DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A MODEL FOR DESIGNING CLIMATE ADAPTIVE SHADING DEVICES TO IMPROVE THE ENERGY PERFORMANCE OF OFFICE BUILDINGS: THE CASE OF BAYRAKLI TOWER

by

Hande ODAMAN KAYA

July, 2018

İZMİR

A MODEL FOR DESIGNING CLIMATE ADAPTIVE SHADING DEVICES TO IMPROVE THE ENERGY PERFORMANCE OF OFFICE BUILDINGS: THE CASE OF BAYRAKLI TOWER

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Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"A MODEL FOR DESIGNING CLIMATE ADAPTIVE SHADING DEVICES TO IMPROVE THE ENERGY PERFORMANCE OF OFFICE BUILDINGS: THE CASE OF BAYRAKLI TOWER"** completed by **HANDE ODAMAN KAYA** under supervision of **ASSOC. PROF. DR. MÜJDE ALTIN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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A MODEL FOR DESIGNING CLIMATE ADAPTIVE SHADING DEVICES TO IMPROVE THE ENERGY PERFORMANCE OF OFFICE BUILDINGS: THE CASE OF BAYRAKLI TOWER

ABSTRACT

Façade is accepted as a determinant component on energy performance of a building, forming the boundaries between inner and outer conditions. Therefore, an existing office building is studied over the shading devices attached to its façade, with an intention to improve the building energy performance by decreasing its cooling energy consumption.

OpenStudio simulation software is used for calculating heating and cooling electricity consumptions. The simulation model of the case building is calibrated through the comparison of the simulation results with the actual monthly electricity bills. In order to decide the shading device requirements, case building is simulated without shading devices and results are studied with sun path diagram analysis results. Shading devices are studied specific to their 'transparency' and 'elevation angle' parameters depending on hourly and seasonal solar movements. Then collected data is used for forming the climate adaptive shading device (CASD) characteristics.

Consequently; existing shading devices and proposed CASD are compared and discussed in terms of electricity consumptions and window solar radiation energy parameters. Through the proposals; shading devices that show both hourly and seasonal adaptivity to the solar movements gave the highest improvement results in terms of decreasing cooling energy consumptions. Also, suggestions are given for developing the best performing façade in further studies.

Keywords: Building energy performance, OpenStudio simulation, Sun path diagram, Climate adaptive shading device, Electricity consumption, Solar radiation energy

OFİS BİNALARININ ENERJİ PERFORMANSINI İYİLEŞTİRMEK ÜZERE İKLİME UYARLI GÖLGELEME ELEMANLARI TASARIMI İÇİN BİR MODEL: BAYRAKLI TOWER ÖRNEĞİ

ÖZ

Bir yapının enerji performansı üzerinde belirleyici bir bileşen olan cephe; iç ve dış şartlar arasındaki sınırı oluşturmaktadır. Bu sebeple, mevcut bir ofis yapısı; soğutma enerjisi tüketimi düşürülerek bina enerji performansını geliştirmek için cephesinde takılı bulunan güneş kırıcı elemanlar üzerinden çalışılmıştır.

Isıtma ve soğutma için tüketilen elektrik enerjisi hesabı OpenStudio simülasyon yazılımı aracılığıyla yapılmıştır. Çalışılan binanın simülasyon modeli, elde edilen simülasyon sonuçlarının aylık elektrik faturalarıyla karşılaştırılması yoluyla calibre edilmiştir. Gölgeleme elemanı ihtiyaçlarına karar vermek için, çalışılan binanın gölgeleme elemanı olmadan simülasyonu alınıp sonuçlar Güneş diyagramı analizi sonuçlarıyla birlikte çalışılmıştır. Güneş kırıcılar 'geçirgenlik özelliği' ve 'yükselme açısı' değişkenleri özelinde, güneşin saatlik ve mevsimsel hareketlerine bağlı olarak çalışılmıştır. Sonrasında, toplanan bilgiler uyarlı gölgeleme elemanlarının karakterini oluşturmak amacıyla kullanılmıştır.

Sonuç olarak; mevcut gölgeleme elemanları ve önerilen uyarlı gölgeleme elemanları, elektrik tüketimleri ve pencerelerin güneş kaynaklı (radyasyonu/ısıl) enerji kazanımı değişkenlerine dayalı olarak karşılaştırılmış ve tartışılmıştır. Öneriler arasından, Güneşin hem saatlik hem de mevsimsel hareketlerine uyarlılık gösteren gölgeleme elemanları, soğutma enerjisi tüketimini düşürmek adına en fazla gelişme gösteren sonuçları vermiştir. Ayrıca, ileriki çalışmalarda en iyi performansı sağlayan cephenin geliştirilebilmesi için öneriler verilmiştir.

Anahtar Sözcükler: Bina enerji performansı, OpenStudio simulasyonu, Güneş diyagramı, İklime uyarlı gölgeleme elemanı, Elektrik tüketimi, Güneş ısıl kazancı

CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER ONE
INTRODUCTION

Starting from the second half of 19th Century environmental issues had drawn attention. As it is realized that environmental disruption has started to be dangerous on human health after 60s, public institutions and voluntary organizations leaded the movements for improvement and inspection of environmental aspects. Even it was impossible to decrease the reached global warming level; national and international targets were set to stop the increasing of global warming. With the improvement of living conditions by the end of 20th Century; negative effects of development policies had become one of the most important global agenda topics. So global policies had turned to meet environmental concerns and existing development policies on a common path.

Construction sector has a huge effect on natural environment with its all; production, transportation, manufacturing, operation, maintenance, repairment and demolishment processes. Construction sector; consumes 40% of raw materials extracted from the Earth, causes 40% of human waste and uses 40% of the produced energy. Since 30% of CO_2 emission is also caused by the built environment; the main users of the World’s resources are construction sector and built environment. (Özdil, 2007)

Buildings consume more than 1/3 of the world’s total energy; which includes 1/2 of the total electric energy that causes nearly 1/3 of the carbon emissions on earth. As 60% of buildings’ energy consumption is caused by heating, cooling and hot water needs which are supplied from fossil fuels in most of the countries; so that we should work on these loads to decrease buildings’ energy consumption. (International Energy Agency, 2015)

1.1 Problem Statement

Regarding to the obvious constraints the built environment is creating on natural environment; construction sector has developed an ‘energy efficient’ approach in global scale. National and International regulations, codes and directives have been the major push for the implementation of new policies in the sector. Following the global steps, Turkey has built up a series of regulations starting from 2008. However, implementation part of the sector shows a strong resistance by keeping the regulations as ‘requirements’ to fulfil, not as an attitude to embrace. So that we still face with implementations which are not matching with ‘energy efficient’ approach in construction sector.

Since 60% of buildings’ energy consumption is caused by heating, cooling and hot water needs; energy efficiency approaches should be mainly focused on these issues. In this case, optimizing the building envelope as a significant factor on buildings’ heating and cooling energy demand would help for minimizing the total energy loads. According to the Organization for Economic Co-operation and Development (OECD, 2001); a building with a high-performance envelope in a cold climate consumes the 20-30% of a standard building’s heating load. Indeed, the cooling load gain in a hot climate is also changing between 10-40%.

This study deals with energy performance of an existing high- rise office building in İzmir. Bayraklı Tower is chosen as the case building of this research to study on its heating and cooling energy consumptions; focused on shading devices of the façade. In consequence of the curtain wall façade, south facing offices of the building have over- heating problems disconcertingly in winter. Even though shading devices are densely placed on the southern façade, occupants have cooling demand both in summer and winter seasons.

1.2 Aim of the Study

The dissertation ‘A Model for Designing Climate Adaptive Shading Devices to Improve the Energy Performance of Office Buildings: The Case of Bayraklı Tower’ aims to present a methodology for improving the energy performance of an existing office building in İzmir by proposing climate adaptive shading devices (CASD).

The study is composed of different methodologies which are based on various components and processes; constituting the steps for reaching the main aim of the study by;

- Generating a calibrated model of the building considering the actual data,
- Establishing the shading device requirements of the building,
- Proposing CASD for the building,
- Presenting the most efficient proposal for improving building energy performance by decreasing cooling energy consumption.

Consequently, the aim of this study is to present an approach for designing alternative shading device solutions in relation with building energy performance.

1.3 Scope and Methodology of the Study

This study presents a methodology for proposing climate adaptive shading devices (CASD) for buildings to improve building energy performance. The presented methodology is applied on a case building to represent a guide for further applications and studies.

CASD are studied under the definition of 'climate adaptive façades' which is still an unclear concept in literature in terms of definition and classification. Therefore, there is no well-defined methodology for evaluating the effect of CASD on building energy performance.

This study is based on a literature review including building energy performance and climate adaptive façades. The concept and main approaches of building energy performance issue is defined through national and international legal aspects. CASD are included in literature review through scientific publications which are covering also building energy performance calculations over simulation tools.

Building energy performance simulation tools are categorized based on existing literature and input- output data requirements are mentioned in detail. The general process of building energy performance simulations is given with the initiatives of each step. Constructed on the given information, methodology and basis of OpenStudio simulation tool is studied thoroughly as the supporting tool of this study.

Climate adaptive façades are studied over the definitions and classifications within the literature. This study covers the climate adaptive façade alternatives that are shaped according to the outdoor climate conditions to provide the indoor comfort conditions depending on the building function.

Energy consumption of heating, cooling and fan usages are considered as energy performance indicators in this study. The outer factor that is expected to affect the façade to adapt is the solar movement in hourly and seasonal manner. Also, the inside parameters that are considered as effective on building envelope are; heat mass/ gain solar control, daylight usage/ control and natural ventilation. (Gür & Aygün, 2009)

Within the given scope of the presented methodology; CASD proposals are developed by using a solar diagram analysis tool (Sunearth Tool web-based software) and results are compared through the energy consumption data obtained from a building energy performance calculation tool (OpenStudio simulation software). As a result; the most efficient proposal is displayed for improving the energy performance of the building.

Although the methodology is assigned to an existing case building in this study, it can be used regardless of the case building (such as new constructions, different building typologies, other climate conditions etc.)

1.4 Framework of the Study

This dissertation consists of six chapters. The First one is the introduction chapter including; the problem statement of the study and the aim of the study, also the used methodology is presented within the scope of this study.

Chapter Two consists of the literature review on the main concepts of the study. Understanding of ‘building energy performance’ in international and national aspects are summarized and ‘climate adaptive façades’ are investigated within the academic publications.

Chapter Three is giving the description of the theoretical framework of this study. Building energy performance calculation and simulation tools are mentioned by their categories, data requirements and simulation process. As the simulation tool used for this study, OpenStudio is introduced in detail; its interface, calculation methodology and simulation settings. Also, the definition and classification of climate adaptive façades are given based on literature review.

Fourth chapter presents the methodology of this dissertation.

In Chapter Five, proposed methodology of the study is executed on a case building. The data used for generating the simulation model is presented. The method used for calibrating the model is mentioned. Shading device requirements of the case building are analysed, and CASD proposals are given. Through the application of proposed shading devices, building energy performance indicators are chosen from outcomes and driven into the comparison.

Sixth is the final chapter, summarizes the methodology proposed by this study and discusses the outcomes of the case study by giving further study suggestions. Also, importance of working on an existing building was mentioned in order to understand the applicability of the proposed methodology.

1.5 Significance of the Study

Followed by the literature, there are many researches on definition and classification of ‘climate adaptive façades’. Even though the issue is widely studied in the context of building energy performance, implementations are generally discussed over hypothetical buildings. Thereby results are never calibrated through actual data. This study aims to cover the gap in the field by approaching the issue through an existing building, so that the acquired data have the possibility to be validated.

The presented model for designing climate adaptive shading devices to improve energy performance of office buildings; is comprised of the application of different methodologies. OpenStudio Simulation is used as a tool for calculating building energy performance where it is also used for shading device requirement analysis together with Sunearth Tool. So that the proposed model of this study is significant in literature also by the presented methodology.

CHAPTER TWO
LITERATURE REVIEW

Literature review on the background of ‘building energy performance calculation’ and ‘climate adaptive building façade’ will be evaluated in this chapter. First and second sections cover building energy performance directive and regulations of European Union and Turkey. Third section focuses on the significant publications in the field which are dealing with climate adaptive façade issue in terms of building energy performance.

2.1 Energy Performance of Buildings Directive (EPBD)

European Commission (EC) published the Energy Performance of Buildings Directive (EPBD) first on 16th of December 2002. It was mainly setting some compulsories as the minimum energy performance demands should be provided; the national methodologies should be provided to calculate and certify the energy performance of the buildings and the building air conditioning systems should be controlled periodically. Directive was replaced on 19th of May 2010 with a revised version including policies on ‘nearly zero-energy buildings’ and ‘cost optimal levels of minimum energy performance requirements’. European Commission proposed the last revision on 30th of November 2016 which is still in the approval process. The draft package titled ‘Clean Energy for all Europeans’ focuses on putting energy efficiency first, achieving global leadership in renewable energies and providing a fair deal for consumers. (European Commission, 2018)

‘Energy performance of a building’ is defined as ‘the calculated or measured amount of energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting’. And ‘energy performance calculation methodologies’ described in Annex-1 of the 3rd Article of the Directive include; ‘in addition to thermal characteristics, other factors that play an increasingly important role such as heating and air-conditioning installations, application of energy from renewable sources, passive heating and cooling elements, shading, indoor air-quality, adequate natural light and design of the building.' It is indicated that a methodology should cover not only the heating season, but the annual energy performance should be also considered within the European standards. (European Commission, 2012) A 'common general framework for the calculation of energy performance of buildings' is defined in directive as:

> 1. The energy performance of a building shall be determined based on the calculated or actual annual energy that is consumed to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs.
>
> 2. The energy performance of a building shall be expressed in a transparent manner and shall include an energy performance indicator and a numeric indicator of primary energy use, based on primary energy factors per energy carrier, which may be based on national or regional annual weighted averages or a specific value for on- site production.
>
> 3. The methodology shall be laid down taking into consideration at least the following aspects:
>
> (a) The following actual thermal characteristics of the building including its internal partitions: thermal capacity, insulation, passive heating, cooling elements and thermal bridges;
>
> (b) Heating installation and hot water supply, including their insulation characteristics;
>
> (c) Air-conditioning installations;
>
> (d) Natural and mechanical ventilation which may include air-tightness;
>
> (e) Built-in lighting installation (mainly in the non-residential sector);
>
> (f) The design, positioning and orientation of the building, including outdoor climate;
>
> (g) Passive solar systems and solar protection;

(h) Indoor climatic conditions, including the designed indoor climate;

(i) Internal loads.

4. The positive influence of the following aspects shall, where relevant in the calculation, be taken into account:

(a) Local solar exposure conditions, active solar systems and other heating and electricity systems based on energy from renewable sources;

(b) Electricity produced by cogeneration;

(c) District or block heating and cooling systems;

(d) Natural lighting.

5. For the purpose of the calculation buildings should be adequately classified into the following categories:

(a) Single-family houses of different types;

(b) Apartment blocks;

(c) Offices;

(d) Educational buildings;

(e) Hospitals;

(f) Hotels and restaurants;

(g) Sports facilities;

(h) Wholesale and retail trade services buildings;

(i) Other types of energy-consuming buildings' (EPBD, 2010)

2.2 Building Energy Performance Regulations of Turkey (BEP)

As a threshold in Turkey, 'Code for Energy Efficiency' was published on 2nd of May 2007 with an attempt of opening a path for ministries to develop regulations on their own study fields. Ministry of Environment and Urbanisation first published 'Building Energy Performance Regulations' on 5th of December 2008; based on 'Energy Performance of Buildings Directive (EPBD) 2002/91/EC' of the European Union and 'Code for Energy Efficiency' of Turkey. Also, national energy performance calculation tool: Bep-TR was presented parallel to the regulations. Bep-TR was generated as a certification system grounded on EN ISO 13790 and national specifications. (ISO, 2008) To present the energy certificate level; whole building's total energy consumptions are calculated according to the primary energy usage and CO_2 emissions caused by climate conditions, indoor environment needs, regional priorities and boundary conditions. The online software had been in use from July 2010 till November 2017 by registered professionals under a governmental network.

By January 2017, the number of existing and new buildings certified by using Bep-TR was 485000: which is showing that 94% of the new constructions and 6% of the existing buildings were already examined by means of their energy performance. With this legal obligation; 73% of the buildings reached to an energy efficiency level which is 20-40%. higher than before. And the 26% of the buildings reached to an energy efficiency level that is 40-60% higher than before.

Besides that; governmental sources show that heat insulation had been applied to 90% of the certified buildings, which is the main understanding of 'energy efficiency' derived by 'TS 825'. (T.C. Çevre ve Şehircilik Bakanlığı, 2017) Turkish Standards Institution published TS 825 on 22nd of May 2008 with the title of 'Thermal Insulation Requirements for Buildings' and a revised version was published in July 2009. The main subject of the standard is 'the net heating energy demand calculation rules' and 'the maximum heating energy usage limitations'. (Standard., T., 825, 1999)

The energy performance of the buildings is calculated by a simple hourly dynamic methodology including;

- Net energy demand value for heating and cooling systems,
- Energy consumptions for the need of air conditioning, hot water and lighting (considering the daylight),
- Total heating and cooling energy consumptions of whole building considering the system efficiencies. (Ganiç, Corgnati, & Yılmaz, 2013)

Ministry of Environment and Urbanisation published repeating "Declaration on Building Energy Performance Calculation Methodology" on 1st of November 2017 to present the new calculation tool. BEP-TR 2 has an offline operation platform which has a two-dimensional drawing and three-dimensional visualization interface. Also

‘Energy Identity Certificate’ (Figure 2.1) had become a more detailed document which will be followed by the government conveniently. (Official Gazette, 2017)

Figure 2.1 Energy identity certificate (Personal archive, 2017)

2.3 Publications

This third section of the literature review is presenting the publications which have attributed importance on climate adaptive façade issue in terms of building energy performance. Even though building energy performance is a common topic for many disciplines; studies on climate adaptive façades have been carried on by a small group of researchers. Studies that are combining both issues are given in a chronological order as follows:

Van Dijk (2010) made a research on possibilities of adaptation in a façade and studied on a case building: the future faculty of Architecture at TU Delft. Adaptivity in a façade is described dependent to many different factors as ‘the building’s user and the coherent practicability; the façade components’ effectiveness in time; the climate profile; the costs and architectural choices.’ With the fact of all these factors, the climate adaptive façade is shown as a good way of contributing good comfort levels of a building for its users and the surroundings.

Loonen (2010), published a booklet from the master thesis project ‘Climate Adaptive Building Shells (CABS)- What can we simulate?’. Overview of 100 CABS includes case studies, prototypes and research projects that can be used as a guide by researches and designers to follow the adaptive building shell technology.

Loonen et al. (2010) studied on exploring the role of ‘Building Performance Simulation (BPS)’ in Climate Adaptive Building Shells (CABS). The features of CABS are presented in relation with BPS and studied over a case building with Smart Energy Glass (SEG). Validated models are used for building energy performance simulation of renovation scenarios in TRNSYS and DAYSIM software and concluded by suggestions. As a result of the case study; it is asserted that BPS is confirmed to be a valuable tool for designing buildings with CABS and proved as an active tool in product design and development.

Loonen et al. (2011) explores and quantifies the latent potential of CABS by using building performance simulation in combination with multi-objective optimization and advanced control strategies. As it is difficult to envision direct applications for the presented results, the specifics of the case-study building are not discussed in detail. The authors are pointing out the novel application area for the use of building performance simulation. Besides of using simulations as a strategic decision-making tool, it is also shown as a router in specifying most valuable directions for future research and development. Approach of the study is characterized by the term ‘inverse’ by the authors as it takes the question of the simulation mentality from ‘what if’ to become ‘how to’; providing a guidance to the user.

Kim and Jarrett (2011), aimed to determine the influence of a climate adaptive façade system on the energy performance of a hypothetical office building located in a cold climate. The whole building energy simulation was run by DesignBuilder. A climate adaptive façade system was developed, consisting of a typical curtainwall system and an operable shading system. The result of the analysis revealed that the climate adaptive façade system substantially decreased heating loads compared to a baseline façade system in a cold climate. Also, the future target is given as, testing the adaptive façade system experimentally and verify the simulated energy performance data against empirical data.

Loonen et al. (2013) published a comprehensive literature review on classification of Climate Adaptive Building Shells (CABS). Regarding to the review on research, design and development issues; CABS found out to be still immature. It is observed that even though it is a growing field, emerging techniques are needed for effective contributions to a more sustainable built environment. The research Dynamic exterior shading systems are mentioned as more applicable in cost-effectiveness manner and pointed out as a smooth transition towards widespread application of more advanced CABS.

Abboushi (2013) presented a master thesis based on three objectives. First is to develop an adaptive overhang that provides shading while increasing daylighting in office spaces. Second is to propose a new type of light shelves, selective reflector light shelf (SRL) which improves daylight admission without increasing the cooling load. And finally, to present a method to increase window area without increasing the total energy consumption and compromising building efficiency. It is stated that: 'Adaptive shading and passive light shelves not only can control heat gain through fenestration areas, but also, can increase and regulate illuminance levels throughout the year resulting in a more visually and thermally comfortable office spaces that significantly consume less energy and enhance occupants' productivity.' With this research adaptive shading and the selective reflector light shelf technologies are studied to develop high performance office buildings façades.

Loonen et al. (2015) made a research with the aim of classifying climate adaptive façade concepts and presented an analysis of existing classification approaches to identify requirements and challenges of these processes. Based on the strong points of the analysed approaches, a comprehensive way is proposed for characterizing climate adaptive façade concepts. The proposed matrix is explained over 3 case studies: dynamic exterior shading façades, glazing with phase change materials and BIPV double-skin façades.

Attia et al. (2015) made a review on current state of the art of assessment strategies for adaptive façades and found out that in literature there is no focus on this field. The researchers couldn't find any agreement on defining what are adaptive façades or any protocol for assessment of climate adaptive façades. The challenges and questions on the assessment of adaptive façades using currently available measuring and evaluation protocols are mentioned. The next step of the study pointed out as working on case studies with climate adaptive façades to understand their performance better and to study their optimization potentials by a detailed monitoring performance data.

Aelenei et al. (2016) studied on analysis of existing concepts and case studies of climate adaptive façades to propose a new approach for characterization of these façade elements. 130 case buildings were analysed based on the need of adaptability associated with the external factors. Solar radiation and outdoor temperature are indicated as the most common external factors associated with climate adaptive façades. As a conclusion of the study; climate adaptive façades are pointed as primary objectives of improving energy performance of buildings and human's comfort.

Loonen et al. (2017) published a review article to collect and analyse the existing information in the field. The study covers; definition of unique requirements for successful modelling and simulation of adaptive façades; review on the capabilities of five widely used BPS tools and discussion on various ongoing trends and research needs. 'This paper has highlighted the potential of simulation-based analysis in various stages of design and development of buildings with adaptive building envelopes. The main requirements and challenges compared to performance prediction of conventional, static building envelopes were identified.'

Bianco et al. (2017) focused on the solution of high energy demand and discomfort conditions in buildings with large transparent façades. They proposed a new dynamic shading device based on the integration of phase change materials (PCM) in an alveolar polycarbonate panel. The concept of the shading is to act as a self-controlling device able to reduce and modulate both light and solar heat gain in the indoor environment and to improve the thermal inertia of the envelope. Study presents different typologies of PCM with different melting temperature and different colour of the polycarbonate panel. The study concluded the findings as; PCMs with paraffin waxes are the most preferable options regarding to their stable thermal properties, high latent heat of fusion and narrow melting temperature range. Bio-based PCMs have slightly better performance due to the thermal resistance of the system and according to the optical characterisation, green and crystal are the preferable polycarbonate colours.

2.4 Conclusion

As a major concept of this study; ‘building energy performance’ was added to literature by European Commission with Energy Performance of Buildings Directive (EPBD), published in 2002. The directive is presenting the definition and methodology of the concept in a clear framework which has been developing with new targets and policies based on the initial methodology.

Also, the attempt of Turkey in developing policies for ‘building energy performance’ has been proceeding since the publication of ‘Code for Energy Efficiency’ in 2007. Even the regulations of Turkey are based upon EPBD; national building energy performance assessment tool ‘Bep-TR is not matching with the calculation methodology recommended by EPBD.

Another important concept of this study; ‘climate adaptive façades’ appear as a new concept in literature but it is new only in terminology. Regarding to the definition of the concept; either a conventional curtain or a photovoltaic shading device working with solar receptors are both included within the wide context of climate adaptive façades. Even the referred meaning is not new, as a new term ‘climate adaptive façades’ are studied by a limited group of people in literature. As the focus of the publications is on definition and classification of the concept through case studies.

In general, effects of climate adaptive façades on energy performance of buildings is studied through hypothetical buildings; some of which are validated. Besides, usage of existing assessment methodologies for the assessment of climate adaptive façades is another issue discussed in literature. On the other hand, usage of simulation tools is pointed out as a potential approach for integrating climate adaptive façades to the building in design or development processes. Also, another viewpoint defines the usage of simulation tools in development of climate adaptive façades; as a guide giving the answer to the question 'how to' rather than 'what if' which is the base of simulation mentality.

Mostly, climate adaptive façades are presented as a 'primary objective' for developing the energy performance of a building. Moreover, dynamic shading devices are taken as a solution for increasing energy performance of buildings having wide glazing on their façade. Above all, considering the cost effectiveness; dynamic shading devices are pointed out as a smooth transition to an extensive usage of advanced climate adaptive façades.

With an intention to increase building energy performance, climate adaptive façades are pointed out as a potential field in literature. Considering the wide scope of climate adaptive façades, the initial step of taking attention to the concept would be working on CASD which seem more feasible to apply. As a remarkable point; in the field of climate adaptive façades, simulation is considered as a tool which is giving the answers to the question 'how to' and this would serve a guidance in design and development processes.

As it is highlighted in literature review; building energy performance is a significant focal point in global scale and it is mainly calculated by computer aided simulation tools. Even majority of the studies are on hypothetical building models, the data produced by the studies on existing buildings have the possibility to be compared with the accurate data to be validated.

Consequently, this study is promising to present a methodology for proposing CASD for buildings to improve their energy performance.

CHAPTER THREE
DESCRIPTION OF THE THEORETICAL FRAMEWORK

3.1 Building Energy Performance Simulation Tools

European Commission published the Energy Performance of Buildings Directive (EPBD) first in 2002, followed by two revisions in 2010 and 2012. The definition of 'energy performance of a building' is given within the directive as; 'the calculated or measured amount of energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting'. (European Commission, 2018)

'Simulation' is one of the methods to calculate the energy performance of a building. Etymologically, it is based on the word 'simulare' in Latin, that means imitating. As a mathematical model based on the question 'what if'; estimations and analyses on the behaviour and performance of the system can be carried out. It is imitating the activities or processes of the real life; mainly depending on the relation in between real dynamic processes and models with iterations. (Hui, 2014)

Based on a complex structure, building energy performance can be calculated; by a real model analysing the building character in detail, or by a physical/mathematical model covering all the design, usage and maintenance processes of a building. The mathematical system models can be produced by an analytical solution approach or by a software simulating the dynamic interaction of heat, light, air and humidity inside of a building. These software help for estimating the energy consumption depending on the climate, occupants and air conditioning systems and all the features of energy performance of a building. When producing a physical model is not feasible because of its high cost and complicated process, simulation should be preferred way to analyse and understand the building performance in detail. Building simulation tools are categorized according to their context; the basic software; analyses the total energy consumption of a building and calculates the heating-cooling loads for the peak temperature values, improved software; also, the hourly lighting and air flow estimation can be done, advanced and complicated software; 2D and 3D fluid dynamics calculation ability is added, the combination of some categories; works as an integrated analysis and design system. (Hui, 2014)

Simulation tools are used for different purposes depending on the lifecycle phase of a new or existing building such as; feasibility and basic energy analysis, schematic design, detailed energy analysis, production knowledge, invoices, proposals, planning and implementation, completion of the work, testing and setting the systems, utilization and maintenance. (Hui, 2014) By the capability of a simulation tool, the dynamic responses and performance of a building can be estimated for different design ideas; comparing the energy performance towards the energy demand and cost-benefit.

