outdoor temperatures of the base case with integrated AFS



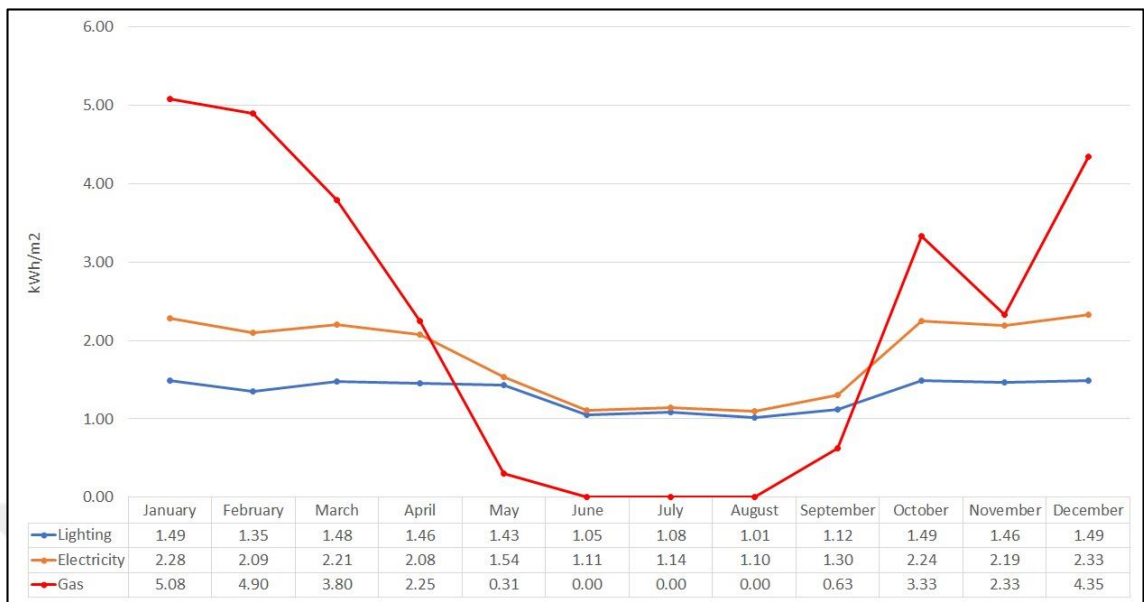
The Figure 5.19 demonstrates that with the integration of AFS the comfort temperatures are met by the ASHRAE standard 55, no exceeding was revealed. The average temperature for winter from 22-23°C and for summer between the 24-25°C.

Figure 5.20: Natural Ventilation and Infiltration of the base case with integrated AFS.



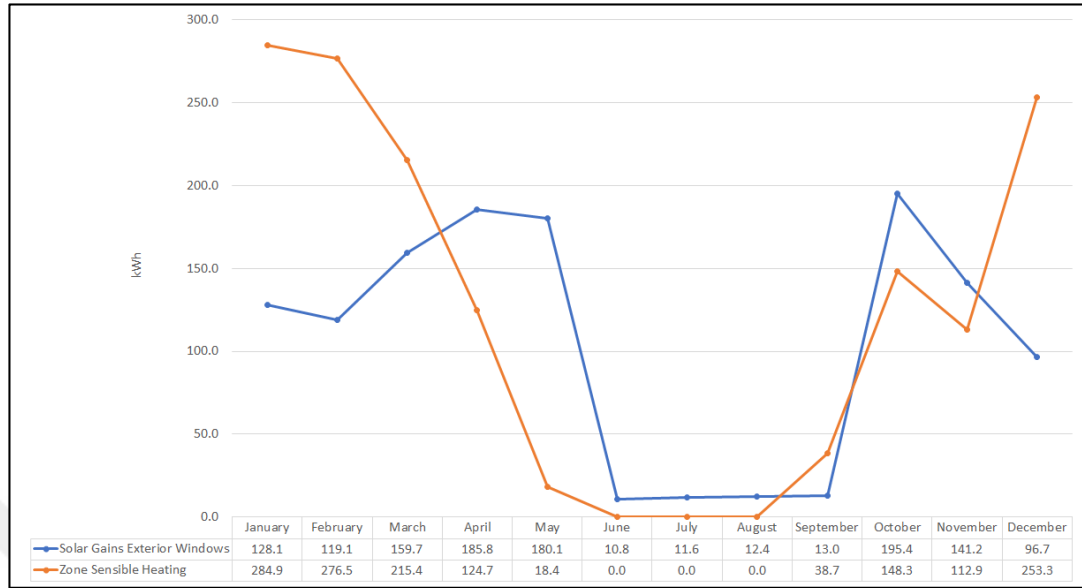
The results of NV calculations show that the vent operation schedules and window openings are works correctly. The detailed comparison between the base case results and results from AFS will be done in the next chapter.