For some projects, it may not be efficient and economical to run a simulation if it is a small project or the time is very limited. Also, when it is too late to change any decision or when the occupant behaviours or the process cannot be directed and even for the cases when the simulation's contribution is not clear, running a simulation may not be the right decision.

The simulation process should start as early as possible; so that the simulation results can be integrated to the early stages of the design process. The simulation model should be simple, and detailing should run parallel to the improvement of the design; so, the simulation model and the design can be evaluated together.

Before starting to a simulation process, the data with the different formats should be prepared; filling the forms interactively, uploading the existing folders and sharing the graphical data by transferring the CAD files.

3.1.1 Categories of building energy performance simulation tools

Even running the simulation before the important design decisions is accepted as the most efficient decision to achieve the optimum building performance; different processes can be followed as well:

- Evaluating the building design (design evaluation tool),
- Calculating the energy consumption and performance (building energy analysis tool),
- Evaluating the energy costs (economic analysis tool),
- Designing and optimizing the building systems (system design/optimization tool),
- Accommodating to the energy codes (code accommodation tool),
- Supporting green building assessment (green design tool). (Hui, 2014)

The diversity of the energy analysis tools should be argued not only about the degree of accuracy, but also the period of the design it is suitable for, the work load requirement and the cost should be considered. Even some of these tools can supply a quick feedback in early design stages; some other has a longer and detailed input processes. Paradis (2010), categorizes the energy analysis tools according to their usage purpose:

Monitoring tools; mostly used for the budgeting and programming processes of the building renovations. Designed for assessing the applicability of the project in early stages of the programming, some of them can run also the economic analysis. In a program depending on correlations; daily, monthly, and seasonal building performance is calculated according to the climate data and thermal characteristic by the help of the predictive correlations. This abolishes the need of hourly simulations. Even such programmes make minimum calculations and work fast; the risk of compromising the accuracy occurs. As these programmes are simplified; it may not be possible to evaluate some interactive energy strategies such as daylight, heating, thermal mass and cooling.

Architectural design tools; are used for the programming, schematizing and design improvement processes of new constructions and big renovations. It helps with the evaluation of important design decisions such as; the building orientation, glazed surfaces, daylight.

• Load calculation and HVAC sizing tools; are used in the new constructions and big renovations for improving the design and documenting the construction. These tools designed for choosing and sizing the equipment as boiler, furnace, and chiller; can also simulate the annual energy.

• Cost evaluating tools; can be used during whole design process.

3.1.2 Input and output data requirements of simulation tools

The general framework for the simulation output includes; space temperature, surface temperature, humidity level, HVAC variables and energy consumption (components, system, whole building) data. To establish the relationship between the real world and the computers; we need the knowledge of a mathematical world that is set on the equations of a theoretical physical world. Therefore, to comply with the restrictions in the model while simulating; we should know how to approach to the problems of the real world as well as possessing the programs' way of thinking for the system, design and interactions.

Data requirements of building energy simulation tools can be generalised as;

• Site data: building type, location, geometry, construction technique, climate data, Building data: surface area, windows area, zoning, room types, materials, mass, shading, finishing details, occupant profile and occupancy plan, inner loads, design conditions,

• Building systems' data: HVAC, lighting and electric suppliers,

• Building utility and equipment data: heating, cooling and other utility performance,

• Economic analysis data: electric rates, fuel rates, equipment costs, interest rate data. (Hui, 2014)

3.1.3 Building energy performance simulation process

The process followed while calculating the annual energy consumption by the help of simulation tools is set on a general framework by Paradis (2010):

1 Defining the thermal zones: The parts of the building that supply the same thermal needs from the same mechanical equipment and control system are called ‘zone’. The number of the zones are decided according to many factors as; the building occupancy, size and geometry.

2 Calculating the loads for each zone: The needs to keep a building in suitable conditions; hourly heat loss ratio for summer and hourly heat gain ratio in winter are called as ‘load’. Hourly peak points of the annual heating and cooling loads should be calculated for each zone.

3 Choosing the HVAC systems: The mechanical equipment of the building is chosen and sized according to the calculated loads. To run a comparative simulation for a multi zoned building; the thermal interactions between the zones should be considered in the calculations.

4 Calculating the hourly energy consumptions: The hourly loads for the chosen equipment should be calculated on meteorological year basis and the needed energy rate should be specified for the equipment.

5 Data input for the electrical infrastructure and energy rates: Entering the data about the energy rates including the peak energy demands depending on the construction site.

6 Calculating the energy costs: The fuel cost is calculated for each hour of the year and the sum of all gives the annual performance. (Paradis, 2010)

Some of the programmes are working based on Excel in some steps of this process. The simplified methods can be preferred because of the input data needs and long working time of the complicated tools which take the problem as whole. Even most of the software deals with the 2nd and 3rd steps successfully; mostly they cannot interact with the requirements of the 4th step as daylight and lighting issues. Today, there are many energy analysis tools developed by different branches of production and as the number increases, the chance of making comparisons between their accuracy decreases.

3.1.4 OpenStudio

As it is stated by EPBD, the energy performance of a building shall be determined based on the calculated or actual annual energy that is consumed to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs. (European Commission, 2012)

The open source software of National Renewable Energy Laboratory (NREL), OpenStudio is covering this statement. Developed as a plug in for the SketchUp 3D modelling environment; the software integrates the energy modelling ability of EnergyPlus software and daylight analysis features of Radiance software, and BEopt interface helps the optimization of the data collected from the various simulations. These platforms are all combined by a Software Development Kit (SDK) to produce a graphical interface. (DoE, 2015) Besides all, founded on the detailed dynamic calculation methodology of EnergyPlus software, OpenStudio can supply realistic output data about the energy performance of a building. (DoE, 2015) In fact, related CEN standards or national building energy performance calculation methodologies that are established according to EPBD are allowed to use for energy performance calculations. However, using a dynamic method is recommended by the Commission to reach reliable results at the first stage. (Ganiç N. , 2012)

OpenStudio process starts by generating a 3D model of the building in SketchUp environment, including the plan scheme and façade fenestration details. After the climate data and the general building information are set, the occupancy schedules should be arranged according to the work and human loads. The requirements of the software are followed by entering the data of construction settings, building boundary conditions, space functions, thermal zones and thermostats. Also, the expected output data can be determined before starting the simulation process. When the ‘daylight’ is an important parameter, also the Radiance interface is included in the simulation process. Running the simulation process, the output data including; heating, cooling, lighting, equipment usage and other mechanical system details can be purchased. For the comparison between the simulations of different alternatives, also the ‘parametric analysis tool’ interface would be activated to learn about the negative or positive effect of the defined variables.

3.1.4.1 eQUEST

A public institution; California's Savings by Design and Energy Design Resources is supporting the software which is free to download with the long-term climate data of more than 1000 locations. The annual average of downloading the program is 10000 users including; building designers, building managers, building proprietors, energy/LEED consultants, universities and researchers. With the online validation reports according to ASHRAE Standards (140) it is one of the most trusted and common software in United States.

The software works on an enhanced DOE-2 simulation engine combined with a wizard for creating the building, a wizard for measuring the energy efficiency (EEM) and the modules for preparing the graphical results.

DOE-2 helps for the hourly simulation of the building depending on the walls, windows, glazing, occupants, and loads in the sockets, ventilation etc.; and even the performance of the other energy consuming devices such as fan, pump, chillers, boiler and others.

eQuest provides the users to see the graphics of different simulation alternatives together. Also, it is possible to apply the listed preventions automatically intended to energy cost estimation, daylight and lighting system control and energy efficiency.

Within the context of building performance; dynamic suppositions, interactive graphics and parametric analysis goes through quickly and continuously from the very early concept stages to the last design stages with the help of wizards.

The graphical summary reports of the first process results include the comparative result summaries of the multiple independent simulations and the quantitative report charts of the comparative annual increase and decrease results. Also, the summary reports present; non-hourly simulation results, hourly simulation results and compatibility analysis reports for California Title 24.

Some of the negative feedbacks for the software is expressed as the impossibility of analysing the compatibility for ASHRAE standards automatically and the limitation of the mechanical system models.

Also, the daylight can be considered just for the spaces facing outwards; so that the daylight passing through the transparent surfaces to the interiors that are not facing outwards is ignored. Furthermore, the ability of DOE2.1E couldn’t be transferred to DOE-2.2 and eQUEST yet; providing the option to specify the codes that should be adapted.

3.1.4.2 EnergyPlus

The modular software based on the most popular features and opportunities of BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2; it has more than 85,000 users including mechanical and energy engineers, architects and companies, local agencies, universities and research laboratories working on these issues. It can be downloaded for free with the climate data of more than 1250 locations all over the world and the BESTest reports of International Energy Agency (IEA) and HVAC tests are available on the website.

With the ability of the subprograms (Space Loads Prediction, Air System Simulation, Central Plant), BLAST provides; estimations for the energy consumption, energy system performance and cost of the new constructions and renovations of all type and size.

The loads are calculated within a time interval set by the user and transferred to the building system simulation module for the same time interval, by the help of the balance engine. The building system simulation module calculates the heating and cooling loads and the reactions between the electric systems and installations within variable time intervals.

This integrated solution can provide accurate results for the space temperatures which have a high importance on the calculations of the system and utility sizes and the user’s health and comfort. The users can run correct and detailed simulations with the complex modelling capacity of the software which presents a high standard architectural interface giving the opportunity to provide the geometries in CAD format. It is also possible to test the simulation results with the existing test sets and publish the results on the webpage. Just a more compelling feature compared to the other programmes working on a graphical interface is to have the input and output data as written files.

3.1.4.3 BEopt

Using the EnergyPlus and eQuest (DOE-2.2) simulation engines, the software compares various design alternatives in optimization mood; to define the cost optimum efficiency for houses and to assess the house designs by analysing the cost and energy. (Orhon & Altın, 2015)

The software gives detailed analysis over the character of the house by the size, architecture, occupants, construction, location and occupancy rates for the new constructions or renovations of the existing buildings. It makes an assessment representing the real implementations and real construction materials for the building envelope and equipment options.

The free software has nearly 2000 users including energy analysts, engineers, architects, employers, public institutions, regional agencies, universities and research laboratories. BEOpt user interface has 3 data input screens as; a drawing tool for creating and monitoring the 3D building geometry, an optional selection screen for setting the measurements of the envelope components, facilities, equipment and occupants, a site information screen for setting the location, occupancy rates and cost data. Moreover, these can be arranged suitable for the new constructions or renovations.

The simulation output is delivered hourly, including the comparison for detailed cost and energy results, multiple design options for the user, financial calculations, energy and end user charts, efficiency measurement definitions and cost. Even the simulation includes the heating, cooling, ventilation, hot water, lighting, equipment and PV usages of a whole building; it is limited with the residential buildings. The easy usage of the detailed simulation engine provides a prevalence of use with the possibility of adding new energy efficiency alternatives to the standard library of the software. It can also make comparisons by the assessments through the references created by the examples formed by the existing energy codes.

3.1.4.4 DOE-2

The software developed by the United States Department of Energy (USDOE); can analyse the hourly detailed energy consumption and energy cost for whole building to design multi zoned, complex buildings, analyse renovation opportunities, developing and controlling the building energy standards. It works depending on the sequential data transfer between a sub-programme for data translation and 4 sub-programmes for simulation.

Input data for the simulation is; hourly climate data, geographical location, building geometry, building orientation, materials and envelope components (walls, windows, shading devices etc.), occupancy schedule, HVAC equipment and control systems, occupancy ratio, cost of the building components.

Reports of the calculations are given as an output; 20 validation report preferences, 50 monthly and annual report summary preferences and hourly reports depending on the user for 700 different energy variables can be achieved.

Including the architects, engineers, energy consultants, building technology researchers and universities; 80% of 1000 foundations using the software are in United States. The tests and validation reports of the infrastructure and the application of the software are available on the website where the software can be purchased.

3.1.4.5 OpenStudio Calculation Methodology

Buildings have many complex processes including construction, environment and building occupancy factors which directly affect heating and cooling loads. Heating loads of a space can be calculated manually by using a fast and basic method in which the heating loads are accepted to be transformed to instant cooling loads. But this method doesn’t present totally reliable results caused by the lack of some processes such as heat storing or radiation transfer. Five main calculation methodologies are shown in Figure 3.1, to understand the relation between complexity and accuracy.

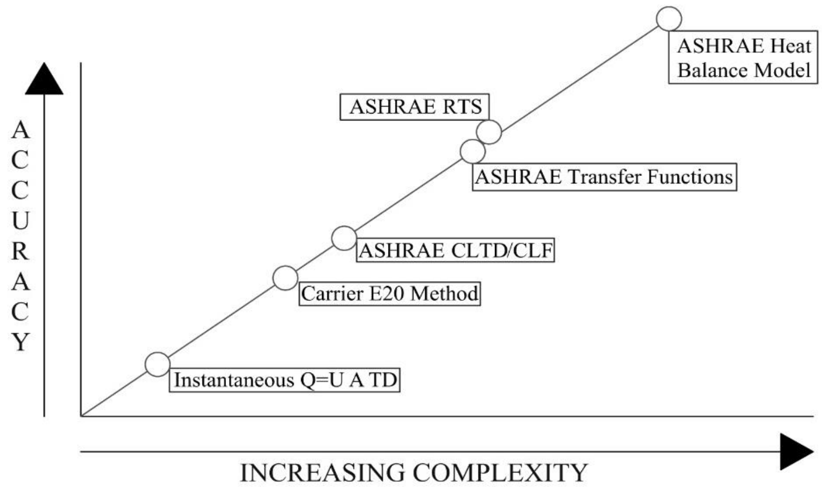


Figure 3.1 ASHRAE load calculations (Spiller, 2014)

For all the calculation methodologies; detail level of the created model and expected proximity to the reality changes according to the purpose of the model. The crucial point is to define the right parameters intended to the problem and avoid all the unnecessary details. Even all heat transfer models created for buildings are complex and impractical solutions; they are still in an acceptable level with the suitable and substantive simplifications and assumptions. Accepting the zone air as a well-stirred mixture is one of the main examples for these assumptions; which means the zone temperature is approximately steady in many cases. Therefore, heat transfer and thermodynamics processes are formulized within many ‘heat transfer models’ depending on this assumption. (Spitler, 2014)

Figure 3.2 shows the ‘Heat Balance Method (HBM)’which is the base of many calculation methodologies by presenting a sensitive approach to building load calculations according to the basics of heat transfer and thermodynamics. All convection, conduction, radiation and heat storage processes are considered by HBM; including solar heat gain, internal gain, internal surface temperatures, natural ventilation, shading, HVAC equipment and heat mass parameters in an hourly-dynamic manner. (Köroğlu Işın, Alaloğlu, Erdoğan, & Acar, 2011)

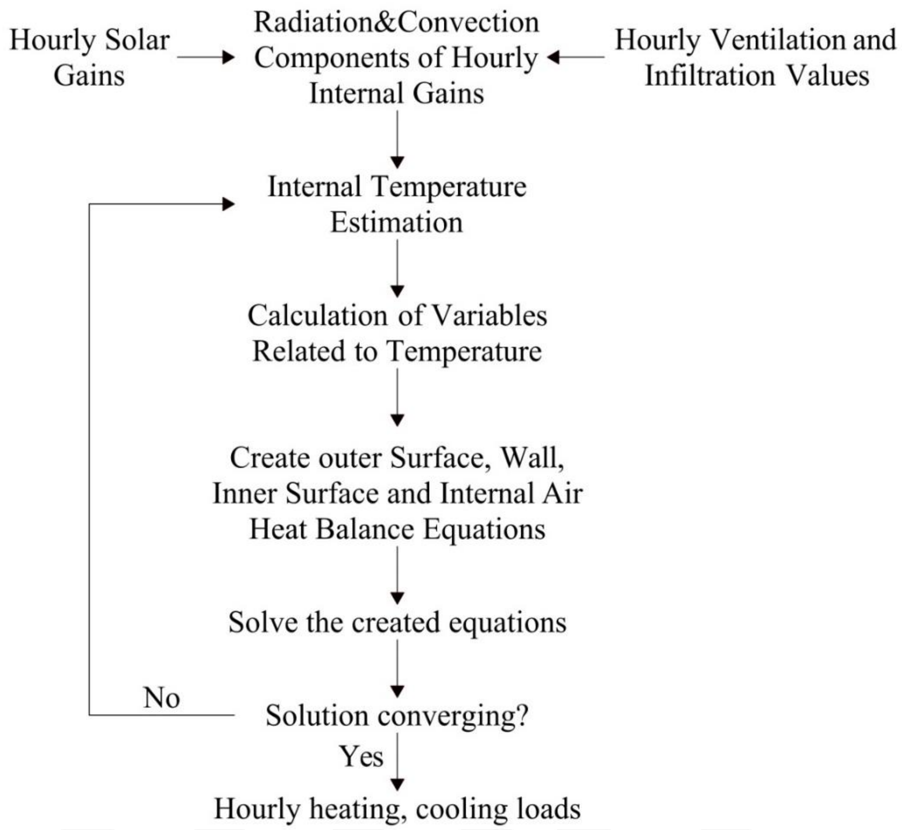


Figure 3.2 ASHRAE heat balance method flow scheme (Yaman & Gökçen, 2009)

Figure 3.3 shows the heat transfer process scheme for an opaque surface. The two-sided arrows present the heat transfer in two-ways where the single arrows are presenting the one-sided interaction. The four main formulas of the mathematical definition of heat transfer are presented within the rectangular frames in the scheme. The grey area in the scheme includes the processes that should be repeated for all the surfaces enclosing the space. The same processes are valid also for a transparent surface; excluding the absorbed solar component of the outside surface but including ‘inward flowing fraction’ and ‘outward flowing fraction’ instead. These two fractions are effective on heat balance of the inner and outer sides of a transparent surface. (Spitler, 2014)

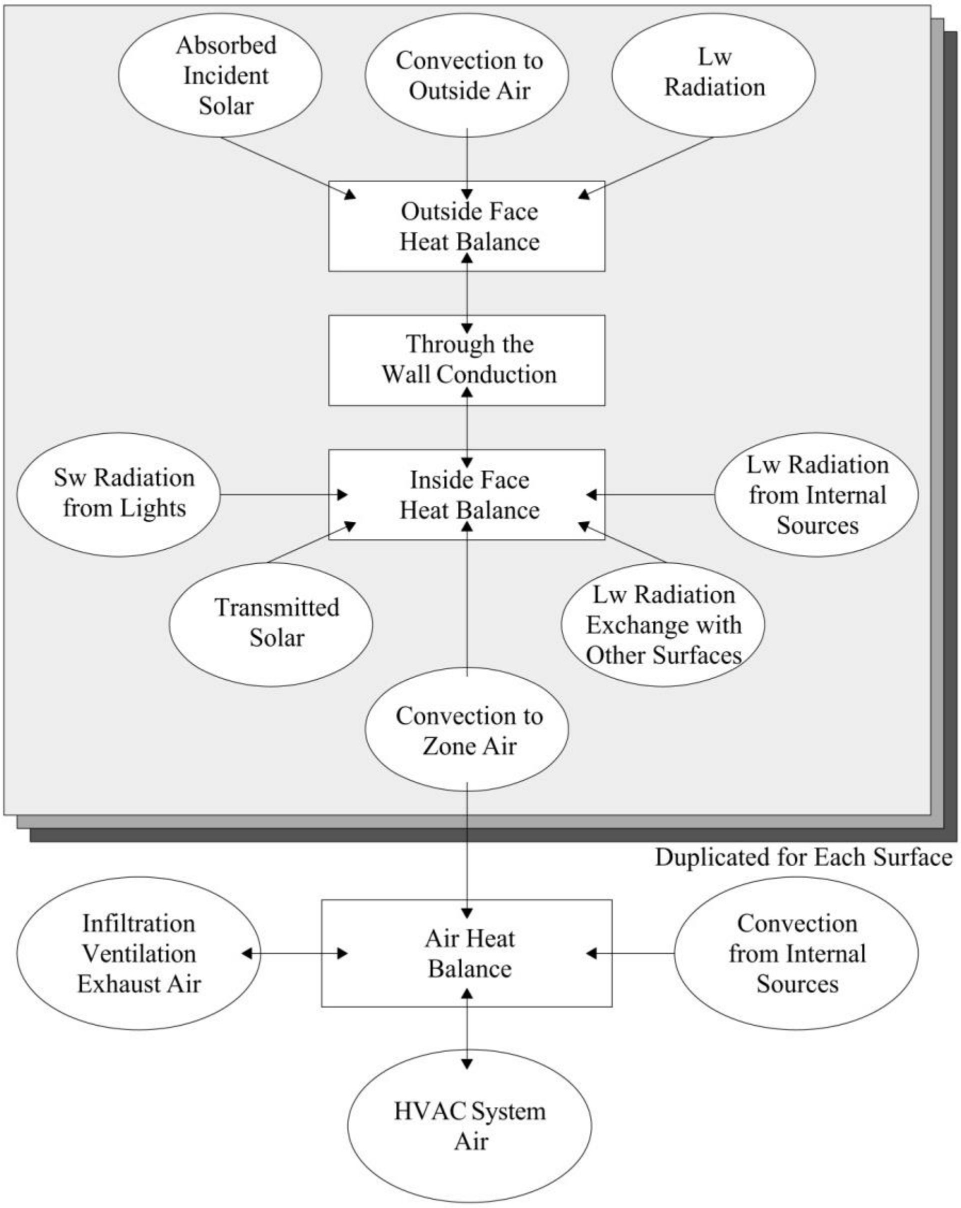


Figure 3.3 Heat balance process scheme (Spitler, 2014)

Building heat transfers are calculated by equations that are written for all surfaces and components. Total heat transfer to the space temperature is determined by solving all these equations simultaneously, so the space heat flow can be examined successfully. HBM works on minimum assumptions and this results with maximum accuracy level. But this requires detailed data input and long calculation duration which can be handled by only complex and powerful computer hardware. (Köroğlu Işın, Alaloğlu, Erdoğan, & Acar, 2011)

3.1.4.5.1 Outside Surface Heat Balance. The heat balance on the outside surface of an opaque wall is presented in Figure 3.4 with all effecting parameters.

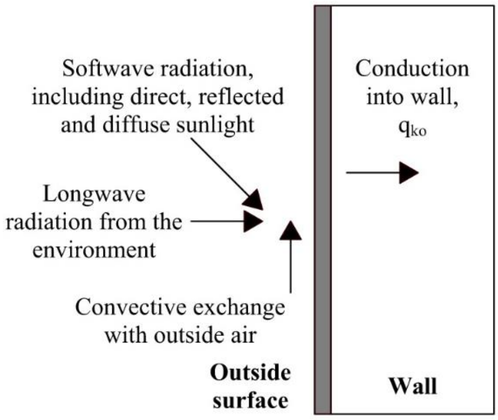


Figure 3.4 Outside heat balance control volume diagram (DoE, 2015)

The mathematical definition for the outside surface heat balance of an opaque wall is given as;

$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0$

Where:

$q''_{\alpha sol}$ ~~= Absorbed direct and diffuse solar (short wavelength) radiation heat flux.

q''_{LWR} ~~= Net long wavelength (thermal) radiation flux exchange with the air and surroundings.

q''_{conv} ~~= Convective flux exchange with outside air.

q''_{ko} ~~= Conduction heat flux (q/A) into the wall.

‘All terms are positive for net flux to the face except the conduction term, which is traditionally taken to be positive in the direction from outside to inside of the wall. Simplified procedures generally combine the first three terms by using the concept of a *sol-air temperature*.’ (DoE, 2015)

3.1.4.5.2 Wall Conduction Process. The mathematical definition for the heat balance of an opaque wall is given as;

$q''_{ko} - q''_{s} - q''_{ki} = 0$

Where:

q''_{ko} ~~= Conduction heat flux (q/A) into the wall.

q''_{s} ~~= Stored heat flux inside the wall

q''_{ki} ~~= Conduction flux through the wall. (Yaman & Gökçen, 2009)

3.1.4.5.3 Inside Surface Heat Balance. The heart of the heat balance method is the internal heat balance involving the inside faces of the zone surfaces. This heat balance is generally modelled with four coupled heat transfer components: conduction through the building element, convection to the air, short wave radiation absorption and reflectance and long wave radiant interchange. The incident short wave radiation is from the solar radiation entering the zone through windows and emittance from internal sources such as lights. The long wave radiation interchange includes the absorption and emittance of low temperature radiation sources, such as all other zone surfaces, equipment and people. (DoE, 2015)

The heat balance on the inside surface of an opaque wall is presented in Figure 3.5 with all effecting parameters.

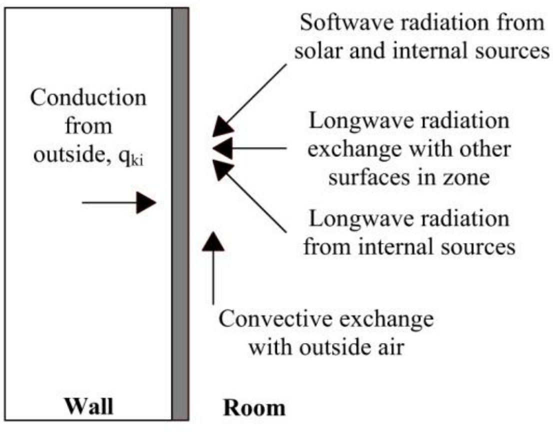


Figure 3.5 Inside heat balance control volume diagram (DoE, 2015)

The mathematical definition for the inside surface heat balance of an opaque wall is given as;

$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0$

Where:

q''_{LWX} = Net longwave radiant exchange flux between zone surfaces.

q''_{SW} = Net short-wave radiation flux to surface from lights.

q''_{LWS} = Longwave radiation flux from equipment in zone.

q''_{ki} = Conduction flux through the wall.

q''_{sol} = Transmitted solar radiation flux absorbed at surface.

q''_{conv} = Convective heat flux to zone air.

3.1.4.5.4 Air Heat Balance. The mathematical definition for the heat balance of the zone air is given as;

$q''_{conv} + q''_{ia} + q''_{inf} + q''_{Pa} = 0$

Where:

q''_{conv} = Convective heat flux to zone air.

q''_{ia} = Indoor air

q''_{inf} = Infiltration

q''_{Pa} = HVAC system loads (Yaman & Gökçen, 2009)

3.1.4.6 OpenStudio Simulation Settings

OpenStudio runs in the three-dimensional (3D) environment of SketchUp software as a plug-in which uses the energy model created by EnergyPlus software. Therefore, the simulation settings of the created model are described based on ‘Input Output Reference: The Encyclopaedic Reference to EnergyPlus Input and Output’. (DoE, 2015)

3.1.4.6.1 Run Period. The needed data for creating a weather file simulation is described from this section. The weather file is created in a format special to EnergyPlus software by using all the detailed definitions (holidays, daylight saving periods, ground temperature, extreme period information).

Date range of the simulation can be defined from the calendar which allows to choose day, month and year.

Sizing Parameters allow the user to define global heating and cooling sizing ratio is defined and applied to all the zones' heating and cooling loads and air flow rates. It is suggested for smoothing the calculated zone design flow sequences, width (in load timesteps) of a moving average window can be specified.

Timestep Averaging Window is the timestep in which the calculated zone loads are averaged. Air-flow rates are limited by duct sizes and system capacity. In calculation; heating and cooling air is accepted as supplying infinitely in a fixed temperature, so this causes extreme levels of high flow rates, mostly when schedules are used for thermostat. To obtain a broader average (which is not affected by the thermostat, which can cause warm up and cool down flow rates to dominate the flow rate calculation) specifying the width of the averaging window will help. Default value is 1.

Timestep is the number of calculation timesteps per hour. Minimum suggested value is 6.

3.1.4.6.2 Simulation Control. It allows the user to specify what kind of a simulation will be performed. Three calculation options are defined in the system:

Do zone sizing calculation uses a theoretical ideal zonal system and determines the zone design heating and cooling flow rates and loads. Default value is 'No'.

Do system sizing calculation should be used with 'zone sizing' when it is 'Yes' simplifies by summing the zone sizing results. Default value is 'No'.

Do plant sizing calculation can also run without zone and system sizing. Plant sizing arrays should be filled, and maximum component flow rates are used. Data on component (coil) is used so system sizing is not a must, component can be auto sized or not. Default value is 'No'.

Run Simulation for sizing periods can be chosen as Yes or No. If the choice is 'Yes' which is the default; then the simulation will be run on all the included Sizing Period objects (Sizing Period: Design Day, Sizing Period: Weather File Days, and Sizing Period: Weather File Condition Type) where each Sizing Period object constitutes an "environment" and warmup convergence.

Run simulation for weather file run periods can be chosen as Yes or No. If the choice is 'Yes' which is the default; the simulation will be run on all the included Run Period objects where each Sizing Period object constitutes an "environment" and warmup convergence.

Maximum number of Warmup Days is used to converge till this number of calculation. 25 is used as it is suggested for a complex building to be helpful to achieve.

Minimum number of Warmup Days is suggested to be minimum 6. For better convergence it could be increased.

Loads Convergence Tolerance Value is the point where load values must agree before convergence is reached. As a fraction of the load, 0.04 is the suggested value but it can be increased up to a reasonable level for finding a tighter convergence solution.

Temperature Convergence Tolerance Value is the number of which the zone temperature must agree before convergence is reached. Convergence of the simultaneous heat balance/ HVAC solution is reached when either the loads or temperature is achieved. 0.04 °K is the suggested value but it can be increased up to a reasonable level for finding a tighter convergence solution.

Solar Distribution is the setting that determines the way of considering beam solar radiation and reflectance from exterior surfaces coming inside of the zone.

• Minimal Shadowing: there is no exterior shadowing, all beam solar radiation entering the zone is falling on the floor and absorbed according to the floor's absorptance. Reflected by the floor radiations are added to transmitted diffuse radiation. Zone heat balance is applied then.

• Full Exterior, Full Exterior with Reflections: detached shading wings, overhangs and exterior surfaces of all zones are computed as shadow patterns. Then the calculation is same with minimal shadowing.

• Full Interior and Exterior, Full Interior and Exterior with Reflections: Transmitted solar beam is calculated as it falls on each surface in the zone as floor, zones and windows. Sun's rays are projected by considering the effect of exterior shadowing surfaces and window shading devices. This option can only be used if all the surfaces of the zone enclose a space totally. Also, the zone should be convex, L shape is non-convex. Since the case building has overhangs and the zones are convex; 'Full Interior and Exterior with Reflections' option is chosen to obtain the effect of transmitted solar beam considering the window shading devices.

3.1.4.6.3 Output Control Reporting Tolerances. **Tolerance for time heating setpoint not met** is the value to adjust the hours when the zone temperature is below the heating setpoint during the occupied hours. The default is 0.2 K which will give the hours when the zone temperature is 0.2 K below the heating setpoint.

Tolerance for time cooling setpoint not met is the value to adjust the hours when the zone temperature is above the heating setpoint during the occupied hours. The default is 0.2 K which will give the hours when the zone temperature is 0.2 K above the cooling setpoint.

3.1.4.6.4 Convergence Limits. **Maximum HVAC Iterations** parameter defines how many times HVAC manager is iterating up to a solution or up to the given number of iteration, then giving a warning error. It is suggested to define 20 iterations in the simulation.

Minimum Plant Iterations parameter defines how many times the HVAC manager iterates connected to a solver while the plant system is modelling. This is the minimum iteration that will be done when the HVAC manager is calling the plant solver. For simple system 1 is enough but for more complicated systems more than 2 times is suggested.

Maximum Plant Iterations is the value which the iterations will finish, and the plant solver will stop. More than 8 times will give better accuracy but makes the time longer. For complex plants more than 8 times is suggested.

Minimum System Timestep can vary from zone timestep but better to enter a divider of that. When it is entered as zero; it will use the zone timestep.

3.1.4.6.5 Shadow Calculations. **Calculation Frequency** is the number of days in each period in which the shadowing calculations will be done. It allows to synchronize the shadowing calculations with changes in shading devices. 20 as default, is the average number of days between significant changes in solar position angles.

Maximum Figures in Shadow Overlap Calculation is used to increase the number of figures in shadow overlaps. The more figures are calculated, the more accurate calculation will be done.

Polygon Clipping Algorithm should be chosen from the defined options;

- Sutherland Hodgmar Method, is the default option which works well when the receiving surfaces are non-convex.

- Weiler- Atherton Method, gives more accurate results when the casting and receiving surfaces are convex.

- Sky Diffuse Modelling Algorithm, has two available choices:

Simple Sky Diffuse Modelling, is calculating once for sky diffuse properties when there are shadowing surfaces which have changing transmittance, this is better to use.

Detailed Sky Diffuse Modelling, If the shading transmittance is variable, or more detailed model is needed this is advised to use.

3.1.4.6.6 Inside Surface Convection Algorithm **Simple:** Constant heat transfer coefficients depending on the surface orientations.

TARP: Correlates the heat transfer coefficient to the temperature differences for various orientations. It is the default option.

Ceiling Diffuser: Mixed model that correlates the heat transfer coefficient to the air change rate for ceilings, walls and floors. (Correlations are picked from an isothermal room model)

Adaptive Convection Algorithm: Dynamic algorithm which selects the best algorithm automatically.

3.1.4.6.7 Outside Surface Convection Algorithm. **Simple Combined:** Roughness and windspeed is used for the algorithm of heat transfer. Radiation to sky, ground and air are combined.

TARP: Algorithms are picked from TARP software which natural and wind driven convection. Correlations are created by laboratory measurements.

DOE2&MoWITT: Correlations are created from field measurements. DOE2 is the default option and it uses rough surfaces for correlations. MoWitt is chosen since it uses smooth surfaces and is suitable for windows.

Adaptive Convection Algorithm: It is a dynamic option that chooses the best algorithm automatically.

Heat Balance Algorithm is used for calculating the performance of the building surface assemblies.

Surface Temperature Upper Limit is suggested to be left as blank unless the simulation fails with a warning mentioning that 'temperature out of bounds for surface'.

Minimum Surface Convection Heat Transfer Coefficient Value is an optional field which is needed for numerical robustness not to have numbers smaller than 0. It can be used for validation of heat transfer with different minimum values. Default value is given as 0.1 W/m^2K.

Maximum Surface Convection Heat Transfer Coefficient Value is another optional field used to give a frame to the values which are defined high in EnergyPlus.

Algorithm should be chosen from the defined options;

- Conduction Transfer Function: Sensible only to heat. (Moisture storage or diffusion in the construction elements are not considered) This is the chosen algorithm; as the context of the study matches with the considered parameters of this method.

- Moisture Penetration Depth Conduction Transfer Function: Sensible to heat diffusion and moisture storage, so additional moisture information is needed.

- Conduction Finite Difference: Sensible to heat only but the output is for phase change and variable thermal conductivity.

- Combined Heat and Moisture Finite Element: Heat and moisture transfer and storage solutions are combined. Needs details of the construction element.

3.1.4.6.8 Zone Air Heat Balance Algorithm. It defines the algorithm that will be used to calculate zone air temperatures and humidity ratios.

- Third Order Balanced Difference: Zone air energy and balance equations are solved by 3rd order finite difference approximation. It is the default setting and chosen for the study.

- The Analytical Solution: zone air energy and heat balance equations are solved by integration approach.

- The Euler Method: First order finite backward difference approximation is used in this method.

3.1.4.6.9 Zone Air Contaminant Balance. This is an optional field; if contaminant concentration levels are needed by the user it should be assigned as 'Yes', in fact the default is 'No'.

3.1.4.6.10 Zone Capacitance Multiple Research Special. This is an advanced feature to control the effective storage capacity of the zone.

- Sensible Heat Capacity Multiplier: Alters the effective heat capacitance of the zone air volume.

- Humidity Capacity Multiplier: Alters the effective moisture capacitance of the zone air volume.

- Carbon dioxide Capacity Multiplier: Alters the effective carbon dioxide capacitance of the zone air volume.

When the values are greater than 1, it smooths the rate of change in the generic contaminant level of zone air from timestep to timestep.

3.2 Climate Adaptive Façades

According to the OECD data, compared to a standard building envelope, a high-performance building envelope is decreasing the heating loads 20-30% in a cold climate and 10-40% of the cooling loads in a hot climate. (OECD, 2001) As building envelope is a key component for reaching a better energy efficiency target, the path of 'climate adaptive façade' concept is followed for increasing building energy performance.

3.2.1 Definition of Climate Adaptive Façades

For maximizing the energy savings in buildings while providing the needed indoor environmental comfort, energy and mass flow can be managed and modulated by 'Adaptive' or 'Responsive Building Elements (RBE)' or systems. (Jin, Overend, & Favoino, 2014) According to a completed project of the International Energy Agency—Energy Conservation in Buildings and Community Systems Programme (IEA-ECBCS), responsive building elements should be developed, applied and implemented for improving the energy efficiency in the built environment. Mainly designed as construction elements, Responsive Building Elements can transfer and store heat, light, water and air actively. IEA–ECBCS Annex 44 indicates that building envelopes has the largest potential to minimize the energy use in buildings by integrating adaptive technologies. (Favoino, Overend, & Jin, 2015)

Creating a boundary between inside and outside, by means of the 'exclusive' approach; a well-insulated and air tight building envelope can be accepted as a 'static' barrier. Following a 'selective' building envelope understanding, heat and mass flow can be adjustable by using adaptive or responsive building elements. (Loonen R. , Trcka, Costola, & Hensen, 2013) Although the daily and yearly changing meteorological conditions affect the occupancy and comfort needs, the conventional building shells are mainly static and don't respond to these changes. (de Boer, et al., 2011) But a climate adaptive building shell (CABS) can adapt itself according to the changing climatic conditions while providing the occupant needs and saving energy. (Loonen R. , Trcka, Costola, & Hensen, 2010) CABS can repeatedly and reversibly change its functions, features or behaviours over time in response to changing performance requirements and variable boundary conditions. This helps to improve the overall building performance in terms of primary energy consumption and provides the needed thermal and visual comfort conditions.' (Ferguson, Siddiqi, Lewis, & de Weck, 2007)

Since the word 'adaptive' refers to the changeable, mutable, flexible, instable features; 'Adaptability' is defined as 'the ability of a system to deliver intended functionality considering multiple criteria under variable conditions through the design variables changing their physical values over time.' (Gür & Aygün, 2009) The words 'active, advanced, dynamic, intelligent, interactive, kinetic, responsive, smart, switchable are also used corresponding to the word 'adaptive'. (de Boer, et al., 2011)

The adaptive behaviour according to the changing environmental conditions in time is not a new concept in architecture; even an operable window on a façade and a curtain are both conventional adaptive solutions. (Orhon, 2013) The first 'adaptive façade' known in literature, was designed by Jean Nouvel for the Institut du Monde Arabe; built between the years 1981-1987 in Paris. (Loonen, Trcka, & Hensen, 2011)

'Climate Adaptive Façades' can be defined as the façade solutions that can adapt themselves to the inner and outer factors manually, mechanically or by the behaviour of smart materials used.

3.2.2 Classification of Climate Adaptive Façades

Energy consumptions and carbon emissions are the main factors on environmental impact of buildings. The efforts for meeting environmental requirements should also include cost and user comfort. Since the building envelope has the main interaction role in between the outdoor and indoor environment, it should be considered with high importance. As a building component; stability and mechanical durability are expected features of a building envelope, which should carry out the health and security needs. Also, acoustic, visual and thermal comfort conditions and heat mass needs should be supplied by the building envelope.

Current approaches are pointing the building façade to contribute in providing the expected performance from the whole building in accordance with time and outer conditions, while creating the physical border with outer environment. The main purpose is to obtain high indoor environment quality by low energy consumption. When building energy performance is the focus, building façade becomes a component on which the renewable energy systems can be integrated, more than this an active role is assigned to 'collect, convert, store, distribute'. But the main approach is focused more on the thermal transmittance.

As a result of a research on 'climate adaptive façades'; the lack of standards, design tools and performance evaluation methods are proposed. Also, the classification and terminology of the subject is unclear in literature. (Loonen, et al., 2015)

Regarding to the classification of Loonen, et al. (2015), targets are taken as the main aspect to classify climate adaptive façades. These targets might be mentioned by codes and standards. The way used for reaching this target is named as 'responsive function'. The control of the chosen process has the title 'operation'.

3.3 General Definitions of the used methodology

- SunEarth Tools; is a web-based tool used for understanding the hourly and seasonal movement of the Sun. The calculation of the position of the sun is based on equations from Astronomical Algorithms, by J.J. Michalsky. (Michalsky, 1988) Accuracy of 0.01 deg, the observed values may vary from calculations because they depend by: atmospheric composition, temperature, pressure and other conditions. (SunEarthTools, 2017)

- Azimuth angle; is the angular distance of Sun from the true North,

- Elevation angle; is the angular distance of Sun from the horizon, (SunEarthTools, 2017)

• Sunrise and sunset; are defined as the instant when the upper limb of the Sun's disk is just touching the horizon, this corresponds to an altitude of -0.833° degrees for the Sun, (SunEarthTools, 2017)

• Summer (21^{st} of June) and Winter (21^{st} of December) solstice days; are considered as reference for the seasonal changes from winter to summer, (SunEarthTools, 2017)

• 21^{st} of March and 23^{rd} of September; are the equinox days when the sun beam angles are perpendicular to the equator. These dates represent the beginning of spring and autumn.

• Zone Windows Total Transmitted Solar Radiation Energy (J); is the total 'Surface Window Transmitted Solar Radiation Energy' of all the exterior windows in a zone. Surface Window Transmitted Solar Radiation Energy (J); is the sum of 'Surface Window Transmitted Beam Solar Radiation Energy' and 'Surface Window Transmitted Diffuse Solar Radiation Energy' entering a zone through an exterior window. Surface Window Transmitted Beam Solar Radiation Energy (J); is the solar radiation transmitted by an exterior window whose source is beam solar incident on the outside of the window. For a bare window, this transmitted radiation consists of beam radiation passing through the glass (assumed transparent) and diffuse radiation from beam reflected from the outside window reveal, if present. Surface Window Transmitted Diffuse Solar Radiation Energy (J); is the solar radiation transmitted by an exterior window whose source is diffuse solar incident on the outside of the window. For a bare window, this transmitted radiation consists of diffuse radiation passing through the glass. For a window with a shade, this transmitted radiation is totally diffuse (shades are assumed to be perfect diffusers). (DoE, 2015)

CHAPTER FOUR
A MODEL FOR DESIGNING CLIMATE ADAPTIVE SHADING DEVICES TO IMPROVE ENERGY PERFORMANCE OF OFFICE BUILDINGS

The main aim of this dissertation is to define a model to increase energy performance of an existing office building by proposing CASD to decrease the cooling energy consumptions. This chapter focuses on the methodology of this study by presenting the general framework.

The presented model is using building energy performance calculation method in different steps as; ‘shading device requirement analysis’ and ‘assessment of CASD’. ‘Shading device requirement analysis’ is carried out by using both ‘building energy performance calculation’ and ‘Sun Path diagram analyses’ to determine the characteristics of the ‘climate adaptive shading’ devices. Then the various CASD application scenarios are assessed by using building energy performance calculation results. The presented model is studied on a case building through 5 scenarios:

- Case 1; presents the existing case building with no changes.

- Case 2; presents the case building without shading devices.

- Case 3; presents the case building with the shading devices that are placed with fixed angles proper to façade orientations and they are always in use (no transmittance).

- Case 4; presents the case building with the shading devices which are placed with fixed angles proper to façade orientations with adaptive transmittance schedules based on hourly and seasonal solar changes.

- Case 5; presents the case building with the shading devices which are placed with angles proper to façade orientations with adaptive transmittance schedules based on hourly and seasonal solar changes. Shading devices of south oriented façades has also adaptive angles based on seasonal solar changes.

- The usage (on/ off) of the shading devices are defined by using the 'transmittance' parameter of the used simulation tool. Even transmittance is given as a fractional value; only the values 1 and 0 are used in this study. Shading devices are not in use (off) when transmittance is 1 and they are in use (on) when transmittance is 0. This approach might be interpreted either as the usage of a smart material which has a variable transmittance value or usage of a system that can be closed physically. Considering the construction detail of the shading devices placed on the façade of the case building; this study approaches the usage status of the shading devices as if it is a change of the transmittance value by the behaviour of a smart material.

The methodology of this study is comprised of 4 main steps given in Figure 4.1. The first step is 'calibration of the simulation model'; which is based on the comparison of electricity consumption data obtained from the actual bills and simulation results of the existing building (Case 1). The second step is the 'shading device requirement analysis'; which is for collecting the hourly and seasonal solar azimuth and elevation angle data from sunpath diagram analysis and simulation results of the existing building without shading devices (Case 2). Third step is for 'CASD proposals'; which are created according to the outputs of the previous step and then the generated building models are simulated in OpenStudio. The simulation results are compared and discussed in the last step to present the best performing CASD proposal.

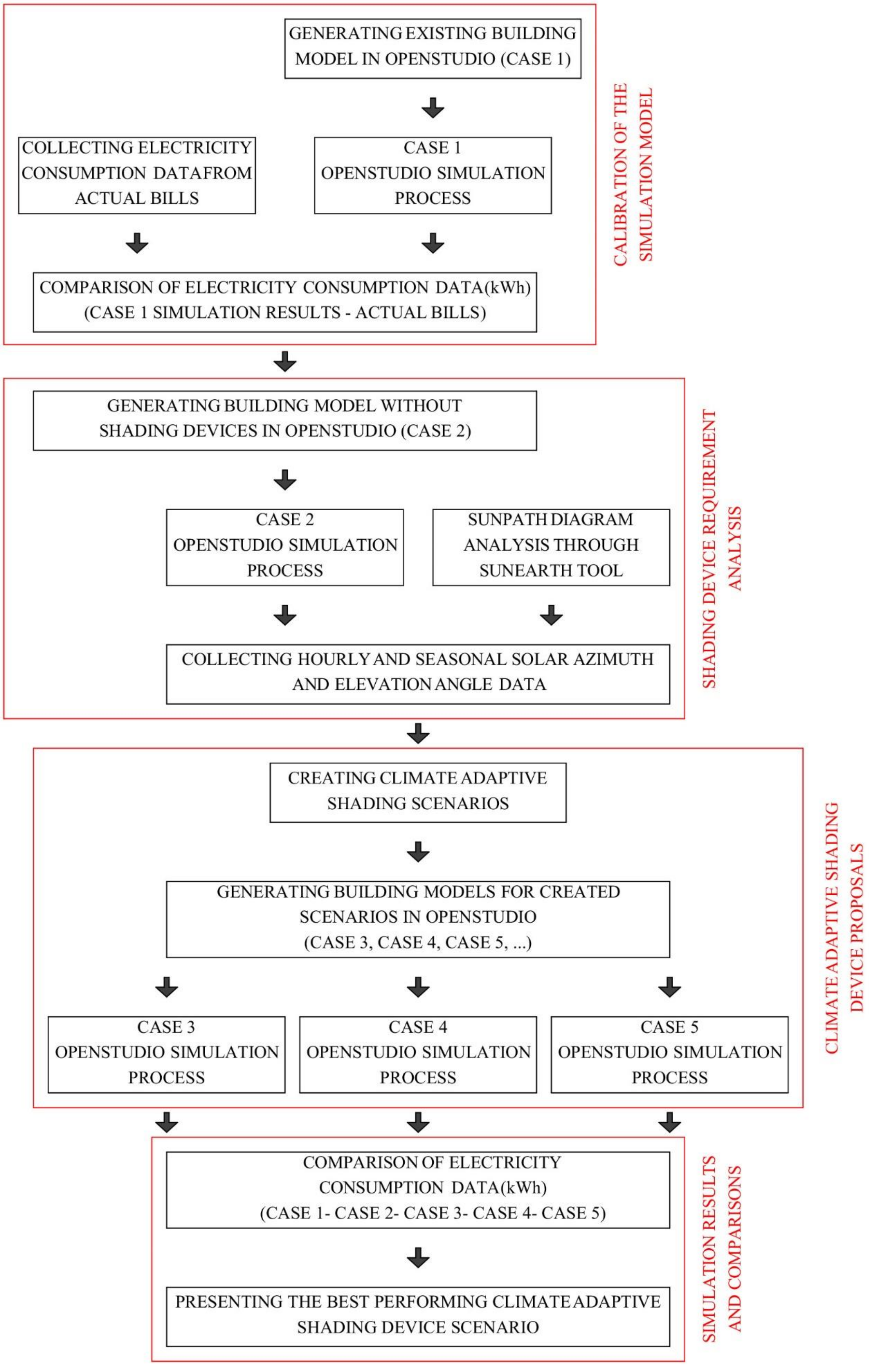


Figure 4.1 Methodology

4.1 Calibration of the Simulation Model

Followed by the flowchart given in Figure 4.2; generated model of the existing building is simulated (Case 1), and electricity consumption values are chosen from the outputs to understand the accuracy of the simulation in comparison with the actual electricity consumption bills. If difference between the nnual totals of simulation results and actual values are more than 10%, than the modelling and simulation processes are revised by elaborating the mechanical system details till the difference is equal or less than 10%. Thus, a calibrated simulation model of the case building is achieved.

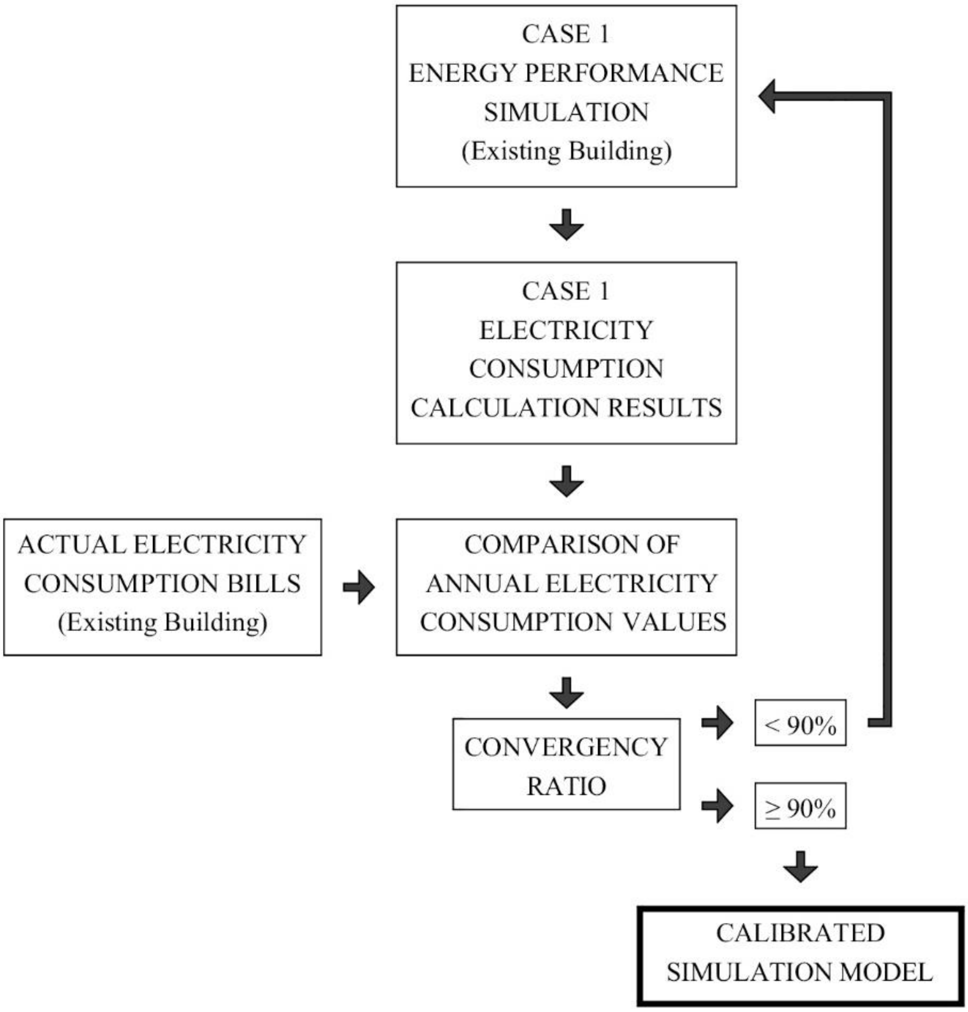


Figure 4.2 Calibration of the simulation model

4.2 Shading Device Requirement Analysis

The methodology of this dissertation presents a process for shading device requirement analysis. According to the façade orientations shading device requirements are examined over shading device angles and shading device schedules. Depending on the previous step of the methodology, shading device angles are decided for each façade orientation which can be fixed or changing by seasons. Also shading device schedules are set according to façades' shading needs that can be changed by hours, seasons or both. Parameters needed for creating CASD are given by the flowchart in Figure 4.3.

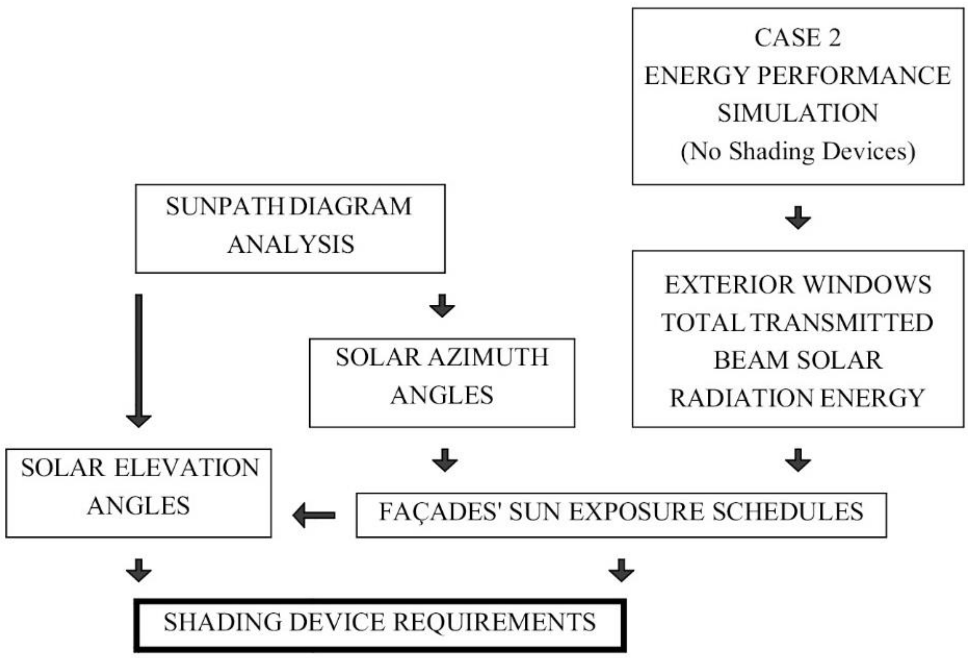


Figure 4.3 Shading device requirement analysis

Firstly, Sun path diagram is obtained for the location of the case building by using the online tool; Sunearth tool. (SunEarthTools, 2017). Given in Figure 4.4; hourly solar elevation and azimuth angles can be seen for the location and date defined as input, also equinox and solstice days are given automatically.