Figure 5.21: Annual energy consumption of the base case with integrated AFS.



The Figure 5.21 shows the results of annual fuel totals, for better evaluation of the usefulness of the proposed approach all significant outcomes such as fuel totals will be compared later in this study.

Figure 5.22: Internal gains of the base case with integrated AFS.



From the results of solar gain by the exterior window and the glass pane of Trombe Wall given in Figure 5.22, it is seen that the defined schedule for closing the shutters in the summer period is reflected in the values, there is a significant difference between the gain in winter and summer.

In the next chapter, all the results from both cases will be analyzed and compared accordingly to the performance improvements and drawbacks of the proposed approach.

5.9 DISCUSSIONS OF RESULTS

This chapter will discuss all the results of the carried-out work in terms of the objectives of this thesis improving energy efficiency and enhancing indoor comfort. The two major challenges such as summer overheating and insufficient level of fresh air were revealed of the base case building, thus the concept of the AFS development was focused on solutions of these particular problems. As well as a factor the lack of cooling systems in the base case was considered. Moreover, throughout experiments and seeking for the best alternative solution the strategies of passive and active systems were also considered since the developed facade was aimed to improve the energy efficiency of the base case as well.

As a result of the experiments, the proposed solution was the hybrid facade with a combination of the Trombe wall and dynamic shading devices.

The Trombe Wall part of the AFS aimed to provide passive heating and cooling in the base case and decrease the energy consumption of it. The natural convection and chimney strategy were provided by applications of vents in the Trombe wall. The vents were assumed to solve the issue of indoor air quality. The active shutters were added to the AFS concept for preventing overheating and heat loss of the base case.

5.9.1 Comparative analysis of results.

In this part, both of the results will be compared and analyzed in terms of previously determined performance aspects of the building. First and foremost, the comparison analysis shown in Table 5.8 between the base case and base case with integrated AFS revealed significant results in terms of energy saving.

Table 5.8: Comparison Between energy consumption of base case and case with AFS.

Results	Total room area m ²	Heating energy demand (kWh)	Lighting energy demand (kWh)	Total primary energy use (kWh)	Total annual primary energy use per area (kWh/m ² a)
Base Case	52.08	1529.33	860.80	3558	68.3
Base Case with AFS	52.08	1297.89	828.51	3251	62.4

It is clear that annual energy consumption for zone heating with integrated AFS is decreased to about 15 %, this is the result of the passive heating approach of Trombe wall. The table with the compared values of solar gain of exterior windows proves that passive heating strategy with applied Trombe wall decreases the heating loads in the case with AFS. The monthly solar gain from the base case with Trombe Wall, especially with the main component - the glass pane high transmissivity dramatically changed the values and as a result, provide the passive heating and decrease the energy consumption of the examined room.

The Table 5.9 demonstrates the annual amount of CO₂ emissions caused by energy used in both cases and the values of reducing the energy consumption of the case with the AFS are reflected in decreasing the CO₂.

Table 5.9: Comparison Between CO₂ reduction of the base case and the case with AFS.

Results	<i>CO₂ emission (kg of CO₂)</i>
Base Case	993.4
Base Case with AFS	925.5

However, it is important to notice that the results of solar gain in the base case have the tendency to increase in summer and that was caused the overheating since there are no shading elements in the existing facade.

In contrast to the results from the case with AFS, the numbers are high in the winter period and decreasing in the summer months as shown in Figure 5.23. This was achieved by the installation of dynamic shading devices, and scheduled operation of them, for winter they opened during the daytime and for summer they closed. Thus, the developed AFS operates properly for achieving the main objectives such as decreasing energy consumption for heating.

Figure 5.23: Solar gain of external windows of the base case and case with AFS.