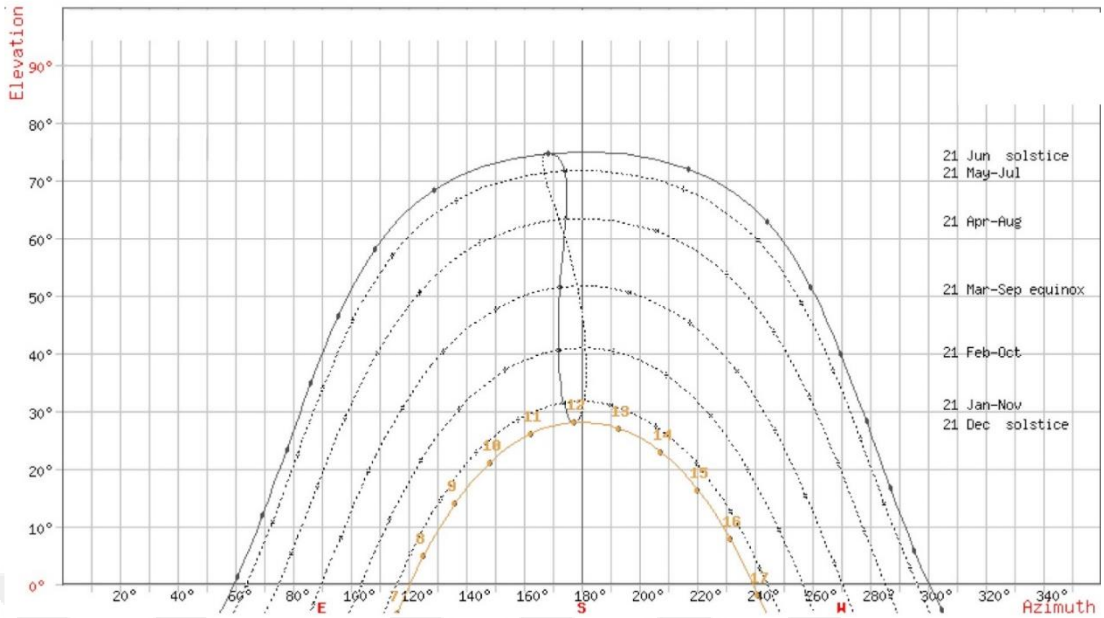


Figure 4.4 Sun path diagram

The hourly solar elevation and azimuth angles obtained from Figure 4.4 is entered in Table 4.1 based on the days which are accepted as critical points for seasonal changes. In this study, time period between 21st March and 23rd September is accepted as summer season and between 23rd September and 21st of December as winter season. The acceptance of seasonal definitions can change according to the location of the case building; summer and winter periods might change; spring and autumn can be defined as well. The table below is coloured for the changes in façade orientations according to azimuth angles; yellow for eastern façade, orange for southern façade and blue for western façade.

Table 4.1 Solar elevation and azimuth angles

21st March			21st June			23rd September			21st December		
Time Period	Elevation Angle	Azimuth Angle	Time Period	Elevation Angle	Azimuth Angle	Time Period	Elevation Angle	Azimuth Angle	Time Period	Elevation Angle	Azimuth Angle

Than the plan scheme of the case building is placed as given in Figure 4.5 and hourly solar azimuth angles are shown to understand the Sun position for each façade orientation. As shown in the figure, the plan scheme is given with the detail of thermal zones in this study for further steps that will consider also the thermal zones.

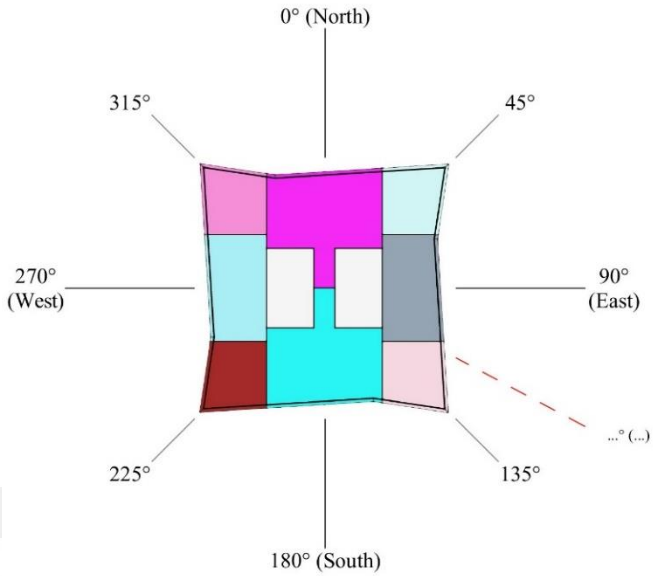


Figure 4.5 Solar azimuth angle plan scheme

Since the study deals with shading devices of a case building, solar elevation angle is the major parameter to decide shading device positions. So that the data taken from Table 4.1 is used to indicate the solar elevation angles regarding to building façade. Figure 4.6 shows the hourly sunbeam angles coming to building façade to understand with which angle the façade is affected on equinox and solstice days which are the critical days for seasonal changes.

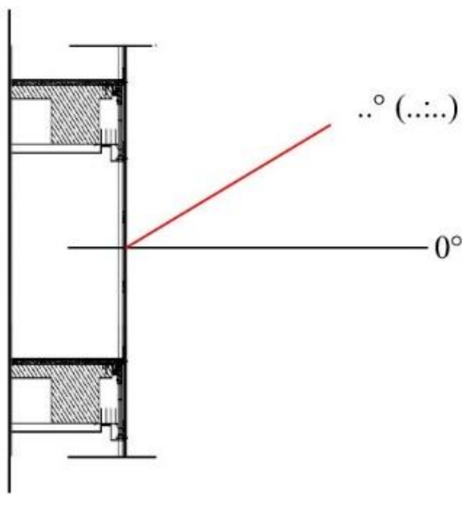


Figure 4.6 Solar elevation angles

Studied angles are transferred to Table 4.2 with the average elevation angles calculated for each façade orientation. For each façade orientation, arithmetic mean of elevation angles is taken for the time periods in which façade is getting direct sun beam.

Table 4.2 Average solar elevation angles for equinox and solstice days

Façade Orientation	**21st March**		**21st June**		**23rd September**		**21st December**	
	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle
Eastern Façade								
Southern Façade								
Western Façade								
Northern Façade								

Than the data given in Table 4.2 are turned into a seasonal format in Table 4.3, for further steps of the study.

Table 4.3 Average solar elevation angles for summer and winter seasons

Façade Orientation	21st March- 23rd September Summer		23rd September- 21st March Winter	
	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle
Eastern Façade				
Southern Façade				
Western Façade				
Northern Façade				

Table 4.4 is for presenting the data collected from shading device requirement analysis. Each thermal zone is defined referring to its façade orientation with the required shading device angle. Shading availability is defined on seasonal and hourly base according to shading demand occurring by direct sun beam effect. Also shading device layout part is given to show the section drawing of the case building with the suggested shading devices.

Table 4.4 Shading scenario

Thermal Zone Number					
Façade Orientation					
Shading Device Angle					
Shading Device Layout					
Shading Availability	Season				
	Time Period				

Then the calibrated model is modified by wiping out the existing shading devices (Case 2) to see the direct solar effects on the unshaded façade. From the simulation results of the case building with no shading devices; hourly 'exterior windows total transmitted beam solar radiation energy' values are chosen to see the sun exposure effects on the façades by means of seasonal and hourly schedules. Since the Sun has the maximum elevation angle on 21st of June and minimum elevation angle on 21st of December; 'exterior windows total transmitted beam solar radiation energy' values are analysed for these days in Table 4.5. Although the methodology is used as a retrofitting approach in this study; the study can start directly from this step when the case building has no shading devices.

Table 4.5 Maximum beam solar radiation energy values transmitted from the windows

Thermal Zone	Façade Orientation	21st June		21st December	
		Max. Beam Solar Radiation Energy	Time Period	Max. Beam Solar Radiation Energy	Time Period

Results are chosen for 4 thermal zones from the same height level of the building, each with only North, East, South or West oriented façades. Meanwhile Sun Path Diagram Analysis is carried out to see the solar elevation and azimuth angles of the sun.

4.3 Climate Adaptive Shading Device Proposals

Depending on the simulation results and the solar azimuth angles; sun exposure schedules are studied for each façade orientation and these schedules are used for understanding the solar elevation angles in that time periods. Following the process given in Figure 4.7; shading device requirements are obtained as seen in Table 4.6.

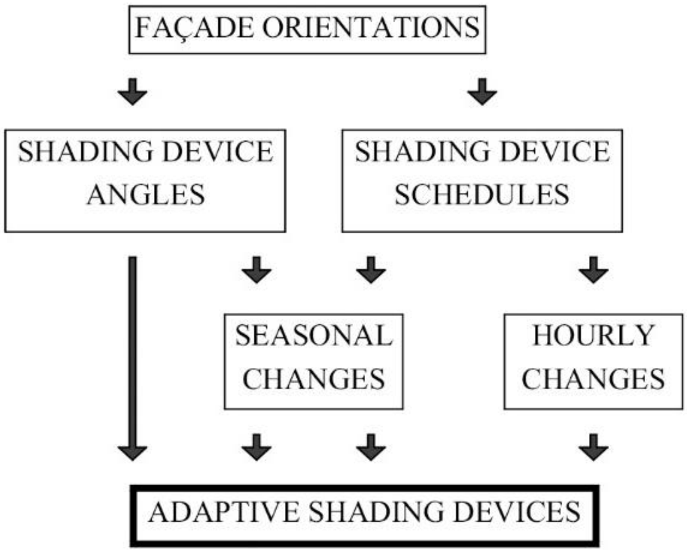


Figure 4.7 Climate adaptive shading devices

Regarding to the parameters defined in the previous step, this study proposes 3 CASD scenarios for the existing case building. Table 4.6 presents the used parameters for each proposal. Firstly Case 3 is proposed by defining the suitable shading device angles for each façade orientations as if they are always in use. Following the defined angles of Case 3; Case 4 is proposed by defining schedules that would determine the shading devices to be in use or not in use depending on seasonal and hourly shading demand. Than following Case 4; Case 5 is proposed by adding schedules that would determine the changes of shading device angles depending on seasonal changes of the Sun elevation angles.

Table 4.6 Climate adaptive shading device proposals

Climate Adaptive Shading Devices		Case 3	Case 4	Case 5
Façade Orientation		✓	✓	✓
Usage On/ Off	Seasonal	-	✓	✓
	Hourly	-	✓	✓
Angle	Seasonal	-	-	✓
	Hourly	-	-	-

Proposed CASD behaviours are applied on the calibrated model of the existing case building by creating 3 different models. Through the simulation process of all the scenarios; 'electricity consumption' and 'zone exterior windows total transmitted beam solar radiation energy' values are chosen and compared. Also, from 3 of the simulations; graphical results of 'windows total transmitted solar radiation energy' values are presented for each thermal zone to present the effects of shading devices visually. Consequently, suggestions are given for developing the best performing façade by using CASD in further studies.

CHAPTER FIVE
APPLICATION OF THE MODEL

5.1 Introduction and Simulation of the Case Building

Presented methodology is applied on a case building. The first intention of this part is to work on the calculation methodology of building energy performance which is a computer aided simulation tool: OpenStudio. Since the literature review is pointing out the lack of studies on existing buildings, the case study is carried out on an existing building to obtain more realistic data.

For increasing energy performance of the case building, climate adaptive façades are studied and examined through proposed scenarios. Considering the wide scope of climate adaptive façades, proposals are given through CASD which can be more feasible to apply. As remarked by the literature review, the chosen simulation tool is used as a guide to find out the answers to the question of 'how to apply CASD?'.

Case building chosen for this study is Bayraklı Tower located in İzmir (latitude: 38.4511138, longitude: 27.1876025), Western Turkey. The building has 40000 m^2 closed area as presented in Figure 5.1; containing 23 stories of mainly offices and sports hall, ground floor with a shopping mall and 3 basements with car park.

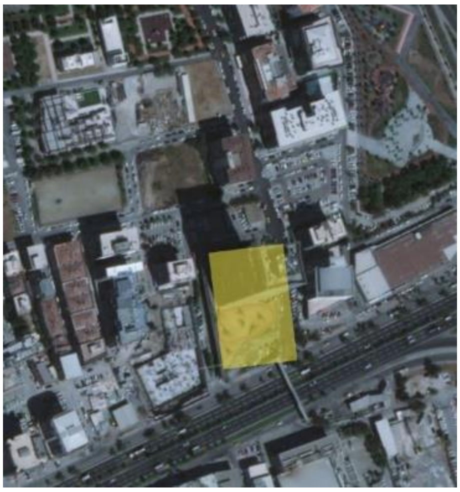


Figure 5.1 Aerial view of Bayraklı Tower (Google Earth, 2018)

All the needed details of the building are taken from the application projects including architectural and mechanical drawings. In Appendix I, typical office plan of the case building is presented. (Bayraklı Tower is photographed from the south-east orientation as in Figure 5.2). Also, the technical data needed for the mechanical systems are obtained from the implementing company.

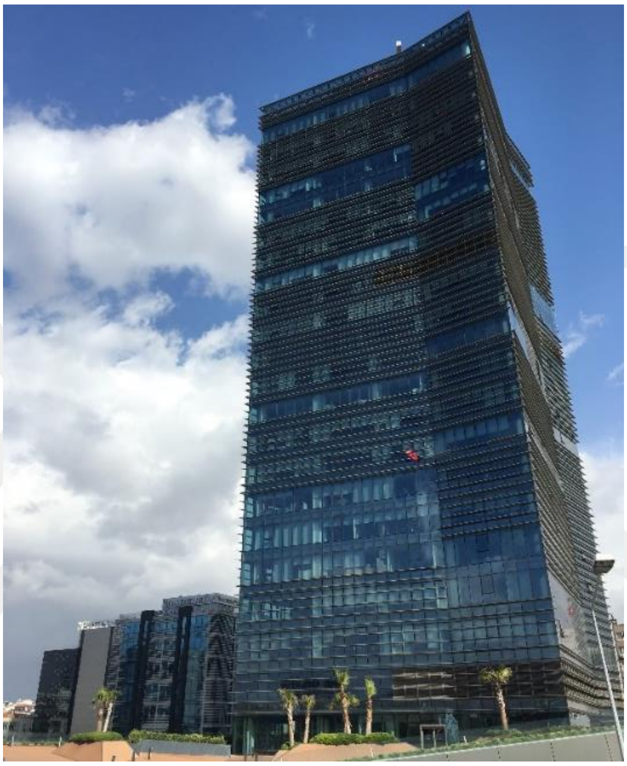


Figure 5.2 Bayraklı Tower (Personal archive, 2016)

The initial phase of the case study is generating the simulation model of the building by using OpenStudio simulation tool; described in Chapter 3. Architectural details are studied from the drawings and transferred to SketchUp 3D environment. Three-dimensional view of the simulation model is given in Figure 5.3.

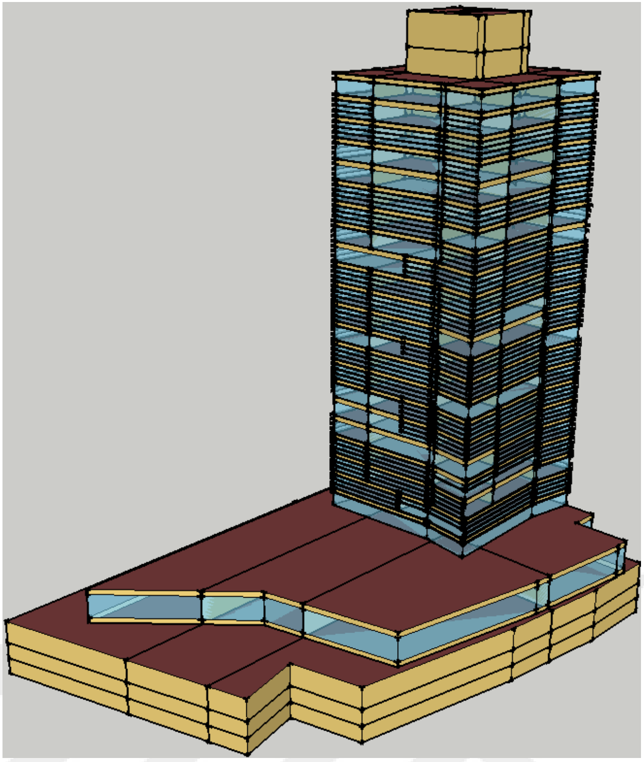


Figure 5.3 Bayraklı Tower 3D model

Since the study is mainly dealing with façade of the case building, exterior surface constructions are defined in detail for non-transparent and transparent elements. Table 5.1 is presenting non-transparent surface of the façade; that is 100 cm height glazing component placed to the outer face of beams hiding the non-transparent insulation layer in between.

Table 5.1 Non-transparent façade surfaces

Materials	Thickness (m)	Conductivity (W/mK)	Density (kg/m3)	Specific Heat (J/kgK)	Thermal Absorptance (emittance)	Solar Absorptance	Visible Absorptance
Tempered glass	0.008	1.4	0.1	0	0.2	0.73	0.021
Air gap	0.02						
Tempered glass	0.006						
Air gap	0.04	0.03	1225	0	0.9	0.7	0.7
Fireproof gypsum board	0.012	0.16	800	90	0.9	0.7	0.7
Heat insulation (rockwool)	0.08	0.05	19	960	0.9	0.7	0.7

Table 5.2 is presenting transparent façade surfaces that are constructed with laminated glass inside and double layered glass outside with a polyvinyl butyral (PVB) film in-between. Also applied details of other construction surface components can be found in Appendix II.

Table 5.2 Transparent façade surfaces

Material	Thickness (m)	U-factor (W/m^{2}K)	Solar Heat Gain Coefficient	Visible Transmittance
Temperated glass	0.008	1.4	0.20	0.16
Air gap	0.014			
Interior glass	0.006			
PVB	0.00076			
Laminated glass	0.006			

Figure 5.4 is presenting a detail drawing of the existing façade; shaded by 40 cm width aluminium panels located 10 cm distant to façade surface with a 90° elevation angle. Physical features of the devices are same in all orientations and they are located 95-cm distant to each other along 380 cm height of the floor. Shading devices are placed with a layout considering the façade orientations, for instance northern façade is significantly less shaded where shading devices has a density on southern façade.

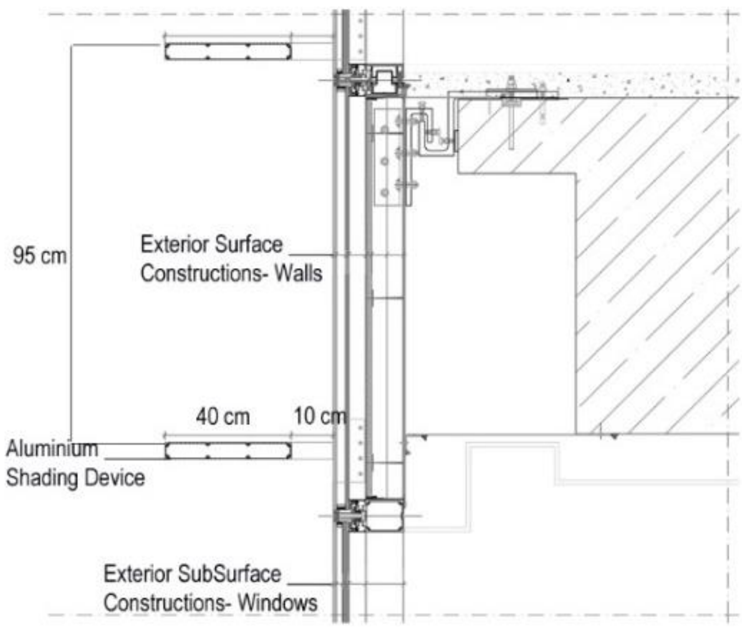


Figure 5.4 Façade detail

After the building model is constructed with architectural details, mechanical projects are studied and transferred to the model. Mechanical plan scheme of a typical office floor is given in Appendix III. Case building is defined by vertical thermal zones which are conditioned by variable refrigerant flow (VRF) systems installed in the technical spaces on 2^{nd} and 14^{th} floors. There are 52 thermal zones with 93 VRF outdoor systems and 506 indoor terminal units. Details of the mechanical equipment are given in Appendix IV for each thermal zone. Also, the Table given in Appendix V presents the mechanical system parameter settings used for the simulation model.

The study deals with the whole building's simulations; however detailed analyses are covering 4 thermal zones (19, 21, 23, 25) which are chosen from the same height level of the building. These are the zones located along 11th, 12th and 13th floors, given as a plan scheme in Figure 5.5.

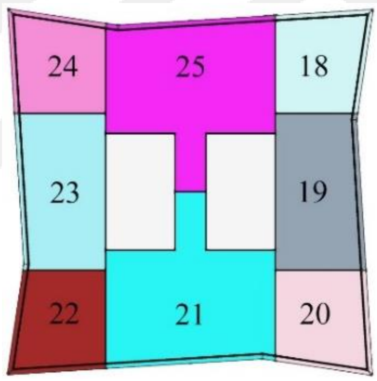


Figure 5.5 Thermal zones- plan

Also, the thermal zone configuration is given in Figure 5.6 as an elevation drawing to indicate the vertical placement of the zones with façade orientations.

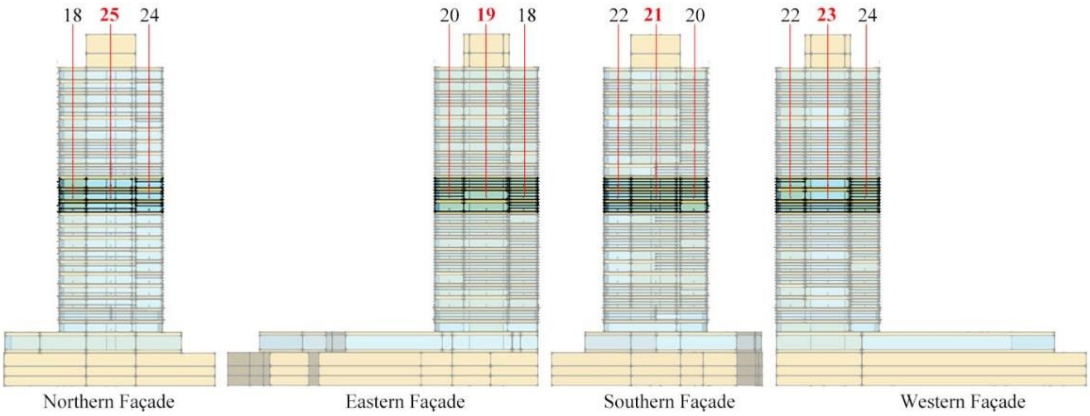


Figure 5.6 Thermal zones- elevation

As it is intended to discuss about the effect of façade on the energy consumptions; the parameters that are not available for the case building are defined by using OpenStudio templates referring to ASHRAE. Lighting, electric equipment and occupancy loads of the defined spaces are given in Table 5.3. (ASHRAE, 2001)

Table 5.3 Building loads

Space Type	People (people/m^2)	Lights (W/m^2)	Electric Equipment (W/m^2)
Breakroom	0.54	8.72	48
Closed Office	0.05	10.66	6.89
Electrical/Mechanical Room	–	4.84	2.91
Stair	–	4.84	–

The loads given in Table 5.3 are the overall values for the spaces which has variable occupancy rates depending on days of the week and hours of the days. These variables are given as fractions from 0 to 1 in Table 5.4 for daily and hourly schedules; defining the valid rates of the loads for the time periods. Also, VRF availability schedule is integrated to Table 5.4 to present the time-based working principle of the heating and cooling systems.

Table 5.4 Schedules

Large Office Building Schedules (Fractional 0-1)		1 January- 31 December																							
				04:00				08:00				12:00				16:00				20:00					
Equipment	Mon-Fri	0.4								0.9				0.8	0.9				0.8	0.6		0.5		0.4	
	Sat	0.3						0.4		0.5						0.35			0.3						
	Sun	0.3																							
Light	Mon-Fri	0.05					0.1		0.3	0.9									0.7	0.5		0.3		0.1	0.05
	Sat	0.05						0.1		0.5						0.15			0.05						
	Sun	0.05																							
Occupancy	Mon-Fri	0						0.1	0.2	0.95				0.5	0.95				0.7	0.4		0.1		0.05	
	Sat	0						0.1		0.5						0.1			0						
	Sun	0																							
VRF Availability	Mon-Fri									1															
	Sat									1															
	Sun	0																							

In Table 5.5, heating and cooling setpoint schedules of a 'Large Office Building' are presented in Celsius degrees (°C). Time slot for the study is defined by means of seasons, days and hours. Seasons are dated according to vernal and autumnal equinoxes. Days of a week are also considered as working days or holidays and days are also split into hours. (ASHRAE, 2001)

Table 5.5 Heating- cooling setpoint schedules

Temperature Setup Profiles			Hourly Time Periods																							
					04:00				08:00				12:00				16:00				20:00					
Summer (22 Mar-23 Sept)	Heating	Mon- Sat	0 °C																							
		Sun	0 °C																							
	Cooling	Mon- Sat	30 °C								26 °C										30 °C					
		Sun	30 °C																							
Winter (24 Sept-21 Mar)	Heating	Mon- Sat	18 °C								22 °C										18 °C					
		Sun	15.6 °C																							
	Cooling	Mon- Sat	30 °C																							
		Sun	30 °C																							

Since OpenStudio is a detailed dynamic simulation tool, there are various simulation settings which are mentioned in detail in chapter 3 and the settings used for this study is given in Appendix VI. After entire building is modelled by the software, simulation is carried out for the year of 2015, using the climate data of ASHRAE Climate Zone: 3C. (ASHRAE, 2011)

5.2 Calibration of the Simulation Model

As the study is mainly based on simulation calculations, it is essential to verify the accuracy of calculation results. So generated model of the existing building is simulated, and electricity consumption values are chosen from outputs to compare with the actual electricity consumption bills that are given in Appendix VII. Since heating and cooling demand is supplied by VRF systems; only the electricity consumption values of VRF systems are presented in Table 5.6 both from the simulation results and actual bills.

Although the comparison between the annual totals are showing that the difference between the simulation results and actual bill values are 10%; difference between the results changes in monthly totals. Table 5.6 shows that the energy consumption values of the simulation result values are more in May, June, November and December and less in January, August and October compared to the actual bill values. Since weather data is the main fact on heating and cooling energy consumptions; monthly measured weather data can have extreme values compared to the statistical weather data which is driven from ASHRAE climate design data; updated every four years. 'Typically, climatic design conditions are calculated with data from the last 25 years. But stations with as little as eight years of data can also be included in the Handbook. Eight years of data should yield design conditions that are within an acceptable tolerance of those calculated using a 30-year period'. (ASHRAE, 2017)

It is reasonable to expect calibrated models for medium to large buildings to have 5-10% difference with the actual building's annual electricity consumption (Cohen, 1998); this study is considering annual energy consumption values. So that modelling and simulation processes are iterated till the simulation results reached 10% difference with the actual bill values. Than the created model is used for investigating a better performing façade in terms of energy efficiency.