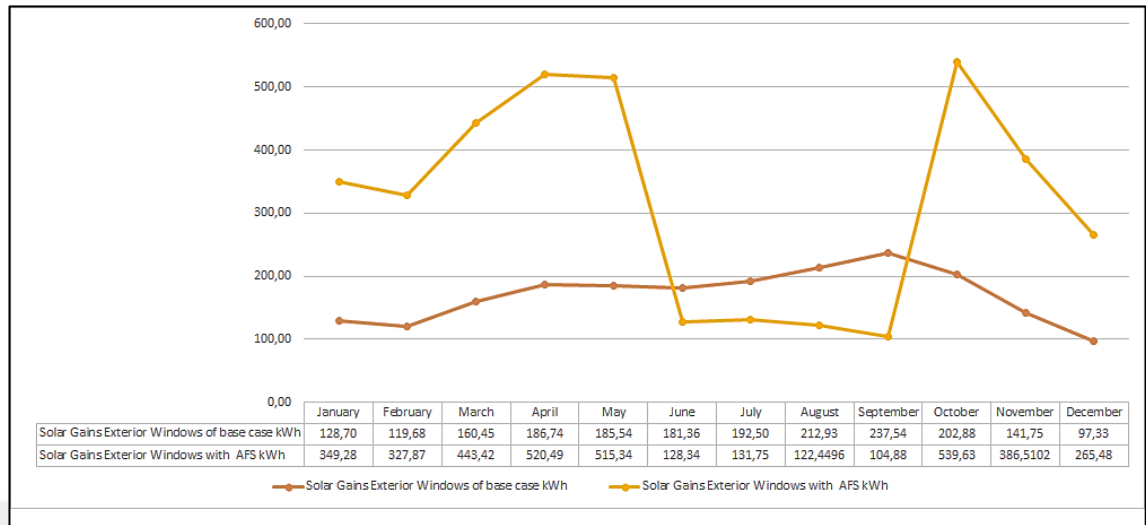
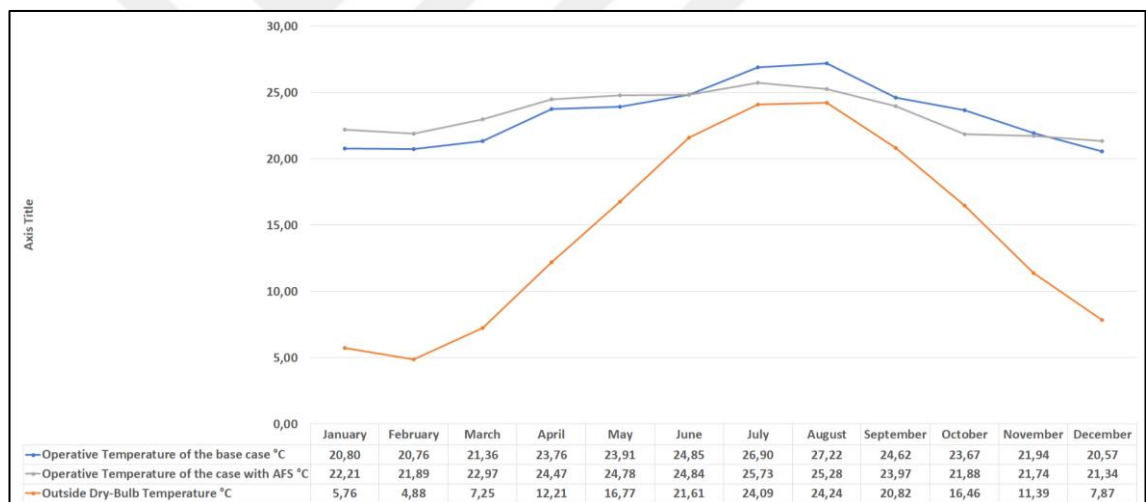


Figure 5.24: The average indoor temperatures of the base case and case with AFS.



The Figure 5.24 demonstrates the average indoor and outdoor temperatures range of two cases in terms of differences in operative temperature. The results from the base case temperatures were acceptable for the winter but critically rose in summer.

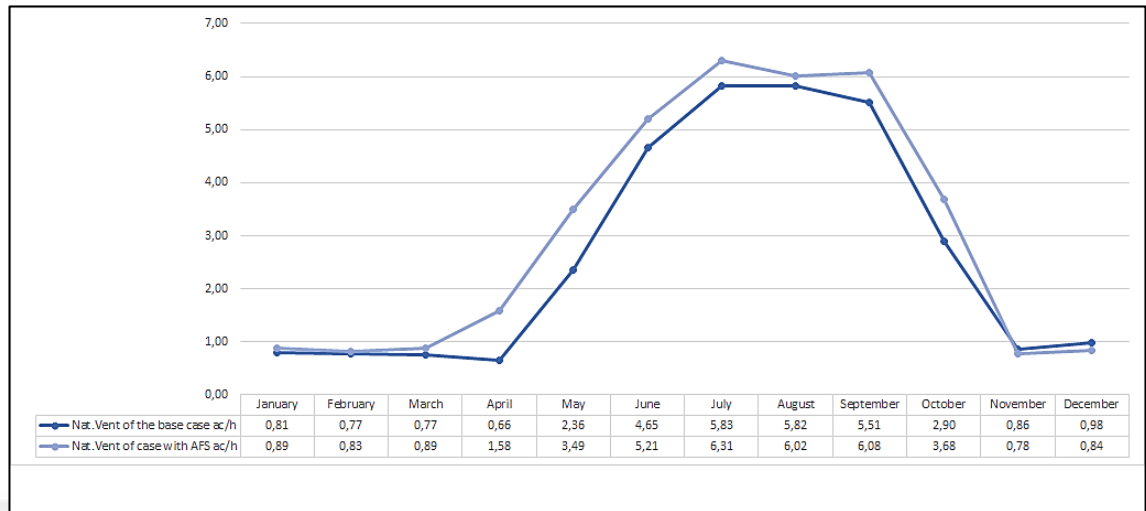
According to the results, the horizontal shutters are operating successfully since the main reason that they were integrated into the concept of the facade is to prevent overheating. The results of comparison have shown that in the case with AFS the average maximum of 25.73°C operative temperature was detected is in July and August when the outside

temperature is about 24 °C. While in the base case the average maximum for the same months is 26.90 -27.22°C. Comparing both outcomes it is proved that the base case with AFS is improving the indoor comfort temperature with decreasing high temperatures approximately 1.0- 2.0°C. The solution for the overheating problem was in the application of dynamic shading devices on the facade.

As it was stated before, the cooling system is not included in the base case building and natural ventilation was provided only by the windows. This is why during the experimental part most of the testing was done for countervailing the absence of cooling with NV.

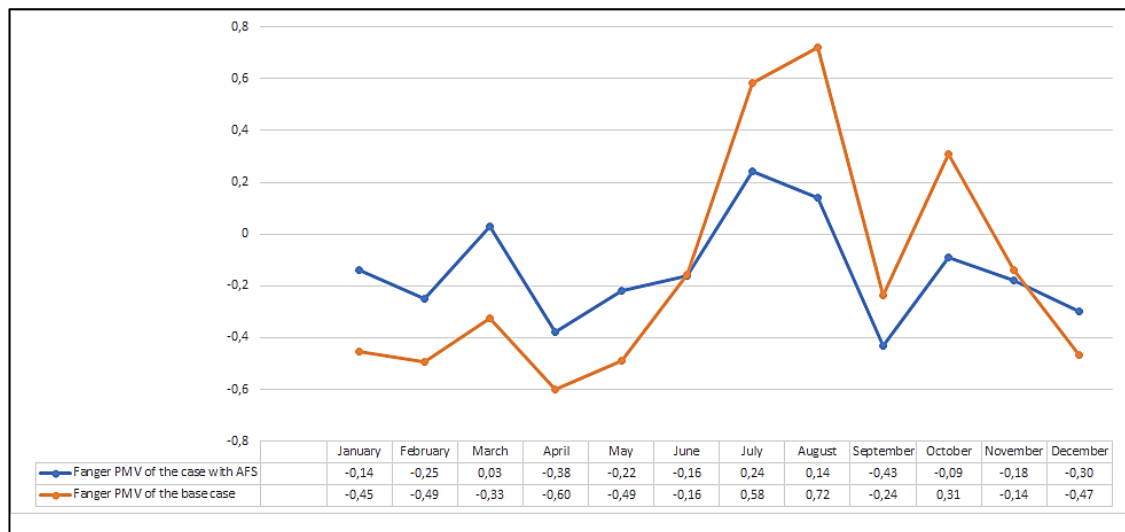
The compromise between the required temperature inside and enhancing natural ventilation was found by defining the operation schedule for the vents. Thereby, the best alternative for providing the fresh air inside in the winter period was when vents were opened in the daytime period when the indoor temperature reached 20°C. The results given in Figure 5.25 shows that the NV improvements are proved by the adequate indoor temperature in the winter period as well as the heating consumption in the base case with integrated AFS. Moreover, the indices of natural ventilation infiltration to the room are slightly higher than in the base case and it increases gradually according to the outside temperatures. In this regard adjustments of the vents improved the level of fresh air distributed to the room even when the windows are closed.