Table 5.6 Monthly electricity consumptions

Months	**Actual Bill** (MWh)	**Simulation Results** (MWh)	**Difference** (%) [(Actual Bill- Simulation Results)*100/ Actual Bill]
January	121	107	12
February	93	101	9
March	76	81	7
April	34	32	6
May	46	78	70
June	69	116	68
July	118	125	6
August	188	132	30
September	108	107	1
October	46	33	28
November	21	66	214
December	56	97	73
Total	**976**	**1075**	**10**

Monthly energy consumption values for heating, cooling and fan usage are chosen from the simulation results and presented by the graphic in Figure 5.7. Since the energy consumption range is obviously close to the actual values, the graphic helps us to understand the monthly electricity usage of the case building. We see that the system is working for heating from October till April, and it is working for cooling from April to October (included), where fans' consumption is nearly constant all year.

And it is clear that electricity consumption values are reaching to peak levels in summer by cooling demand, which is the expected result for this study considering the climatic conditions. In the first chapter, it is stated that the case building has cooling demand even in winter season but there is no sign of such an information in the given chart below. Due to the low values of electricity consumption in winter, it is not presented in the graphical visual, but the values can be seen clearly in Table 5.16.

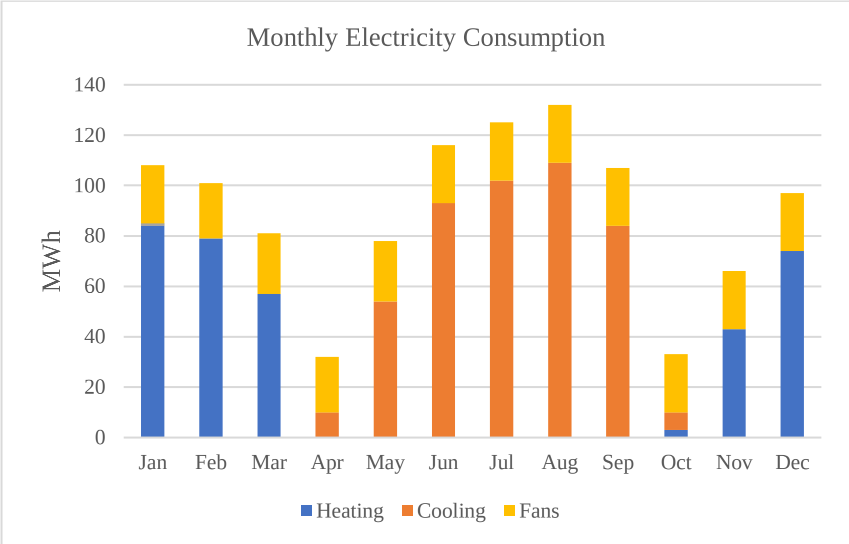


Figure 5.7 Monthly simulation results

As we know that; ‘energy modelling of VRF systems is challenging because the operation of the VRF system requires to control numerous operational factors at various indoor and outdoor conditions. The energy models of the VRF systems in EnergyPlus utilize a series of performance curves to accurately define their part-load performances at various operating conditions. However, an existing study shows that there existed large gaps between the measured energy consumption of the VRF system and the predicted energy use by the VRF model in EnergyPlus.’ (Yun & Song, 2017)

One of the important outputs of this study is the simulation results; as the achieved energy consumption values are 90% converging to actual values in annual totals. Therefore, created simulation model is accepted as validated and the study is based on this model in following steps.

5.3 Shading Device Requirement Analysis

Though the façade’s energy efficiency properties change depending on various parameters; this study emphasises effects of the shading devices. Therefore, existing shading devices are interpreted by changing their physical conditions according to solar factors. Solar elevation and azimuth angles are the main determinants affecting the physical conditions of shading devices; so, Sun path diagram in Figure 5.8 is used for the analysis of solar angles. (SunEarthTools, 2017)

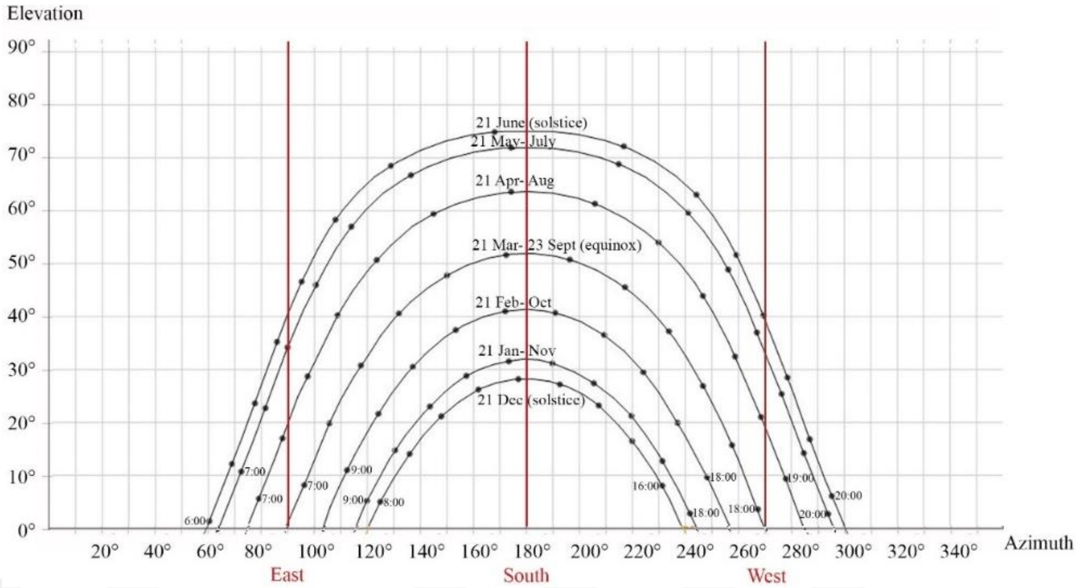


Figure 5.8 Sun path diagram

Hourly values of solar azimuth and elevation angles for the equinox and solstice days are chosen from the graphic and hourly solar angles for the indicated dates are given in Table 5.7.

Table 5.7 Solar elevation and azimuth angles

21st March			**21st June**			**23rd September**			**21st December**		
Time Period	Elevation Angle	Azimuth Angle	Time Period	Elevation Angle	Azimuth Angle	Time Period	Elevation Angle	Azimuth Angle	Time Period	Elevation Angle	Azimuth Angle
07:14	-1°	89°	05:47	-1°	59	06:59	-1°	89°	08:24	-1°	120°
08:00	8°	96°	06:00	1°	61°	07:00	-1°	89°	09:00	5°	125°
09:00	20°	106°	07:00	12°	69°	08:00	11°	99°	10:00	14°	136°
10:00	31°	118°	08:00	23°	78°	09:00	22°	109°	11:00	21°	148°
11:00	40°	132°	09:00	35°	86°	10:00	33°	121°	12:00	26°	162°
12:00	48°	150°	10:00	47°	96°	11:00	42°	136°	13:00	28°	178°
13:00	52°	173°	11:00	58°	108°	12:00	49°	155°	14:00	27°	193°
14:00	51°	196°	12:00	68°	129°	13:00	52°	178°	15:00	23°	208°
15:00	45°	217°	13:00	75°	169°	14:00	49°	202°	16:00	16°	220°
16:00	37°	234°	14:00	72°	217°	15:00	43°	222°	17:00	8°	232°
17:00	27°	247°	15:00	63°	244°	16:00	34°	237°	17:53	-1°	240°
18:00	15°	258°	16:00	52°	259°	17:00	24°	249°			
19:00	4°	267	17:00	40°	270°	18:00	12°	260°			
19:23	-1°	271°	18:00	28°	279°	19:00	1°	269°			
			19:00	17°	287°	19:07	-1°	271°			
			20:00	6°	295°						
			20:38°	-1°	301°						

In Figure 5.9Figure 5.11 solar azimuth angles are shown on the thermal zone plan scheme of the case building for 21st March. It is seen that direct sunlight is coming on eastern façade starting from 07:14 and moves to southern façade after 11:00; then moves to western façade after 15:00, stays till 19:23 and northern façade never faces the direct sunlight.

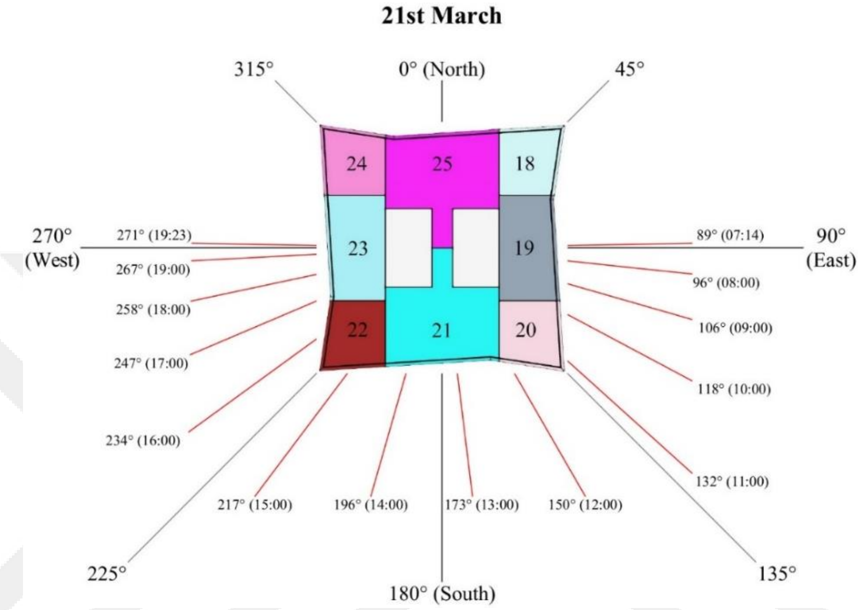


Figure 5.9 21st March solar azimuth angles

In Figure 5.10 solar elevation angles are given for each façade orientation on section drawings of the case building for 21st March. Eastern façade is facing the sunlight with a changing elevation angle from -1° to 40°; southern façade is facing the sunlight with a changing elevation angle from 45° to 52° and western façade is facing the sunlight with a changing elevation angle from 37° to -1°.

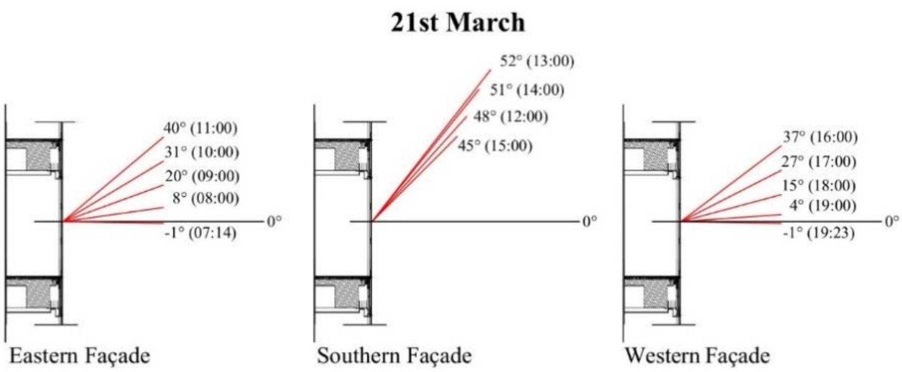


Figure 5.10 21st March solar elevation angles

In Figure 5.11 solar azimuth angles are shown on the thermal zone plan scheme of the case building for 21st June. It is seen that direct sunlight is coming on eastern façade starting from 05:47 and moves to southern façade after 12:00; then moves to western façade after 14:00, stays till 20:38 and northern façade never faces the direct sunlight.

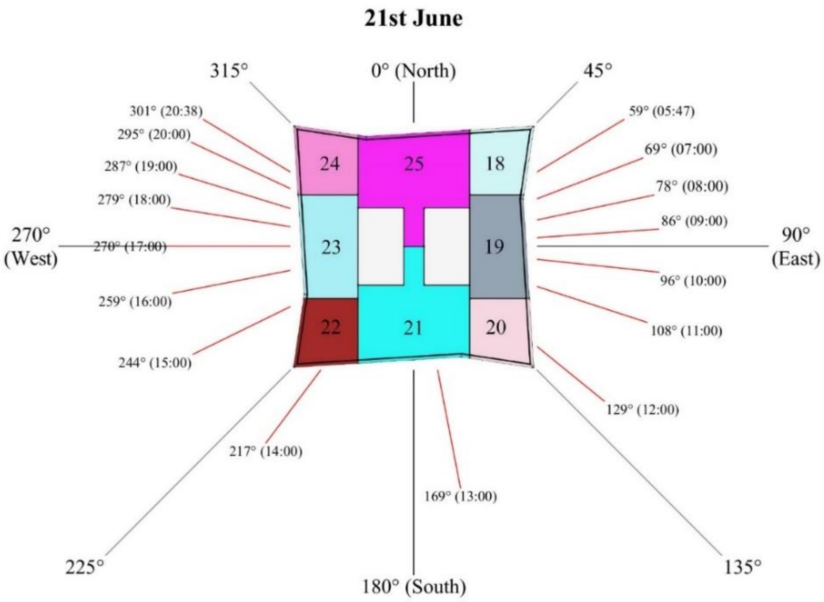


Figure 5.11 21st June solar azimuth angles

In Figure 5.12 solar elevation angles are given for each façade orientation on section drawings of the case building for 21st June. Eastern façade is facing the sunlight with a changing elevation angle from -1° to 68°; southern façade is facing the sunlight with a changing elevation angle from 72° to 75° and western façade is facing the sunlight with a changing elevation angle from 63° to -1°.

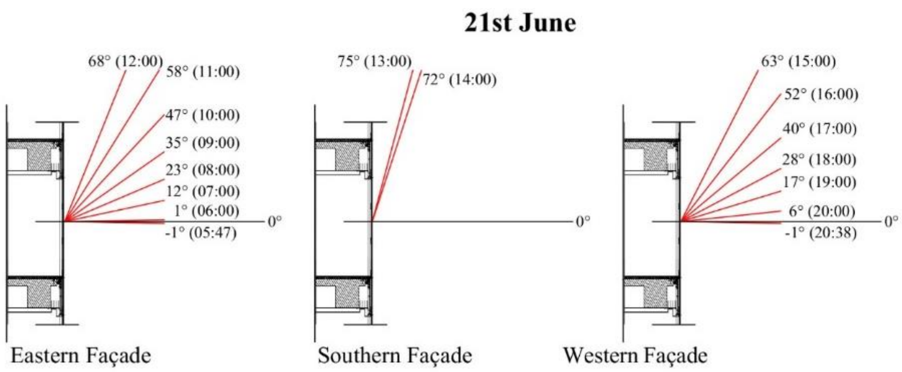


Figure 5.12 21st June solar elevation angles

In Figure 5.13 solar azimuth angles are shown on the thermal zone plan scheme of the case building for 23rd September. It is seen that direct sunlight is coming on eastern façade starting from 07:00 and moves to southern façade around 11:00; then moves to western façade after 15:00, stays till 19:07 and northern façade never faces the direct sunlight.

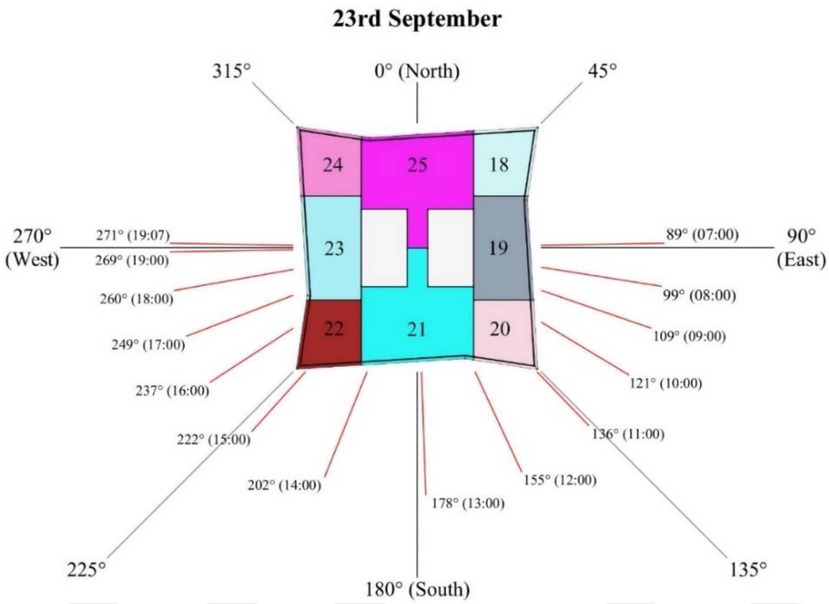


Figure 5.13 23rd September solar azimuth angles

In Figure 5.14 solar elevation angles are given for each façade orientation on section drawings of the case building for 23rd March. Eastern façade is facing the sunlight with a changing elevation angle from -1° to 42°; southern façade is facing the sunlight with a changing elevation angle from 43° to 52° and western façade is facing the sunlight with a changing elevation angle from 34° to -1°.

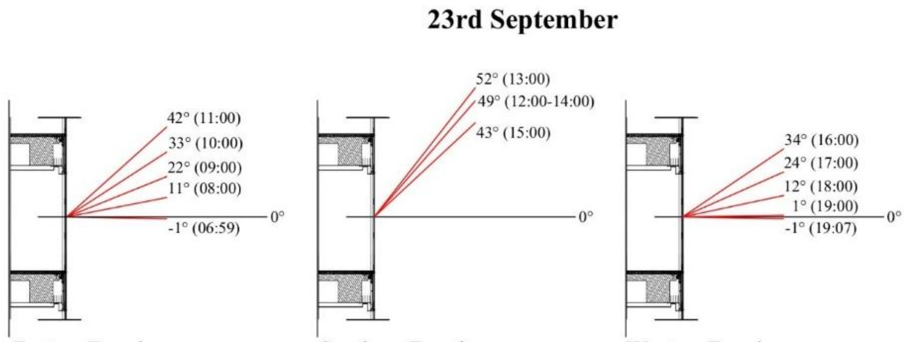


Figure 5.14 23rd September solar elevation angles

In Figure 5.15 solar azimuth angles are shown on the thermal zone plan scheme of the case building for 21st December. It is seen that direct sunlight is coming on eastern façade starting from 08:24 and moves to southern façade around 10:00; then moves to western façade after 16:00, stays till 17:53 and northern façade never faces the direct sunlight.

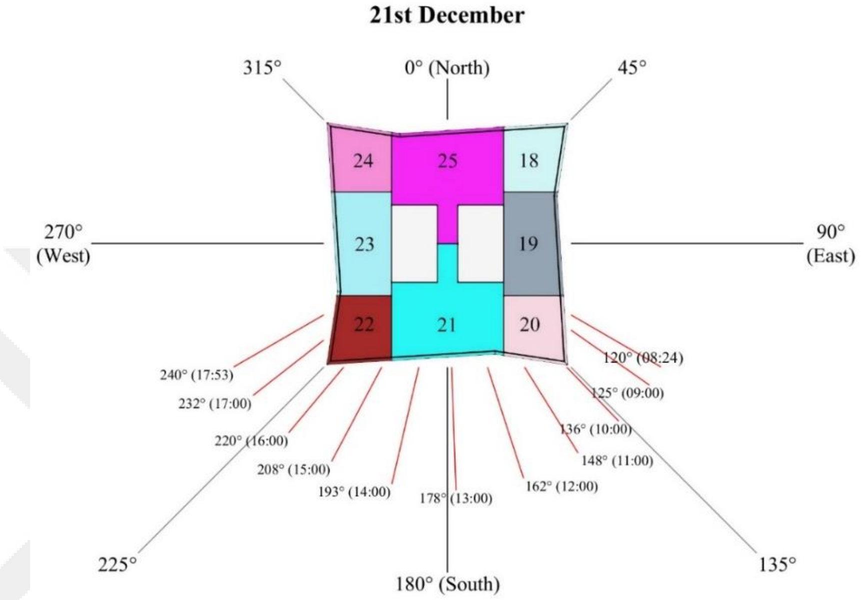


Figure 5.15 21st December solar azimuth angles

In Figure 5.16 solar elevation angles are given for each façade orientation on section drawings of the case building for 21st December. Eastern façade is facing the sunlight with a changing elevation angle from -1° to 14°; southern façade is facing the sunlight with a changing elevation angle from 16° to 28° and western façade is facing the sunlight with a changing elevation angle from 17° to -1°.

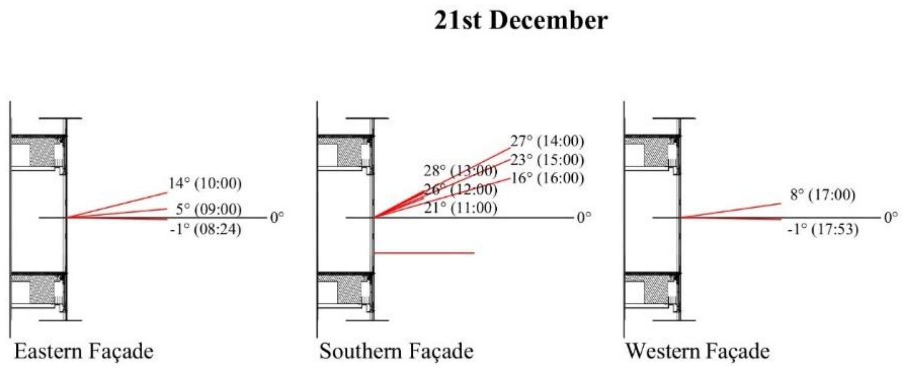


Figure 5.16 21st December solar elevation angles

In Table 5.8 hourly average solar elevation angles are studied according to the building façade orientations for the solstice and equinox days of the year 2015.

Table 5.8 Average solar elevation angles for equinox and solstice days

	21st March		**21st June**		**23rd September**		**21st December**	
Façade Orientation	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle
Eastern Façade	08:00-11:00	25°	06:00-12:00	35°	08:00-11:00	27°	09:00-10:00	9°
Southern Façade	12:00-15:00	49°	13:00-14:00	73°	12:00-15:00	48°	11:00-16:00	24°
Western Façade	16:00-19:00	21°	15:00-20:00	34°	16:00-19:00	18°	17:00	8°
Northern Façade	-	-	-	-	-	-	-	-

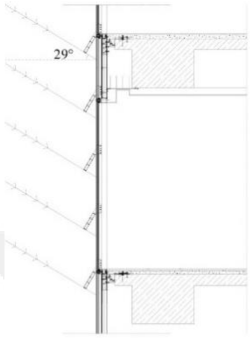
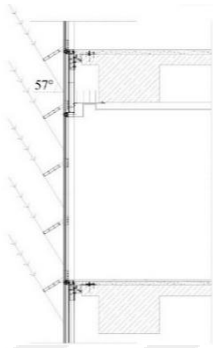
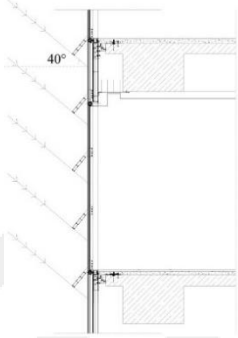
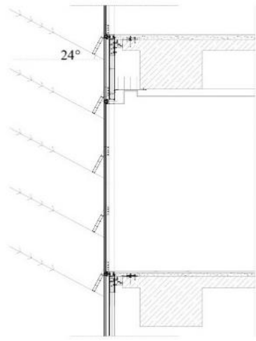
Table 5.9 presents the data collected from this analysis considering the seasonal changes.

Table 5.9 Average solar elevation angles for summer and winter seasons

Façade Orientation	21st March- 23rd September Summer		23rd September- 21st March Winter	
	Time Period	Average Elevation Angle	Time Period	Average Elevation Angle
Eastern Façade	06:00-12:00	29°	08:00-11:00	20°
Southern Façade	12:00-15:00	57°	11:00-16:00	40°
Western Façade	15:00-20:00	24°	16:00- 19:00	16°
Northern Façade	-	-	-	-

Since the study aims to propose CASD, the changes in solar elevation angles are analysed for each façade orientation according to the time periods that the façade is facing direct sunlight. Given in Table 5.10 Seasonal shading device requirement layout, the average values of these solar elevation angles are determined to be the reference angles for proposing the CASD.

Table 5.10 Seasonal shading device requirement layout

Eastern Façade- Thermal zone 19	Southern Façade- Thermal zone 21		Western Façade- Thermal zone 23
Summer	Summer	Winter	Summer
			

So that existing shading devices are positioned as shown in Table 5.10 with proper elevation angles according to seasonal changes and façade orientations to prevent direct sunbeam effect on the façade.

In second phase of the shading device requirement analysis; case building is modelled without shading devices (Case 2) and 'exterior windows total transmitted beam solar radiation energy (J)' values are chosen from simulation results. To understand the seasonal changes of sunbeam elevation angles; summer and winter solstice days are used as reference and chosen results are presented in Table 5.11.

Table 5.11 Maximum beam solar radiation energy values transmitted from the windows; case 2

Thermal Zone	Façade Orientation	21st June		21st December	
		Max. Beam Solar Radiation Energy (J)	Time Period	Max. Beam Solar Radiation Energy (J)	Time Period
19	East	3778190	8:30	1429110	9:30
21	South	592977	12:30	4117050	11:30
23	West	3853840	16:30	1352930	14:30
25	North	132645	18:00	0	-

On 21st of June maximum beam solar radiation energy transmitted from the window of east oriented Thermal Zone 19 is 3778190 J at 8:30, which is 592977 J at 12:30 for south oriented Thermal Zone 21, 3853840 J at 16:30 for west oriented Thermal Zone 23 and 132645 J at 18:00 for north oriented Thermal Zone 25.

On 21st of December maximum beam solar radiation energy transmitted from the window of east oriented Thermal Zone 19 is 1429110 J at 9:30, which is 4117050 J at 11:30 for south oriented Thermal Zone 21, 1352930 J at 14:30 for west oriented Thermal Zone 23 and value is zero for north oriented Thermal Zone 25 all day long.

Regarding to the calculated data in Table 5.11; east and west oriented façades are mostly affected with high solar radiation in Summer because of the low solar elevation angles of sunbeam that passes through the façade to interior spaces. For south facing façades it is changing as sunbeam grazes the façade due to its high elevation angle and north facing façades are just affected by the indirect solar radiation. As a result, shading devices are interpreted for both seasons in only south facing façades. Shading devices of East and West oriented façades are considered only for Summer. Apparently North façade is never facing direct sunbeam, so it is excluded from the field of this study.

5.4 Climate Adaptive Shading Device Proposals

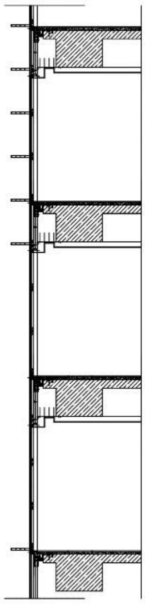
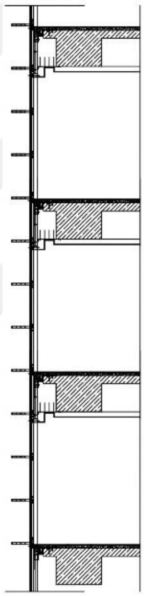
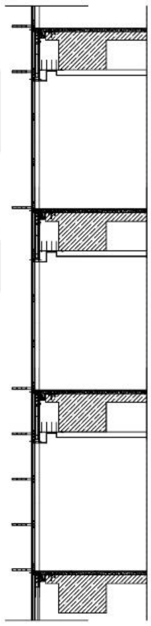
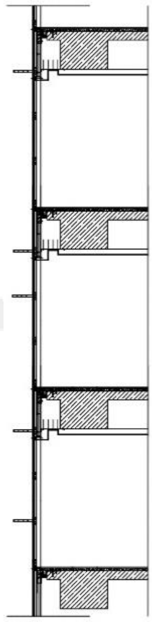
Considering the data achieved by shading device requirement analysis; we can say that shading device requirements of a façade changes during a day parallel to the changing solar azimuth and elevation angles. To understand when shading is needed for a façade; solar azimuth angles are studied on hourly base for each façade orientation and existing shading devices are positioned with proper elevation angles to have a better performing façade for the case building. Since the word ‘adaptive’ refers to the changeable, mutable, flexible, instable features; ‘Adaptability’ is defined as ‘the ability of a system to deliver intended functionality considering multiple criteria under variable conditions through the design variables changing their physical values over time.’ (Gür, 2007); this study approaches ‘adaptability’ in relation with the position and material transmittance of shading devices.

Existing building model; Case 1 and the model used for shading device requirement analysis; Case 2 are given in Table 5.12 and Table 5.13. Also, 3 CASD scenarios are proposed by the collected data from Sun Path diagram analysis and presented in detail: Table 5.14, Table 5.15, Table 5.16. Tables include the details of 4 thermal zones regarding to their façade orientations; shading device angles, shading device layouts and shading device availability schedules.

Position of the shading devices are driven out from solar elevation angles and material transmittance are driven out from solar azimuth angles as the required shading characteristics. Apart from the adaptivity parameters; quantity of the shading elements has changed with the proposed façades. While existing building has a designed layout with some reductions in shading devices regarding to the orientation, in the proposal northern façade has no shadings, though east, south and west oriented façades are fully shaded. Shading devices are placed with the same construction detail in Figure 5.4.; keeping the size in all proposals same with the existing devices.

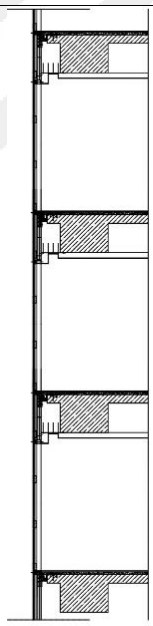
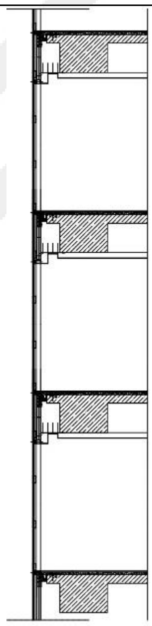
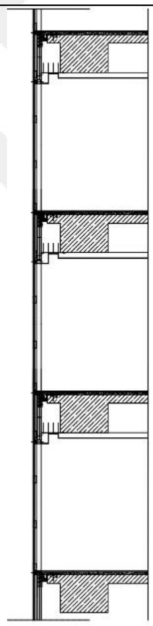
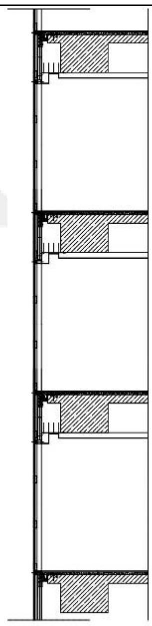
Existing shading devices of the case building are given in Table 5.12 for Case 1; which is used for the model calibration and energy performance comparison of the case building with the existing and proposed shading devices.

Table 5.12 Shading scenario; case 1

Thermal Zone Number		19	21	23	25
Façade Orientation		East	South	West	North
Shading Device Angle		90°	90°	90°	90°
Shading Device Layout					
Shading Availability	Season	Summer-Winter	Summer-Winter	Summer-Winter	Summer-Winter
	Time Period	24 Hours	24 Hours	24 Hours	24 Hours

Case 2 is representing the existing building without shading devices as seen in Table 5.13 Case 2 is used for shading device requirement analysis through the ‘Exterior Windows Total Transmitted Beam Solar Radiation Energy (J)’ values chosen from the simulation results This parameter is also used for understanding the efficiency of shading devices in comparison with the existing and proposed conditions.

Table 5.13 Shading scenario; case 2

Thermal Zone Number		19	21	23	25
Façade Orientation		East	South	West	North
Shading Device Angle		-	-	-	-
Shading Device Layout					
Shading Availability	Season	-	-	-	-
	Time Period	-	-	-	-

The shading device details of Case 3 are given in Table 5.14; based on 'shading device requirement analysis' results, shading devices are placed with fixed angles proper to façade orientations and they are always in use.

Table 5.14 Shading scenario; case 3

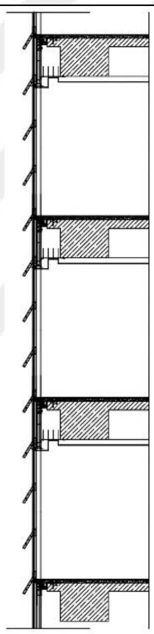
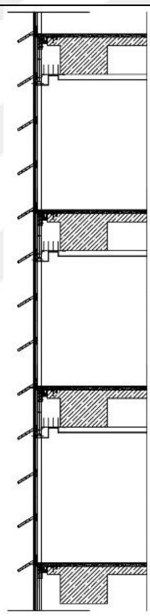
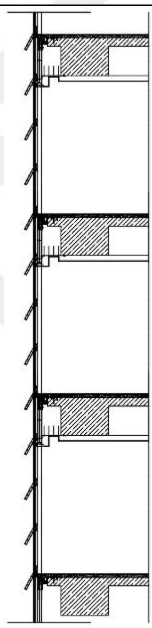
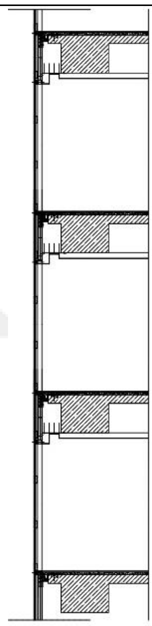
Thermal Zone Number		19	21	23	25
Façade Orientation		East	South	West	North
Shading Device Angle		29°	57°	24°	-
Shading Device Layout					
Shading Availability	Season	Summer-Winter	Summer-Winter	Summer-Winter	-
	Time Period	24 Hours	24 Hours	24 Hours	-

Table 5.15 is showing the details of the proposed CASD in Case 4. CASD are placed with fixed angles proper to façade orientations with adaptive transmittance schedules based on hourly and seasonal solar changes.

Table 5.15 Shading scenario; case 4

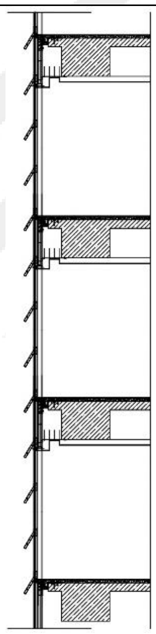
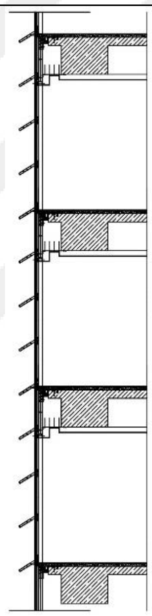
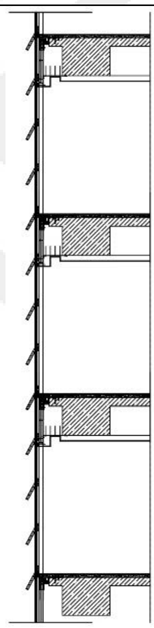
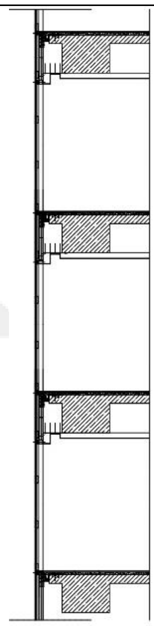
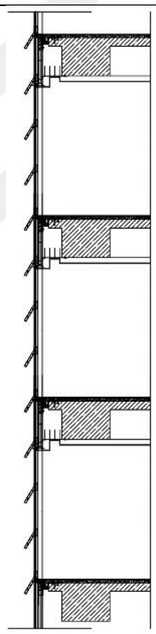
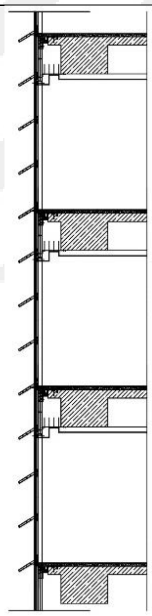
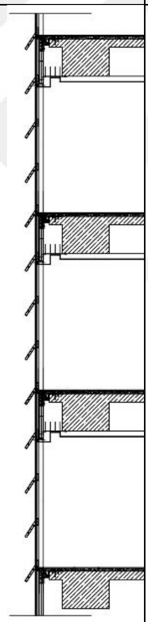
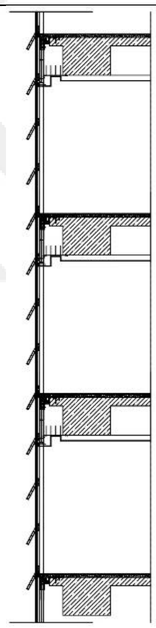
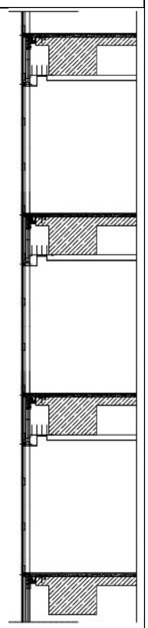
Thermal Zone Number		19	21	23	25
Façade Orientation		East	South	West	North
Shading Device Angle		29°	57°	24°	-
Shading Device Layout					
Shading Availability	Season	Summer	Summer	Summer	-
	Time Period	05:00- 11:00	10:00- 14:00	14:00- 18:00	-

Table 5.16 defines the CASD proposed with Case 5. Shading devices are placed with angles proper to façade orientations with adaptive transmittance schedules based on hourly and seasonal solar changes. Shading devices of south oriented façades has also adaptive angles based on seasonal solar changes.

Table 5.16 Shading scenario; case 5

Thermal Zone Number		19	21		23	25
Façade Orientation		East	South		West	North
Shading Device Angle		29°	57°	40°	24°	-
Shading Device Layout						
Shading Availability	Season	Summer	Summer	Winter	Summer	-
	Time Period	05:00- 11:00	10:00- 14:00	09:00- 16:00	14:00- 18:00	-

5.5 Simulation Results and Comparisons

The case building of this study is chosen with an intention to propose a methodology for increasing building energy performance focusing on over- heating problems caused by glazed curtain wall façade which effects heating and cooling loads directly. The graphics showing the heating and cooling loads of all 5 cases are given in Appendix IX.

Since heating and cooling demand of the case building is supplied by VRF systems, electricity consumption is considered as the building energy performance indicator in this methodology. Annual Electricity consumption values are firstly used for verification of the created simulation model through the comparison with actual electricity bills. Then the study continued over comparisons of electricity consumptions achieved by the simulations of different CASD proposals. Electricity consumption caused by VRF systems, including heating, cooling and fan usages are presented for all five cases in Table 5.17.

Table 5.17 Electricity consumption values (kWh)

Consumption source	Case number	Monthly Electricity Consumptions (kWh)												Annual total
		January	February	March	April	May	June	July	August	September	October	November	December	
Heating	1	84276	78663	57387	256	0	0	0	0	0	3127	42719	74186	340613
	2	85685	72484	51434	159	0	0	0	0	0	2905	42028	73732	**328427**
	3	87813	82344	61384	810	0	0	0	0	0	4708	46399	76564	360024
	4	90668	77297	56562	186	0	0	0	0	0	4312	47229	78111	354364
	5	88424	81691	59467	425	0	0	0	0	0	4129	46285	77453	357874
Cooling	1	343	373	508	9946	54421	93341	102276	108512	83627	7322	873	345	461887
	2	377	418	716	11966	55518	93428	108078	108378	90018	8337	1074	364	478672
	3	324	359	449	8463	49591	89446	98963	104058	77654	5197	574	333	435409
	4	349	383	467	9668	46301	85198	101386	100519	80311	5430	565	334	430911
	5	324	362	467	8641	48085	87670	97526	102461	76079	5674	549	332	**428169**
Fans	1	23292	21505	24189	22422	24293	23434	23439	24344	23430	23314	23294	23295	280250
	2	24634	21900	23723	23757	23830	23868	24794	23880	23870	24662	22813	24640	286370
	3	22356	20643	23216	21514	23310	22488	22493	23360	22480	22367	22357	22359	**268943**
	4	24130	21452	23236	23255	23325	23365	24272	23374	23362	24141	22343	24136	280391
	5	23229	21447	24123	22351	24214	23359	23365	24265	23352	23241	23230	23232	279408
Total	1	107911	100541	82083	32624	78714	116775	125716	132856	107056	33763	66886	97825	1082750
	2	110697	94801	75873	35882	79348	117297	132872	132258	113887	35905	65915	98736	1093470
	3	110493	103346	85050	30788	72900	111934	121456	127418	100133	32272	69329	99256	**1064376**
	4	115146	99132	80265	33108	69626	108564	125659	123893	103673	33883	70137	102581	1065666
	5	111977	103500	84057	31416	72299	111029	120891	126726	99430	33044	70063	101017	1065451

Heating and cooling electricity consumption values are examined both separately and in total, including also the fans, regarding to the values given in Table 5.17. It is seen that lowest annual heating electricity consumption value is 328427 kWh in Case 2 where the building has no shading devices. In Case 1, consumption value is 340613 kWh by the effect of existing 90° shading devices. Placing the shading devices with proper angles which are only active in summer season, and applying hourly adaptivity behaviours in Case 4, created 354364 kWh heating electricity consumption. When shading devices of southern façade became active also in winter season with the proposal in Case 5, the consumptions raised to 357874 kWh. And the highest heating electricity consumption value is seen in Case 3 as 360024 when shading devices are placed with proper angles but no adaptivity schedules, that means they are in use all the time.

For annual cooling electricity consumption, the lowest value is reached as 428169 kWh by the proposed shading devices in Case 5 which are showing both hourly and seasonal adaptivity behaviour of shading devices added with the proper elevation angles. Then cooling electricity consumption is rising to 430911 kWh in Case 4 which doesn't offer any shading in winter season for any façade. Even the shading devices are placed with proper angles in Case 3, since the elevation angle of the southern façade is not adapting itself to winter season like Case 5; the value rises to 435409 kWh. And the existing conditions of the building presented in Case 1, results with 461887 kWh cooling electricity consumption which is pointing out the focus of this study. It is clear that the highest cooling electricity consumption is 478672 kWh in Case 2, which has no shading devices on the glazed curtain façades.

Annual total of heating and cooling electricity consumptions including also fan usages, are giving the lowest value as 1064376 kWh in Case 3 where the shading devices are placed with proper angles that are fixed in summer and winter seasons without any adaptivity schedules. Then the shading devices in Case 5, that are proposed with hourly and seasonal adaptivity schedules and adaptive elevation angles in southern façade, gives a consumption result as 1065451 kWh which is 1065666 kWh for Case 4. Existing building situation presented in Case 1, gives total electricity consumption value as 1082750 kWh and Case 2 with no shading devices results with the highest consumption value as 1093470 kWh.

Table 5.18 Monthly electricity consumption comparisons (kWh)

Months	Actual Bill	Case 1	Case 2	Case 3	Case 4	Case 5
January	121119	107911	110697	110493	115146	111977
February	93394	100541	94801	103346	99132	103500
March	76158	82083	75873	85050	80265	84057
April	34000	32624	35882	30788	33108	31416
May	45600	78714	79348	72900	69626	72299
June	68800	116775	117297	111934	108564	111029
July	118106	125716	132872	121456	125659	120891
August	187489	132856	132258	127418	123893	126726
September	107678	107056	113887	100133	103673	99430
October	45603	33763	35905	32272	33883	33044
November	21311	66886	65915	69329	70137	70063
December	56294	97825	98736	99256	102581	101017
Total	**975553**	**1082750**	**1093470**	**1064376**	**1065666**	**1065451**

As a result of the comparisons it is seen that lowest electricity consumption values are achieved; for cooling in Case 5, for heating in Case 2 and for total in Case 3. It is clear that to decrease the total electricity consumptions; shading devices should be placed with proper elevation angles as it is done in Case 3. But these shading devices create negative effect on heating electricity consumptions even if the usage is limited by hourly schedules. Since the intention of this study is to decrease the cooling energy consumption, the proposed scenario in Case 5 can be stated as the best performing proposal for the case building.

In Table 5.19, façades are studied through 'Zone exterior windows total transmitted beam solar radiation energy values (J)' in order to understand the solar effects on a zone-based analysis. Since the solar elevation angle is minimum on 21st of December and maximum on 21st of June; these are taken as reference days to understand the dramatic solar effects on building façade. So maximum values of 'Zone exterior windows total transmitted beam solar radiation energy (J)' are chosen for each façade orientations relevant to time of the peak point. To understand when the solar effect is maximum on a façade without any prevention, simulation results of Case 2 are used as there are no shading devices on any façade.

According to the maximum values of 'zone exterior windows total transmitted beam solar radiation energy (J)', peak values reached;

- East facing façade of thermal zone 19: at 9:30 on 21st of December and at 8:30 on 21st of June,

- South facing façade of thermal zone 21: at 11:30 on 21st of December and at 12:30 on 21st of June,

- East facing façade of thermal zone 23: at 14:30 on 21st of December and at 16:30 on 21st of June,

- West facing façade of thermal zone 25: at 12:30 on 21st of December and at 18:30 on 21st of June.

Obviously, maximum values are seen in the scenarios that offer no shading devices (Case 2). Since the target of this study is to increase energy efficiency; the study looked for the scenario which decreases cooling energy demand while increasing heating energy demand. So that, Table 5.19 is studied to find out the 'zone exterior windows total transmitted beam solar radiation energy' values that are lowest on 21st June and highest on 21st December.

Table 5.19 Zone exterior windows total transmitted beam solar radiation energy values (J)

Thermal Zone	Façade Orientation	Case Number	21st June		21st December	
			Time of Max. Value Reached	Max. Beam Solar Radiation Energy (J)	Time of Max. Value Reached	Max. Beam Solar Radiation Energy (J)
19	East	1	08:30	3129940	09:30	1268740
		2		3778190		**1429110**
		3		**1590530**		697009
		4		**1590530**		**1429110**
		5		**1590530**		**1429110**
21	South	1	12:30	1610	11:30	3112580
		2		592977		**4117050**
		3		**1006**		2323750
		4		**1006**		**4117050**
		5		**1006**		2014330
23	West	1	16:30	3300060	14:30	1184660
		2		3853840		**1352930**
		3		**1752030**		653926
		4		**1752030**		**1352930**
		5		**1752030**		**1352930**
25	North	1	18:00	**102783**	12:30	0
		2		132645		0
		3		132645		0
		4		132645		0
		5		132645		0

For thermal zone 19 (eastern façade); on 21st of June, Case 3, Case 4 and Case 5 are giving the lowest transmitted solar energy value which is 1590530 (J) and on 21st of December, Case 2, Case 4 and Case 5 are giving the highest transmitted solar energy value. which is 1429110 (J).

For thermal zone 21 (southern façade); on 21st of June, Case 3, Case 4 and Case 5 are giving the lowest transmitted solar energy value which is 1006 (J) and on 21st of December, Case 2 and Case 4 are giving the highest transmitted solar energy value which is 4117050 (J).

For thermal zone 23 (western façade); on 21st of June, Case 3, Case 4 and Case 5 are giving the lowest transmitted solar energy value which is 1752030 (J) and on 21st of December, Case 2, Case 4 and Case 5 are giving the lowest transmitted solar energy value which is 1352930 (J).

For thermal zone 25 (northern façade); on 21st of June, Case 1 is giving the lowest transmitted solar energy value which is 102783 (J) and on 21st of December, there is no solar energy value transmitted

As a result of the given analysis; for eastern and western façades, Case 4 and Case 5, for southern façade Case 4 and for northern façade Case 1 are giving the best performing results. So, it is seen that even the northern façades have shading demand in Summer season. Eastern and western façades have shading demand only in Summer that should be supplied by the shading devices positioned with the proper angles and that are adapting to the hourly changes. Even if the southern façades are proposed to have shading devices in winter; the results show that prevention of solar effects in winter; causes less solar energy gain and this would increase the heating energy demand. Table 5.19 is presenting the zone exterior windows total transmitted beam solar radiation energy values for solstice days and since this study is dealing with the building energy performance in total and the reference parameter is accepted as electricity consumptions, major outcomes of the study will be concluded considering Table 5.17

CHAPTER SIX
CONCLUSION

Since the ‘best performing façade’ is still an indefinite notion in terms of energy efficiency, this study aims to find out the limitations in energy performance of the existing glazed façade system of a case building in a hot humid climate by a simulation tool and to propose a methodology for implementing CASD alternatives.

Consequently, the study focuses on how to manage the effects of the façade on building energy performance; the features that are needed and the features that should be avoided. Solar movement is the main factor effecting the façade decisions relevant to the requirements of the indoor environment, depending on the building function, so the topic is discussed within a framework made of the parameters specific to the case building.

An existing case building is modelled by using OpenStudio software in detail of the actual project data. Monthly electricity consumption values that are discussed as heating and cooling energy consumptions are accepted as the building energy performance indicators in this study. Through the analysis on simulation results, effects of shading devices on building energy performance are presented. Results are analysed both in all building and thermal zone scales through different parameters.

Based on the stated overheating problems of the south facing offices, the study focused on the shading devices assembled to the glazed façade. Case building’s shading device requirements as shading device elevation angle, hourly and daily shading schedules are determined considering the seasonal changes according to the solar movement. Also, ‘exterior windows transmitted beam solar radiation energy’ parameter is examined for seasonal periods to understand the shading need of façades according to their orientation.

These analyses came out as; for north oriented façades shading is not a requirement in any time of any season; east and west oriented façades require shading devices only in summer where the south oriented façades require shading devices both in summer and winter. CASD should be applied with proper angles and schedules, determined according to the façade orientations.

Considering the location of the case building, climate conditions create cooling demand rather than the heating demand. So, the focus of this study is the over- heating problems of the building especially in southern façades which causes high cooling electricity consumption values.

It is clear that existence of the shading devices is affecting heating and cooling energy consumptions inversely. When the effectiveness of shading devices increases, benefit of solar effect on heating loads decrease. That is why the shading devices increase the heating loads even if they are climate adaptive. Since focus of this study is over- heating problem of the case building, decreasing the cooling demands is pointed out as a solution. So, the scenario of Case 5 is the most effective solution in these terms by proposing hourly adaptive shading device schedules which are placed with seasonal adaptive shading device angles specific to the façade orientations; which are 29° for eastern façade in summer between 05:00- 11:00, 57° for southern façade in summer between 10:00- 14:00, 40° for southern façade in winter between 09:00- 16:00 and 24° for western façade in summer between 14:00- 18:00.

Another important outcome of this study comprised due to the solar elevation and azimuth angles; southern façades are facing the Sun with a higher elevation angle (43°- 75°) for a shorter time period (12:00-15:00) in summer season, compared to the winter sun which is staying for a longer time period (11:00-16:00) with a lower elevation angle (16°- 52°). So that beam solar radiation energy is much effective in winter compared to summer for south facing façades and this is the most crucial output of the study.

Consequently, by proposing CASD for an existing case building, this study reveals a solution for a stated problem, which is the occupants' compliant about the overheating problems of the case building.

The presented methodology of this study is applied on an existing building to support the literature of the study field by giving simulation results of building energy performance calculations that are comparable with the accurate data. Since the concept of climate adaptive façades is not mature enough to be applied and examined it is not supported by sufficient information yet. This study is expected to examine the effects of CASD on building energy performance through the outputs derived from simulation results of an existing building; so that the outputs of this study are accepted to be validated.

However, the study covers the parameters of a case building, its methodology is presenting a path that can be applied on different building types and different locations. Also, the scope of the study can be varied by changing the minor parameters. In further studies; CASD can be studied considering the monthly changes of the solar angles.