Figure 5.25: Comparison of Nat.Vent of the base case and case with AFS.



In this regard adjustments of the vents improved the level of fresh air distributed to the room even when the windows are closed. In addition, in the summer, when the vents are opened the whole day and the shutters are creating the required shading in the room, the NV is providing a cooling effect and it's reflected in the summer temperature results in the base case with the integrated AFS.

Figure 5.26: The results of Fanger PMV index of the base case and case with AFS.



The analysis of the indoor comfort of both cases was discussed in terms of the comfort temperature range as well as indoor air quality. However, concluding overall comfort in

the room that related to the several factors the Fanger PMV index calculations method is chosen. The comparing results in the graph below show are considered according to these average values. The PMV values ranging between $(-0.5 < \text{PMV} < +0.5)$, where 0 is neutral ideal value for comfort, (-) value cold (+). Comparing the results from the base case, the PMV in the winter period are defined as too cold, while in the case with AFS these values are decreased to slightly cool, this means that proposed approach is useful for enhancing human comfort in the base case. There are some exceeding from accepted values in the base case, for example in August the value is equal to 0.72 this means that it is too hot inside when in the case with integrated AFS the index in August is acceptable warm 0.14. According to the results in the case with AFS, the PMV is better rather than in the base case, not exceeding more than -0.43 are observed. Thus, means that the developed AFS is beneficial for improving indoor comfort.

6. CONCLUSION

In this study, the first chapter presents the introduction and main objective of the thesis, as well as a theoretical background about the building stock and energy efficiency is provided in the literature review part. The main subtopics of the study such as energy efficiency and indoor comfort and strategies to develop AFS is described in the second and third chapters of the paper. In chapter 4 the developed methodology framework of the research, the approach is presented by the general guideline for developing and integrating AFS in the building. The information about the experimental part of the study and results evaluation are explained in the 5 parts.

This study was aimed to improve base case performance in terms of energy consumption and indoor comfort level. The base case was examined by compiled the required architectural, mechanical and behavioral data. Analyzed project drawings and results from the survey, were used as input parameters for the energy model. The energy model of the existing base was simulated in terms of the following aspects:

- a. Energy consumption;
- b. CO² emissions;
- c. Outdoor and indoor temperatures;
- d. Internal gains;
- e. Natural ventilation infiltration;
- f. Fanger PMV.

The survey of occupants and analysis of the simulation results revealed the current problems of the base case such as overheating in the summer period and an insufficient amount of fresh air during the winter. These issues were selected as the main challenges for further improvements. In addition to primary objective decreasing energy consumption for heating in the base case.

Within the framework of this thesis, the investigation for the best AFS alternative was done and as a result of the experiments, the solution was proposed.

The developed AFS represents a combination of a ventilated Trombe wall with dynamic shading devices. The concept of a Trombe wall was selected due to energy efficiency

since the Trombe wall represents a passive heating system with natural convection. Besides, the possibility to integrate active shading to the Trombe wall was very beneficial for solving the main challenges. As a result of these combinations, the developed approach represents the adaptive facade system that reacts to the external conditions providing indoor comfort and reduce energy consumption.

According to the results, the primary energy use decreased by approximately 10%. This was done by integrating the concept of the Trombe wall. This was done by integrating the concept of the Trombe wall, due to the high transmissivity glazing pane, and the natural absorption of solar radiation by the internal thermal mass. With increasing the solar gain by exterior windows in the Trombe wall for twice that in the base case, we achieved the maximum solar radiation gain, that was stored in the mass wall and heated the room during the evening hours, as a result, we achieved the desired effect of the passive heating.