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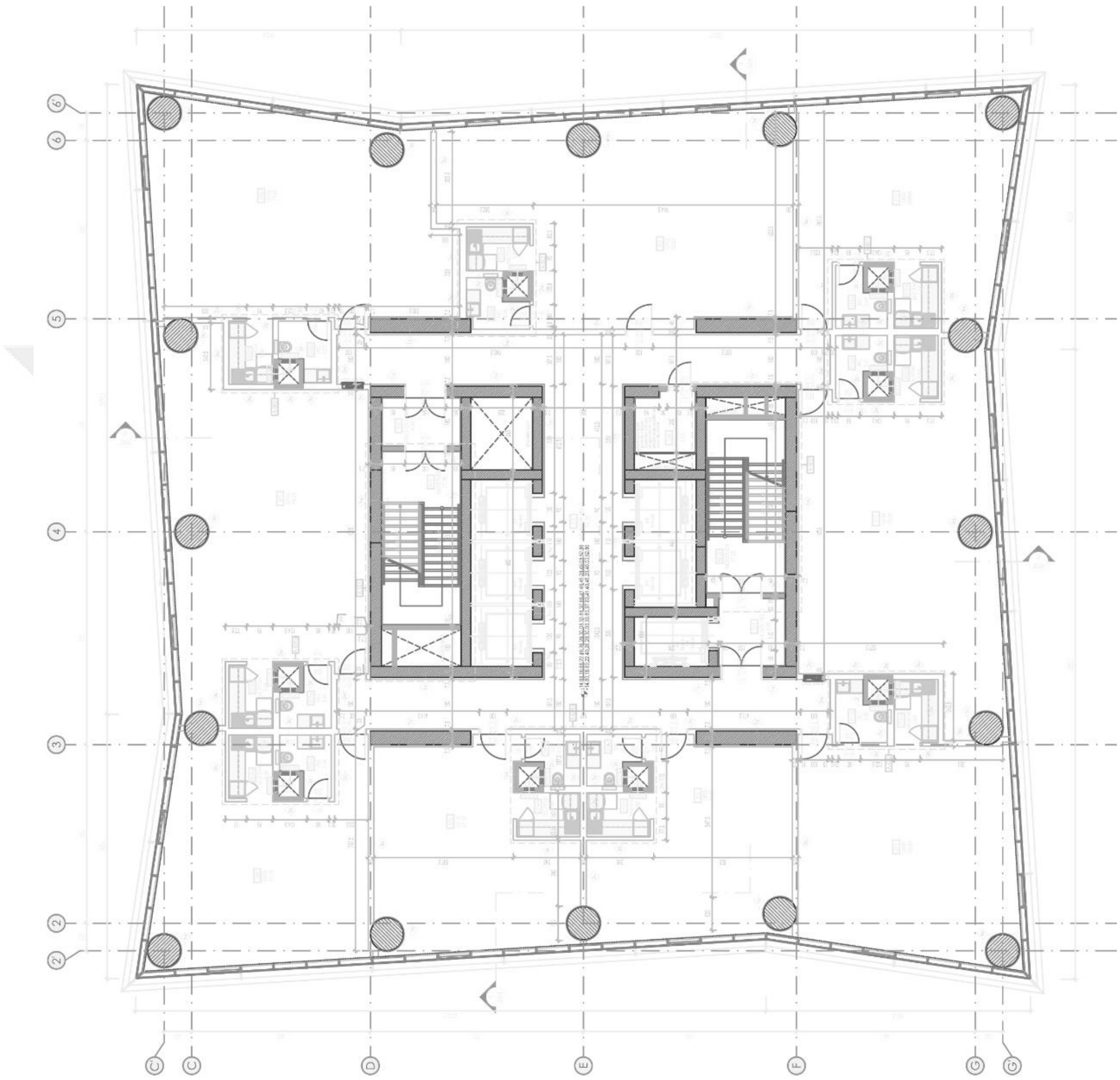
APPENDICES

APPENDIX I- Architectural Plan Scheme of a Typical Office Floor



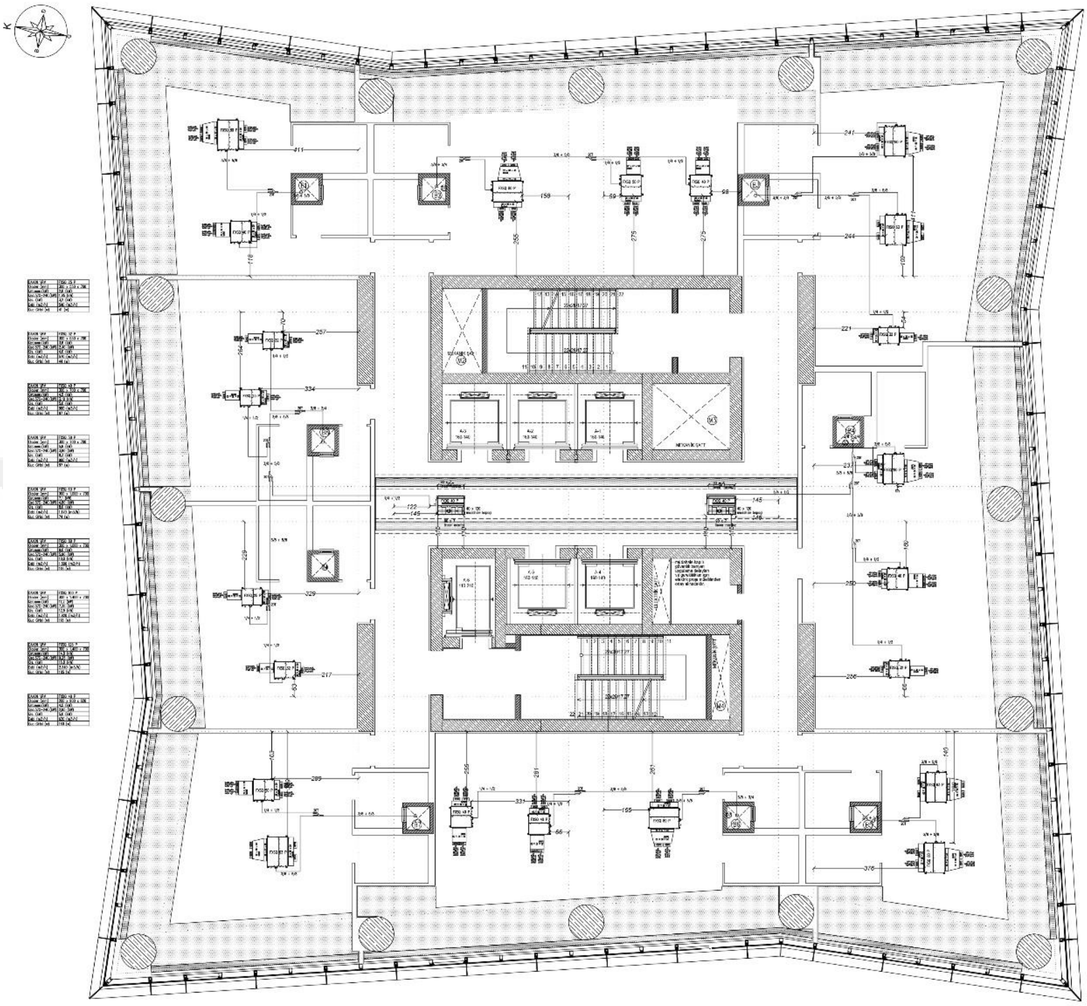
APPENDIX II- Construction Details

Exterior Surface Constructions	Material	Thickness (m)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)	Thermal Absorptance (emittance)	Solar Absorptance	Visible Absorptance
Walls	Tempered glass	0.008	1.4	0.1	0	0.20	0.73	0.021
	Air gap	0.02						
	Tempered glass	0.006						
	Air gap	0.04	0.03	1225	0	0.9	0.7	0.7
	Fireproof gypsum board	0.012	0.16	800	90	0.9	0.7	0.7
	Heat insulation (rockwool)	0.08	0.05	19	960	0.9	0.7	0.7
Floors	Natural stone finishing	0.04	1.45	82.40	900	0.9	0.7	0.7
	Mortar	0.05	0.69	858	837	0.9	0.92	0.92
	Heat insulation layer (XPS)	0.05	0.03	29	210	0.9	0.7	0.7
	2nd layer waterproofing	0.003	0.16	121.29	460	0.9	0.7	0.7
	1st layer waterproofing	0.003	0.16	121.29	460	0.9	0.7	0.7
	Grading concrete	0.05	1.45	82.40	900	0.9	0.7	0.7
	Filling	0.31	1.45	82.40	900	0.9	0.7	0.7
	Reinforced concrete slab	0.18	1.73	243	837	0.9	0.65	0.65
Roofs	Composite timber deck panel	0.025	0.11	425	630	0.9	0.7	0.7
	Deck construction	0.03	0.12	800	380	0.9	0.7	0.7
	Grading concrete	0.05	1.45	82.40	900	0.9	0.7	0.7
	Heat insulation layer (XPS)	0.05	0.03	29	210	0.9	0.7	0.7
	2nd layer waterproofing	0.003	0.16	121.29	460	0.9	0.7	0.7
	1st layer waterproofing	0.003	0.16	121.29	460	0.9	0.7	0.7
	Levelling concrete	0.04-0.14	1.45	82.40	900	0.9	0.7	0.7
	Reinforced concrete slab	0.18	1.73	243	837	0.9	0.65	0.65

Interior Surface Constructions	Material	Thickness (m)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)	Thermal Absorptance (emittance)	Solar Absorptance	Visible Absorptance
Walls	Gypsum board	0.019	0.16	800	90	0.9	0.7	0.7
	Gypsum board	0.019	0.16	800	90	0.9	0.7	0.7
	Stonewool	0.05	0.05	19	960	0.9	0.7	0.7
	Stonewool	0.05	0.05	19	960	0.9	0.7	0.7
	Gypsum board	0.019	0.16	800	90	0.9	0.7	0.7
	Gypsum board	0.019	0.16	800	90	0.9	0.7	0.7
Floors	Finishing material	0.03	0.11	420	630	0.9	0.7	0.7
	Alum	0.05	0.69	858	837	0.9	0.92	0.92
	Reinforced concrete	0.18	1.73	243	837	0.9	0.65	0.65
Ceilings	Finishing	0.03	0.11	420	630	0.9	0.7	0.7
	Alum	0.05	0.69	858	837	0.9	0.92	0.92
	Reinforced concrete	0.18	1.73	243	837	0.9	0.65	0.65

Ground Contact Surface Constructions	Material	Thickness (m)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)	Thermal Absorptance (emittance)	Solar Absorptance	Visible Absorptance
Walls	Plaster+painting	0.025	0.16	784.9	830	0.9	0.4	0.4
	Reinforced concrete wall	0.4	1.73	243	837	0.9	0.65	0.65
	1st layer waterproofing	0.003	0.16	121.3	460	0.9	0.7	0.7
	2nd layer waterproofing	0.003	0.16	121.3	460	0.9	0.7	0.7
	Protection layer (XPS)	0.05	0.03	29	210	0.9	0.7	0.7
Floors	Alum	0.08	0.69	858	837	0.9	0.92	0.92
	Raft foundation	0.50	1.73	243	837	0.9	0.65	0.65
	Protection alum	0.05	0.69	858	837	0.9	0.92	0.92
	Geotextile mat	0.003	0.16	121.3	460	0.9	0.7	0.7
	2nd layer waterproofing	0.003	0.16	121.3	460	0.9	0.7	0.7
	1st layer waterproofing	0.003	0.16	121.3	460	0.9	0.7	0.7
	Blinding concrete	0.1	1.14	922.23	900	0.9	0.7	0.7
	Stabilized soil	0.31	1.45	82.4	900	0.9	0.7	0.7
Ceilings	Finishing	0.03	0.11	420	630	0.9	0.7	0.7
	Alum	0.05	0.69	858	837	0.9	0.92	0.92
	Reinforced concrete	0.18	1.73	243	837	0.9	0.65	0.65

APPENDIX III- Mechanical Plan Scheme of a Typical Office Floor



APPENDIX IV- Thermal Zone Definitions

Thermal Zones	Floors	Outdoor Unit Capacity (kW)		Indoor Unit Number								
		Cooling	Heating	125P	100P	80P	63P	50P	40P	32P	25P	40P7
3	0	82.5	94	3	4							
7	1	61.5	69		4	2						
8	1	89	101.5		2	7		1				
9	2	116	131.5	1	3	2	7	1				1
10	3, 4, 5, 6	49	56.5			4			4			
11	3, 4, 5, 6	71.4	81.5			4		4	4			
12	3, 4, 5, 6	82.5	88			4	4			4		
13	3, 4, 5, 6	82.5	94			4			4	4		4
14	3, 4, 5, 6	61.5	69			4	4					
15	3, 4, 5, 6	67	75			4			8			
16	3, 4, 5, 6	49	56.5				4	4				
17	3, 4, 5, 6	67	75							8	8	4
18	7, 8, 9, 10	49	56.5			4			4			
19	7, 8, 9, 10	71.4	81.5			4		4	4			
20	7, 8, 9, 10	82.5	88			4	4			4		
21	7, 8, 9, 10	82.5	94			4			4	4		4
22	7, 8, 9, 10	61.5	69			4	4					
23	7, 8, 9, 10	67	75			4			8			
24	7, 8, 9, 10	49	56.5				4	4				
25	7, 8, 9, 10	67	75							8	8	4
26	11, 12, 13	40	45			3			3			
27	11, 12, 13	55.9	62.5			3		3	3			
28	11, 12, 13	55.9	62.5			3	3			3		
29	11, 12, 13	61.5	69			3			3	3		3
30	11, 12, 13	45	50			3	3					
31	11, 12, 13	49	56.5			3			6			
32	11, 12, 13	40	45				3	3				
33	11, 12, 13	49	56.5							6	6	3
34	14	55.9	62.5	1	3	1						1
35	14	49	56.5		3	1	1					1
36	15, 16, 17, 18	49	56.5			4			4			
37	15, 16, 17, 18	71.4	81.5			4		4	4			
38	15, 16, 17, 18	82.5	88			4	4			4		
39	15, 16, 17, 18	82.5	94			4			4	4		4
40	15, 16, 17, 18	61.5	69			4	4					
41	15, 16, 17, 18	67	75			4			8			
42	15, 16, 17, 18	49	56.5				4	4				
43	15, 16, 17, 18	67	75							8	8	4
44	19, 20, 21, 22	49	56.5			4			4			
45	19, 20, 21, 22	71.4	81.5			4		4	4			
46	19, 20, 21, 22	82.5	88			4	4			4		

47	19, 20, 21, 22	82.5	94			4			4	4		4
48	19, 20, 21, 22	61.5	69			4	4					
49	19, 20, 21, 22	67	75			4			8			
50	19, 20, 21, 22	49	56.5				4	4				
51	19, 20, 21, 22	67	75							8	8	4

APPENDIX V- Mechanical System Settings of the Simulation Model

Cooling Sizing Parameters	
Zone cooling design supply air temperature (°C)	14
Zone cooling design supply air humidity ratio	0.0085
Zone cooling sizing factor	0
Cooling minimum air flow per zone floor area ($m^3/s.m^2$)	0
Design zone air distribution effectiveness in cooling mode	1
Cooling minimum air flow fraction	0
Cooling design air flow method	Flow/ zone
Cooling design air flow rate (m^3/s)	0
Cooling minimum air flow (m^3/s)	0
Heating Sizing Parameters	
Zone heating design supply air temperature (°C)	40
Zone heating design supply air humidity ratio	0.008
Zone heating sizing factor	0
Heating maximum air flow per zone floor area ($m^3/s.m^2$)	0
Design zone air distribution effectiveness in heating mode	1
Heating maximum air flow fraction	0
Heating design air flow method	Flow/ zone
Heating design air flow rate (m^3/s)	0
Heating maximum air flow (m^3/s)	3

APPENDIX VI- OpenStudio Simulation Settings

```
Simulation Control,
  Yes,                          !- Do Zone Sizing Calculation
  No,                           !- Do System Sizing Calculation
  No,                           !- Do Plant Sizing Calculation
  Yes,                          !- Run Simulation for Sizing Periods
  Yes;                          !- Run Simulation for Weather File Run Periods

Convergence Limits,
  1,                            !- Minimum System Timestep {minutes}
  ,                             !- Maximum HVAC Iterations
  4,                            !- Minimum Plant Iterations
  10;                           !- Maximum Plant Iterations

Heat Balance Algorithm,
Conduction Transfer Function,   !- Algorithm
200,                            !- Surface Temperature Upper Limit {C}
0.1,                            !- Minimum Surface Convection Heat Transfer
Coefficient Value {W/m2-K}
1000;                           !- Maximum Surface Convection Heat Transfer
Coefficient Value {W/m2-K}

Run Period,
Run Period 1,                   !- Name
1,                              !- Begin Month
1,                              !- Begin Day of Month
12,                             !- End Month
31,                             !- End Day of Month
Sunday,                         !- Day of Week for Start Day
No,                             !- Use Weather File Holidays and Special Days
No,                             !- Use Weather File Daylight Saving Period
```

No, !- Apply Weekend Holiday Rule
Yes, !- Use Weather File Rain Indicators
Yes, !- Use Weather File Snow Indicators
1; !- Number of Times Run period to be Repeated
Shadow Calculation,
Average Over Days in Frequency, !- Calculation Method
30, !- Calculation Frequency
15000, !- Maximum Figures in Shadow Overlap Calculations
Sutherland Hodgman, !- Polygon Clipping Algorithm
Detailed Sky Diffuse Modelling; !- Sky Diffuse Modelling Algorithm

Surface Convection Algorithm: Inside,
TARP; !- Algorithm

Surface Convection Algorithm: Outside,
MoWiTT; !- Algorithm

Timestep,
6; !- Number of Timesteps per Hour

Sizing: Parameters,
1, !- Heating Sizing Factor
1, !- Cooling Sizing Factor
1; !- Timesteps in Averaging Window

Zone Air Contaminant Balance,
No; !- Carbon Dioxide Concentration

Zone Air Heat Balance Algorithm,
Third Order Backward Difference; !- Algorithm

Zone Capacitance Multiplier: Research Special,

,	!- Temperature Capacity Multiplier
,	!- Humidity Capacity Multiplier
,	!- Carbon Dioxide Capacity Multiplier
;	!- Gene

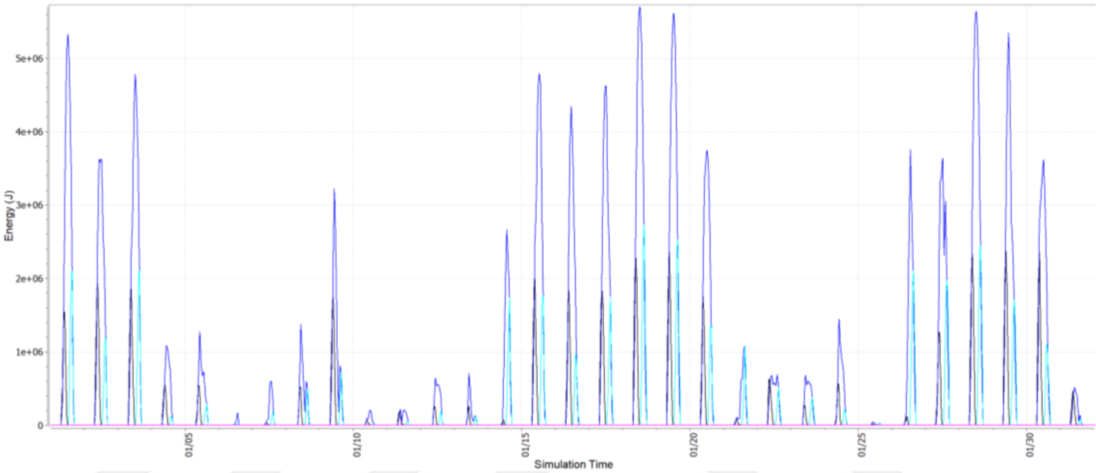
APPENDIX VII- Actual Electricity Consumption Bills of the year 2015

Heating- Cooling Electricity Consumptions (kWh)		Energy Rate	Service Charge	Rate Transferred to Distribution Company					Rate Transferred to Funds and Foundations				Sub Total	Value Added Tax (KDV)	Climatization (TL)
				Leakage/ Loss Rate	Distributio n Rate	Service Charge	Transmissio n System Usage Rate		Energ y Fund	TRT Lot	Electricity Consumption Tax				
		0.19047	0.00995	0.035809	0.0364	0.59	0.008949		1%	2%	5%			18%	
January	121118.67	23069.47	0.00	4337.14	4408.60	0.59	1083.89	9830.22	274.07	548.13	1370.33	2192.53	**35092.22**	6316.60	41408.82
February	93394.08	17788.77	0.00	3344.35	3399.45	0.59	835.78	7580.17	211.33	422.66	1056.66	1690.65	**27059.59**	4870.73	31930.32
March	76158.27	14505.87	0.00	2727.15	2772.08	0.59	681.54	6181.37	172.33	344.66	861.65	1378.64	**22065.87**	3971.86	26037.73
April	33999.98	6475.98	0.00	1217.51	1237.57	0.59	304.27	2759.93	76.93	153.87	384.67	615.48	**9851.38**	1773.25	11624.63
May	4559994	8685.42	0.00	1632.89	1659.79	0.59	408.07	3701.34	103.18	206.37	515.92	825.46	**13212.23**	2378.20	15590.43
June	68800.00	13104.34	0.00	2463.66	2504.25	0.59	615.69	5584.19	155.68	311.36	778.40	1245.44	**19933.95**	3588.11	23522.06
July	118106.33	22495.71	0.00	4229.27	4298.95	0.59	1056.93	9585.75	267.25	534.50	1336.25	2138.00	**34219.46**	6159.50	40378.96
August	187489.48	35711.12	0.00	6713.81	6824.43	0.59	1677.84	15216.67	424.25	848.50	2121.25	3393.99	**54321.79**	9777.92	64099.71
Septembe r	107677.90	20509.41	0.00	3855.84	3919.37	0.59	963.61	8739.41	243.65	487.30	1218.26	1949.22	**31198.03**	5615.65	36813.68
October	45603.39	8686.08	0.00	1633.01	1659.92	0.59	408.10	3701.62	103.19	206.38	515.95	825.53	**13213.23**	2378.38	15027.75
November	21311.22	4059.15	0.00	763.13	775.71	0.59	190.71	1730.14	48.22	96.45	241.11	385.78	**6175.08**	1111.51	7286.59
December	56293.85	10722.29	0.00	2015.83	2049.04	0.59	503.77	4569.23	127.38	254.76	636.91	1019.05	**16310.57**	2935.90	19246.47
Total	**975553.10**														332967.15

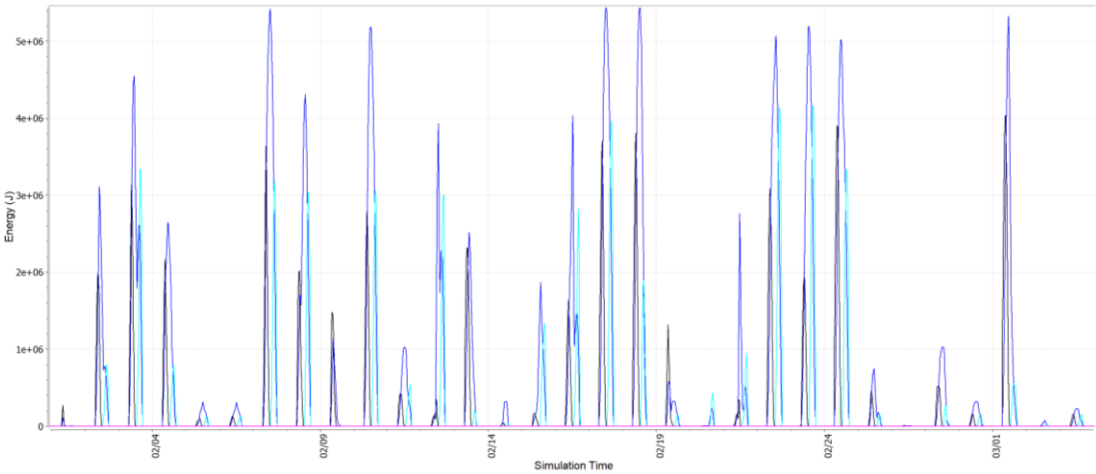
APPENDIX VIII- Case 2; Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy Line Graphics (Annual)

(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 19
(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 21
(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 23
(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 25