Revealed high operative temperatures in July 26.90°C and in August 27.22°C was decreased by the integration of AFS. This major challenge was solved by installation horizontal metal shading shutters with medium reflectivity properties. The shutters were applied to the outside of the glass pane, and capable of totally closing the facade when it is needed. The optimal angle and open/close parameters were defined according to the schedule of operation that activates the shutters when the indoor temperature is about 24°C . As a result of these actions, the temperature in the base case with integrated AFS decreased to 25.73°C in July, and 25.28°C in August, which means that overheating is not exist, since the maximum indoor comfort temperature in summer is 26.7°C .

Another observed issue of the base case such as the lack of sufficient fresh air in the winter was resolved. The distribution of external air infiltration was increased by including the appropriate vents to internal and external in the Trombe Wall. Such a practice solution was observed in the literature review where the concept of air exchange by the air loop effect was described.

The right adaptation of vent parameters according to the wall dimensions and the placement is obligatory. However, the operation schedule of the vents opening also plays a significant role in the strategy. As a result, we achieved the aim to provide a sufficient amount of fresh air into the room, even when in the low outside temperatures when all

the windows were closed. Moreover, the Fanger PMV in the case with integrated AFS shows better values in terms of occupant comfort which indicates the usefulness of the proposed approach in terms of human comfort.

The considerable findings regarding the experiment of developing the AFS are mostly related to the design aspects. The factors such as material properties of the system have to be considered elaborately, especially the selection of the thermal mass wall and the glazing type.

Furthermore, the right choice of the shading device, its surface properties, and the placement is a must part for the development of AFS. In the meantime, the significant discoveries of the successfulness of AFS were found with the defining operation schedule of the vent operation and shading shutters. The right pick of the configuration of the control schedule played an important role in the proposed approach.

The role of the decision maker in the development of AFS as a retrofit approach is to clearly understand the requirements of the existing building and to predict all the scenarios that can have a negative impact on the building after the modernization.

Indeed, achieving a better energy performance and indoor comfort requires professionals from different disciplines to be involved in the early design stage. The aspects like daylighting, shading and human behavior are main things that should be addressed in the very beginning of improving addressed energy performance and enhancing indoor comfort. Besides, it is important to avoid one overwhelming building performance parameters to influence all others. In the development of AFS, all the improvements towards energy efficiency and indoor comfort must be considered simultaneously.

Indeed, AFS leads to better indoor and energy performance, however current drawbacks in this field such as high cost, lack of performance criteria in designing, operation, and maintenance are inhibiting the implementation process of these systems.

However, it is expected that a developed methodology in this thesis will assist other researches and decision-makers to use them as recommendations to reach particular performance characteristics in terms of actions for achieving energy efficiency and indoor comfort with the integration of AFS.

REFERENCES

Books

- Atagündüz, G., 1989. *Güneş Enerjisi Temelleri ve Uygulamaları*. Ege Üniversitesi.
- Baker, N. and Steemers, K., 2000. *Energy and Environment in Architecture: A Technical Design Guide*. 1st ed. Taylor & Francis.
- Fox, M., 2016. *Interactive Architecture: Adaptive World*. Princeton Architectural Press
- Humphreys, M. and Nicol F., 1998. *Understanding the adaptive approach to thermal comfort*. United States.
- Markus, T.A. and Morris, E.N., 1980. *Buildings, Climate and Energy*. Pitman Publishing.
- Wigginton, M. and Harris J., 2002. *Intelligent skins*. Architectural Press.

Periodicals

- Aelenei, D., Aelenei, L., Pacheco, K., 2015. Adaptive Façade: concept, applications, research questions. *International Conference on Solar Heating and Cooling for Buildings and Industry*.
- Aksamija, A., 2015. High-Performance Building Envelopes: Design Methods for Energy Efficient Facades. *Advances in Building Energy Research*.
- Allouhi, A., Fouih, Y., Kousksou, T., Jamil, A., 2015. Energy consumption and efficiency in buildings: current status and future trends. *Journal of Cleaner Production* 109, pp. 118–130.
- Aslani, A., Bakhtiar, A., Akbarzadeh, M., 2019. Energy-efficiency technologies in the building envelope: Life cycle and adaptation assessment. *Journal of Building Engineering* 21, pp. 55–63.
- Atthajariyakul, S. and Leephakpreeda, T., 2004. Real-time determination of optimal indoor-air condition for thermal comfort, air quality and efficient energy usage. *Energy and Buildings* 36(7), pp. 720–733.
- Attia, S., 2017. Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. *Science Connect* 2017(2), pp. 6.
- Bilgiç, S., 2003. *Passive Solar Design Strategies for Buildings: A Case Study on Improvement of an Existing Residential Building's Thermal Performance By Passive Solar Design Tools*. İzmir Institute of Technology
- Chel, A. and Kaushik, G., 2018. Renewable energy technologies for sustainable development of energy efficient building. *Alexandria Engineering Journal* 57(2), pp. 655–669.
- Dabaieh, M. and Elbably, A., 2015. Ventilated Trombe wall as a passive solar heating and cooling retrofitting approach; a low-tech design for off-grid settlements in semi-arid climates. *Solar Energy* 122, pp. 820–833.
- Dear, R. and Brager, G., 1997. Developing an Adaptive Model of Thermal Comfort and Preference. *UC Berkeley: Center for the Built Environment*.
- Diakaki, C., Grigoroudis, E., Kabelis, N., Kolokotsa, D., & Kalaitzakis, K., 2010. A multi-objective decision model for the improvement of energy efficiency in buildings. *Energy* 35(12), pp. 5483–5496.
- Ferguson, S., Siddiqi, A., Lewis, K., DeWeck, O., 2007. Flexible and reconfigurable systems: nomenclature and review. *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*
- Haase, M. and Grynning, S., 2017. Optimized facade design - Energy efficiency, comfort and daylight in early design phase. *INTEF Building and Infrastructure*.

- Kensek, K. and Hansanuwat, R., 2011. Environment Control Systems for Sustainable Design: A Methodology for Testing, Simulating and Comparing Kinetic Facade Systems.
- Kolokotsa, D., Niachou, K., Geros, V., Kalaitzakis, K., & Santamouris, M., 2005. Implementation of an integrated indoor environment and energy management system. *Energy and Buildings* 37(1), pp. 93–99.
- Kundakçi, B., 2004. Mevcut bina kabuğunun dolayli kazanimli güneş enerjisi sistemi ile iyileştirilmesi için bir yaklaşım önerisi. *ITU*.
- Leech, J.A., Nelson, W., Burnett, R., Aaron, S., Raizenne, M., 2002. It's about time: a comparison of Canadian and American time-activity patterns. *Journal of Exposure Analysis and Environmental Epidemiology* 12(6), pp. 427–432.
- Loonen, R.C.G.M., Trčka, M., Cóstola, D., Hensen, J.L., 2013. Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews* 25, pp. 483–493.
- Marysse, C., 2015. Structural Adaptive Façades. *Universiteit Gent*.
- Sousa, J. 2006., Energy Simulation Software for Buildings: Review and Comparison.
- Stevanović, S., 2013. Optimization of passive solar design strategies: A review. *Renewable and Sustainable Energy Reviews* 25, pp. 177–196.
- Synnefa, S., Santamouris, M., Livada, I., 2006. A study of the thermal performance and of reflective coatings for the urban environment. *Solar Energy* 80.
- Thobaiti, M.A., 2015. Intelligent and Adaptive Façade System: The Impact of Intelligent and Adaptive Façade on The Performance and Energy Efficiency of Buildings.
- Walsh, A., Cóstola, D., Labaki, L., 2017. Review of methods for climatic zoning for building energy efficiency programs. *Building and Environment* 112, pp. 337–350.
- Yılmaz, Z., 1983. İklimsel Konforun Sağlanması ve Yoğuşma Kontrolünde Optimum Performans Gösteren Yapı Kabuğunun Hacim Konumuna ve Boyutlarına Bağlı Olarak Belirlenmesinde Kullanılabilecek Bir Yaklaşım. *İTÜ Mimarlık Fakültesi, İstanbul*.

Other Publications

ASHRAE 55: Thermal environmental conditions for human occupancy. American National Standard Institute, 2017.

BS EN 15251:2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. British Standard, 2007.

EPBD, 2002: Energy Performance of Buildings Directive. The European parliament and of the council, 2002.

IEA 2015: International Energy Agency Report. World Energy Outlook, 2015.

IEA 2013: International Energy Agency Report. World Energy Outlook, 2013.

Passive Solar Design for the Home. National Renewable Energy Laboratory Document, 2001.