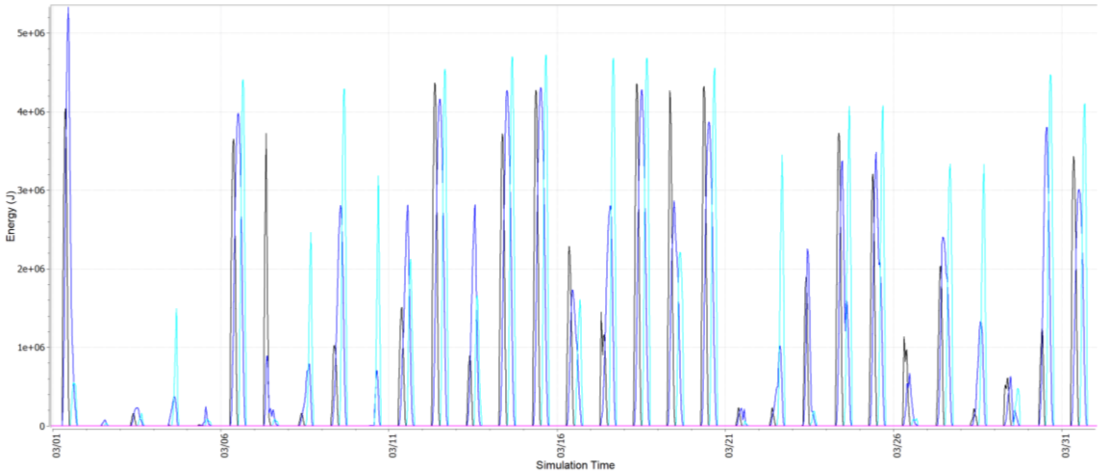
January 2015



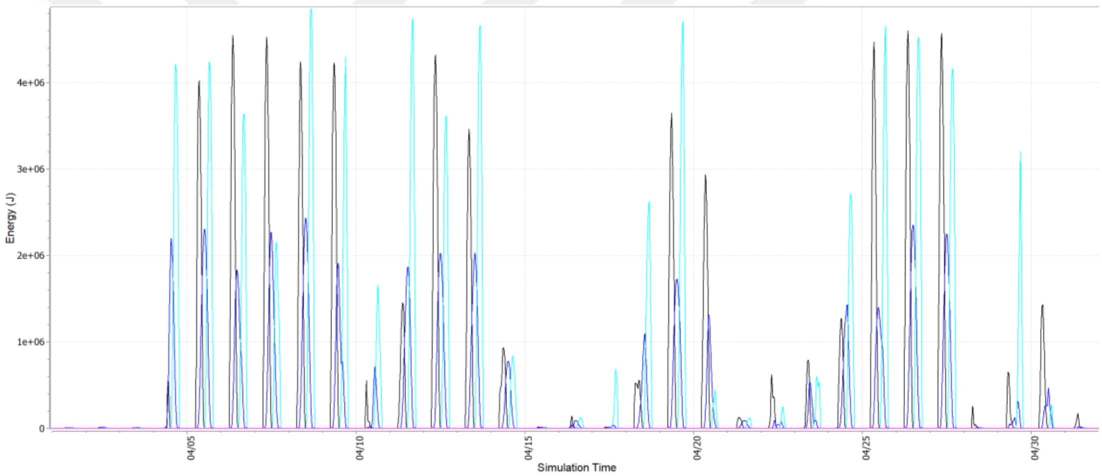
February 2015



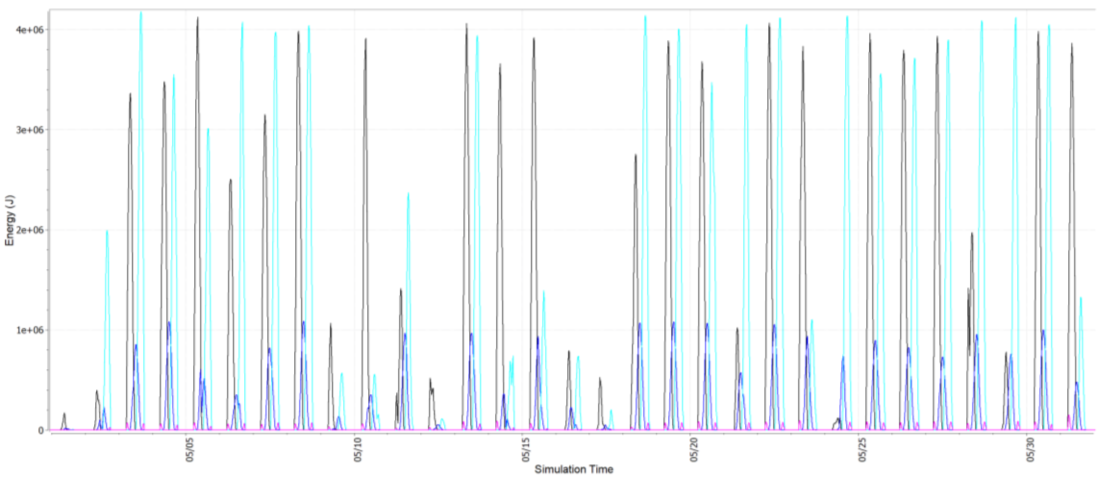
March 2015



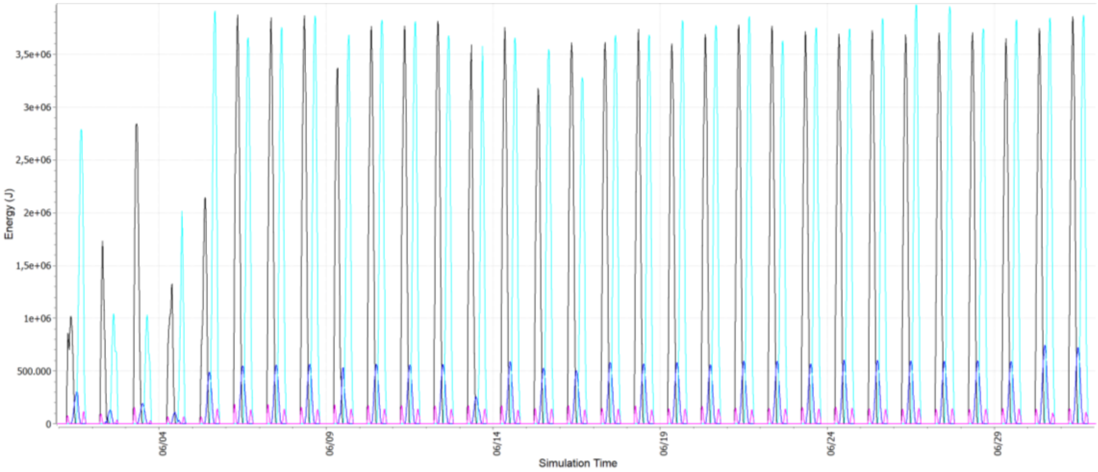
April 2015



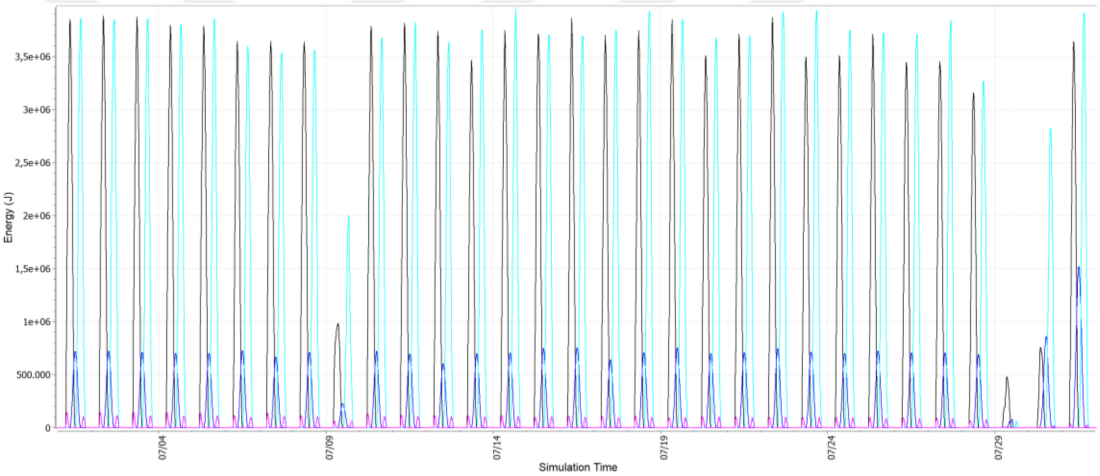
May 2015



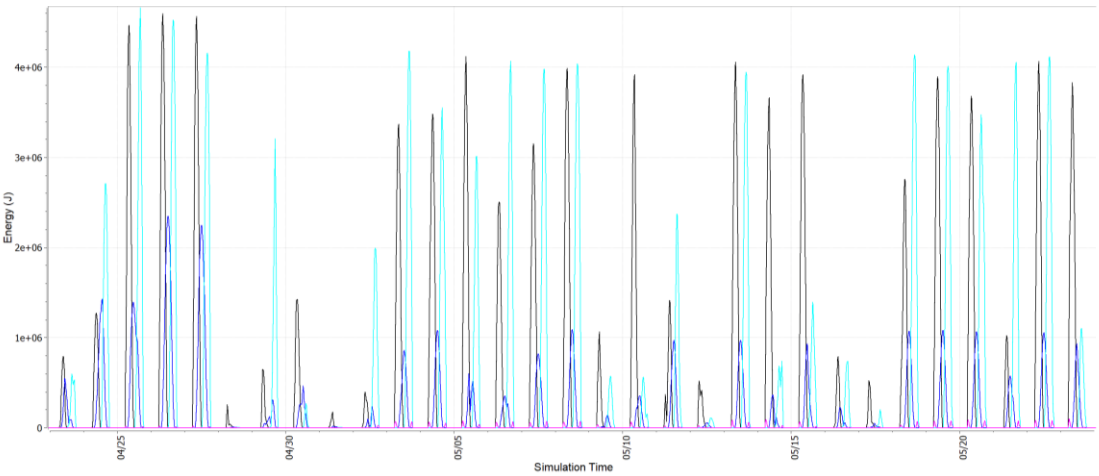
June 2015



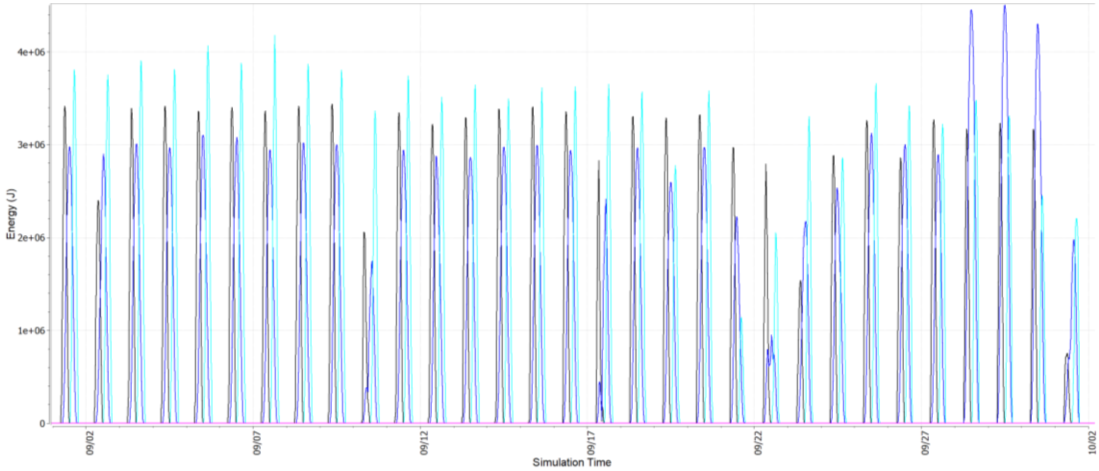
July 2015



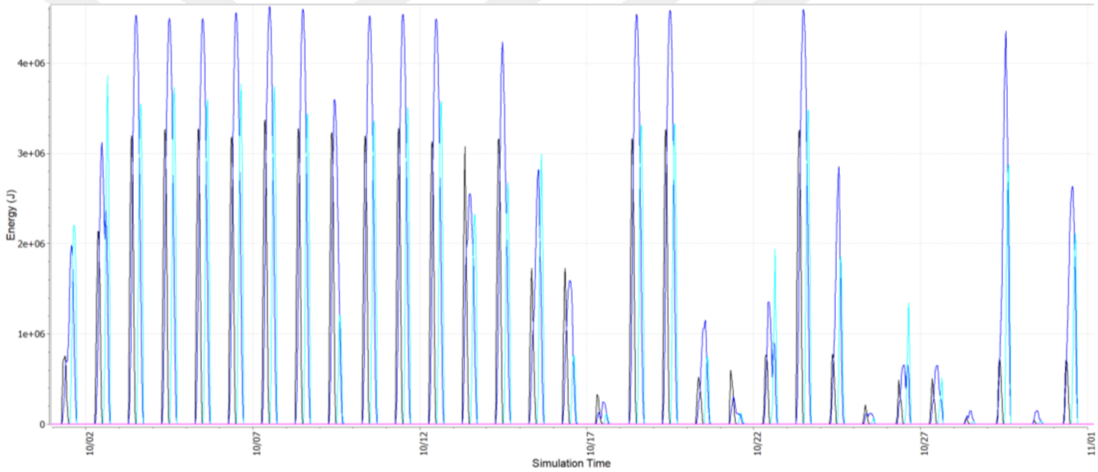
August 2015



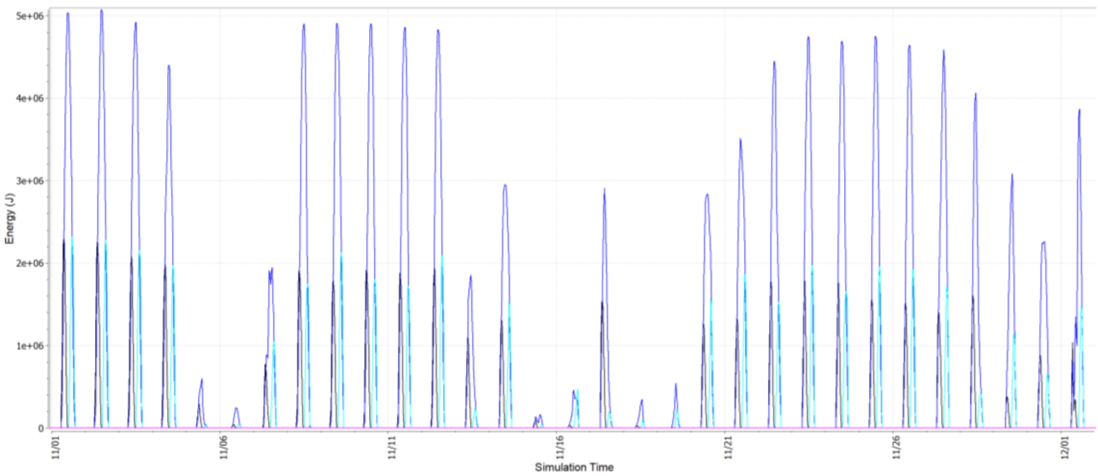
September 2015



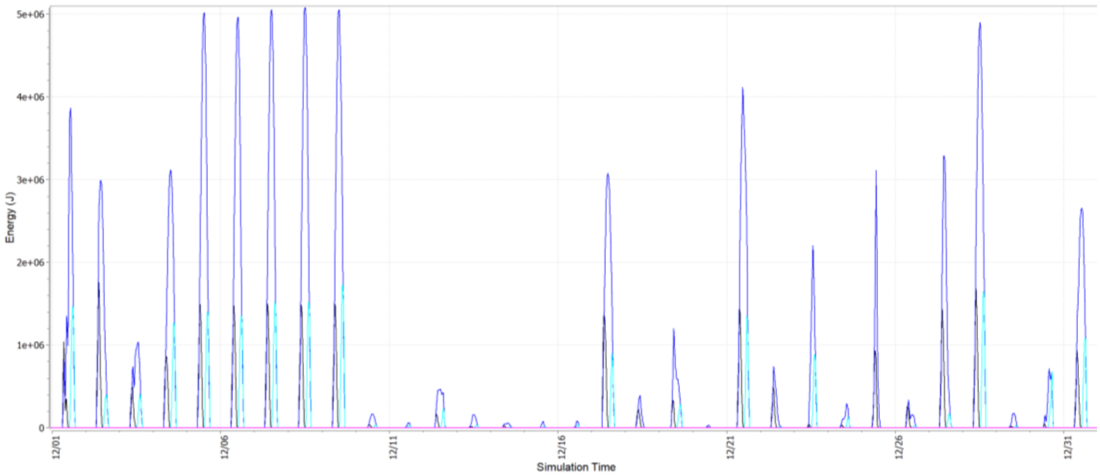
October 2015



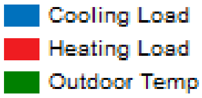
November 2015



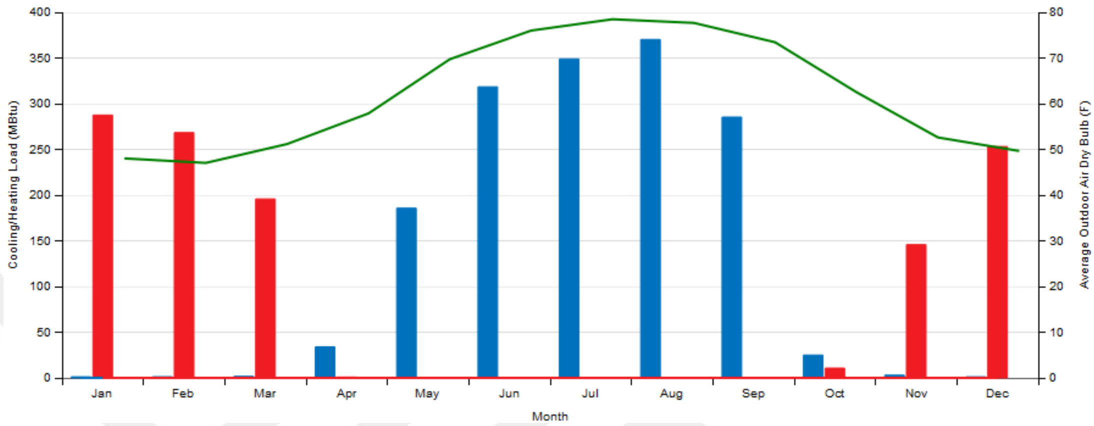
December 2015



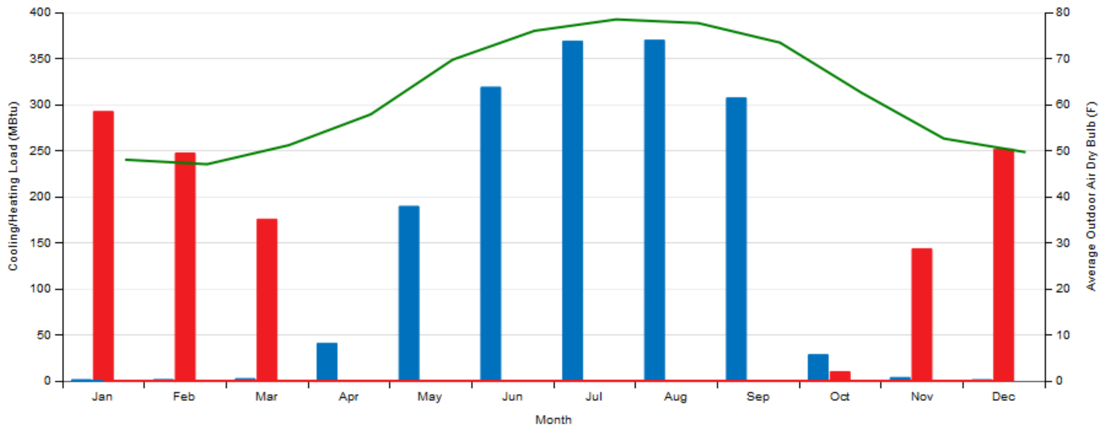
APPENDIX IX- Annual Heating - Cooling Loads



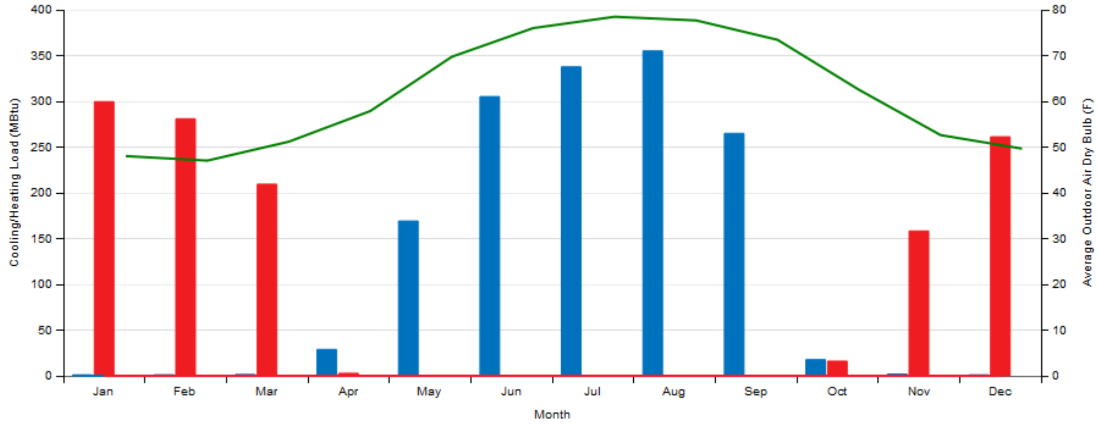
CASE 1



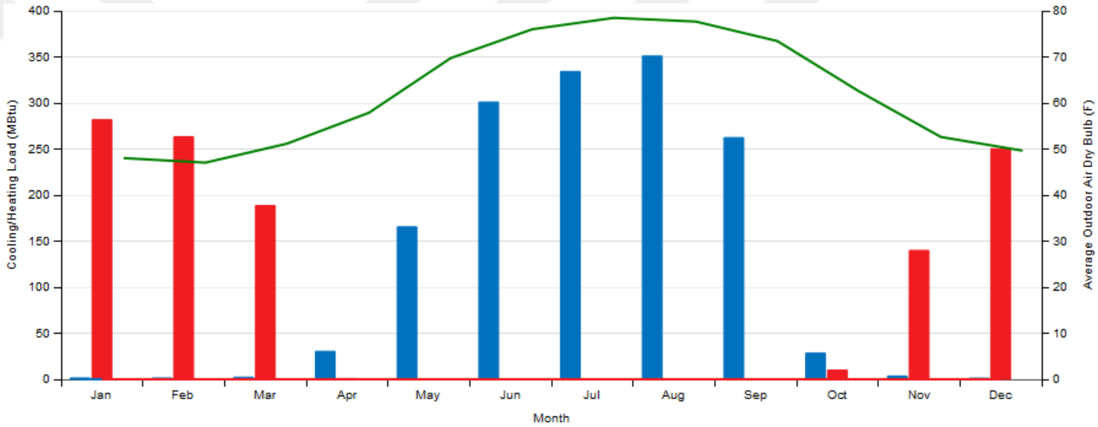
CASE 2



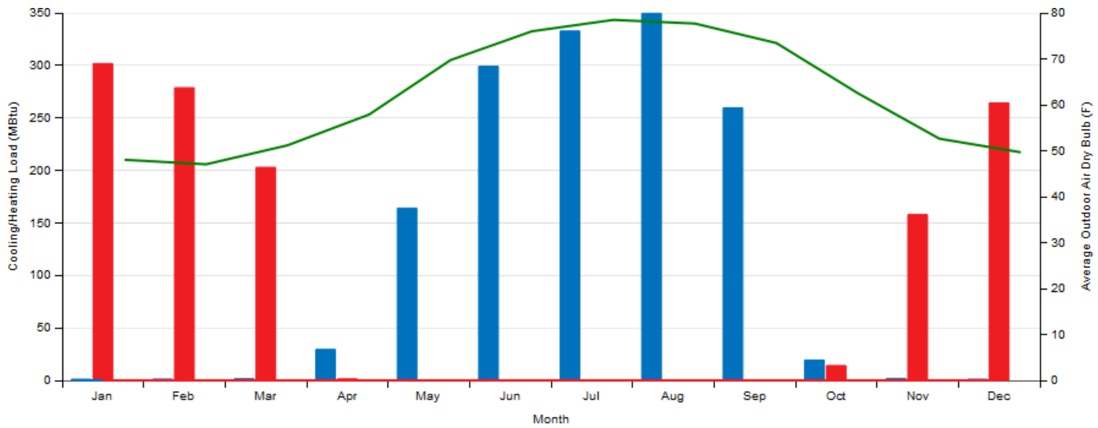
CASE 3



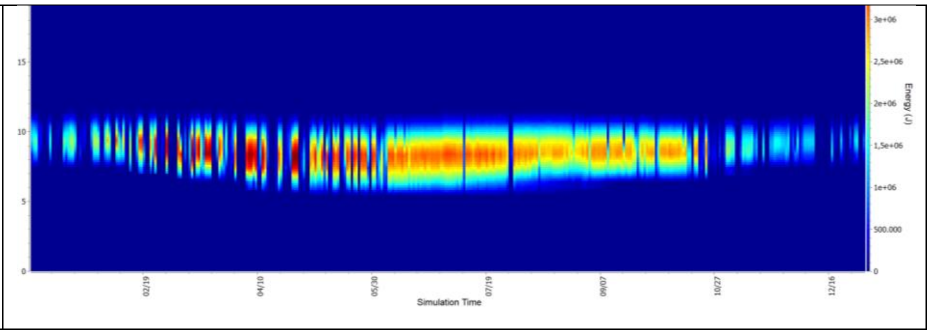
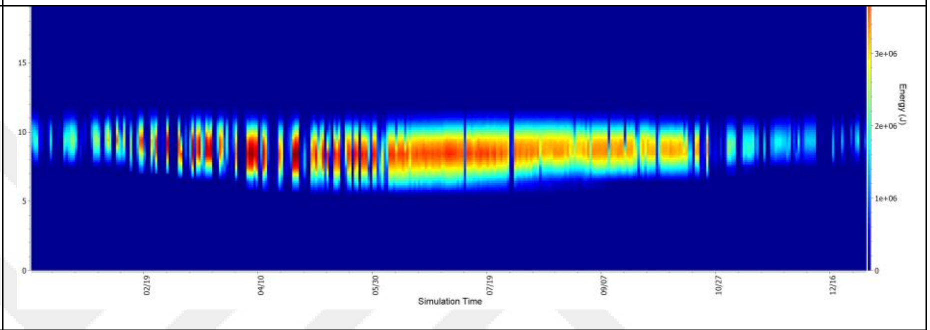
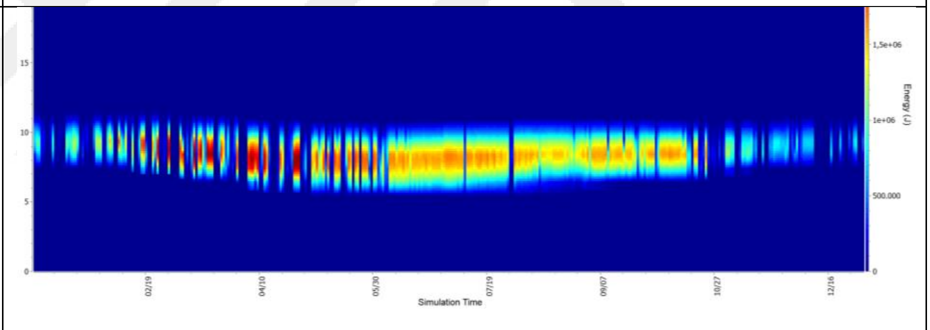
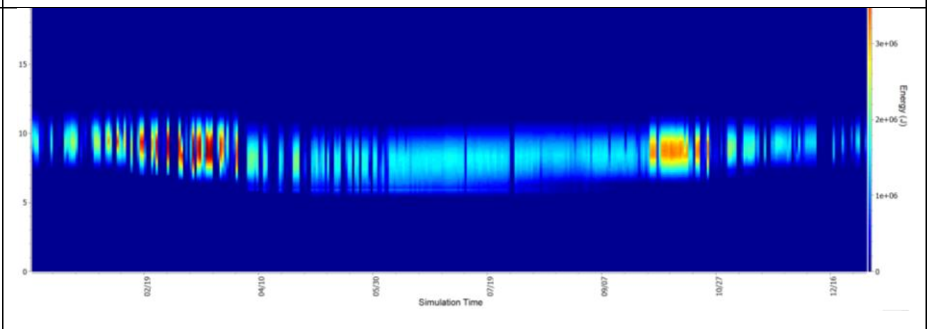
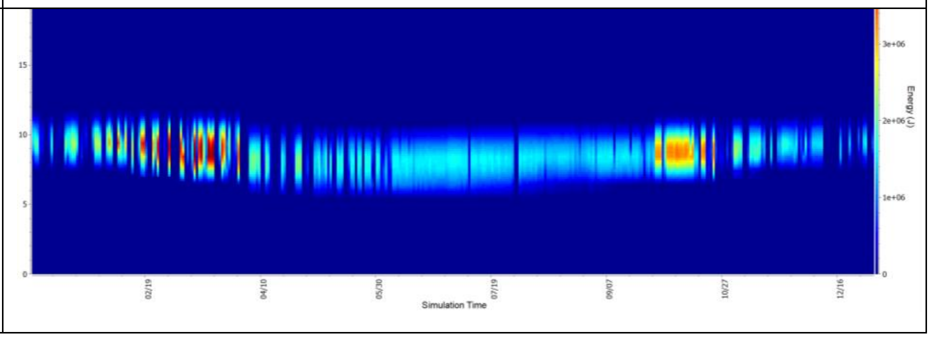
CASE 4

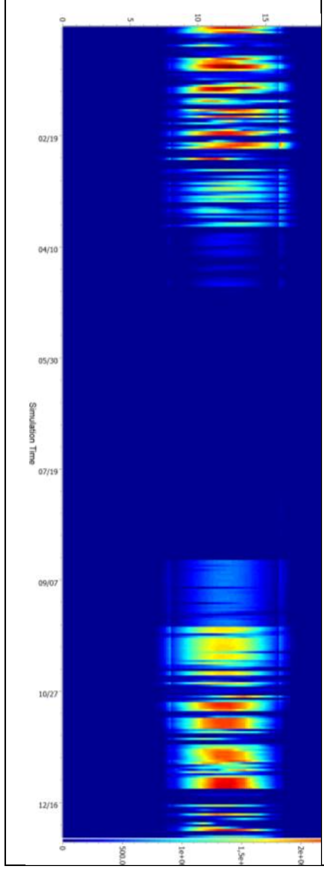
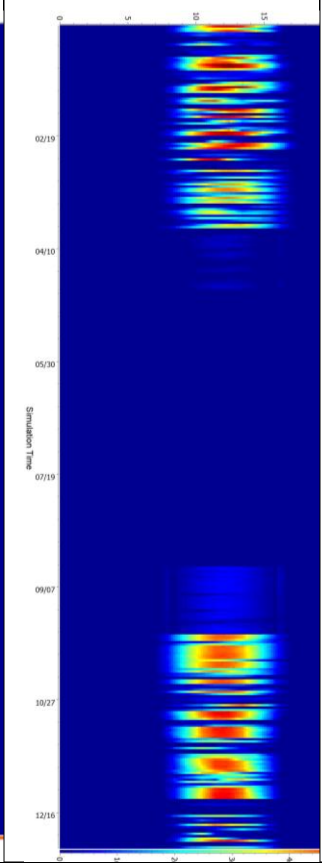
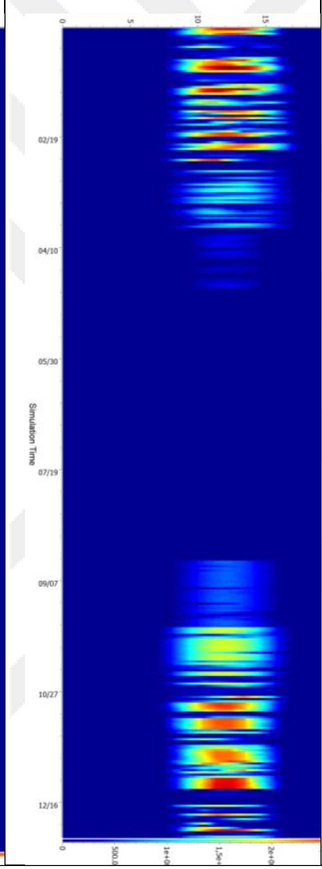
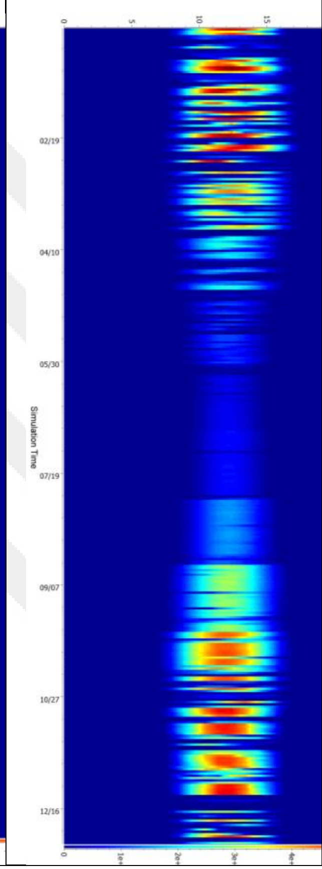
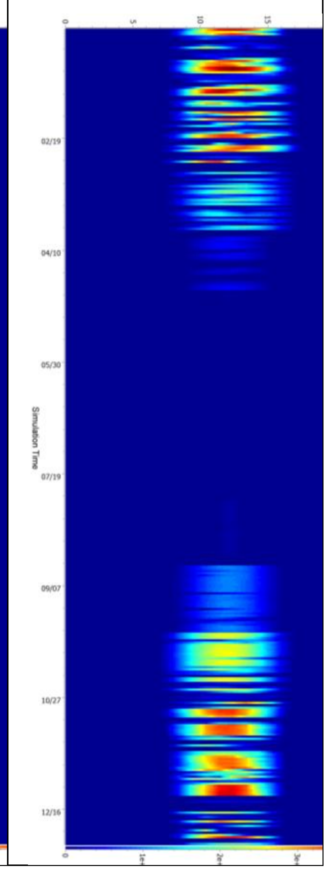


CASE 5



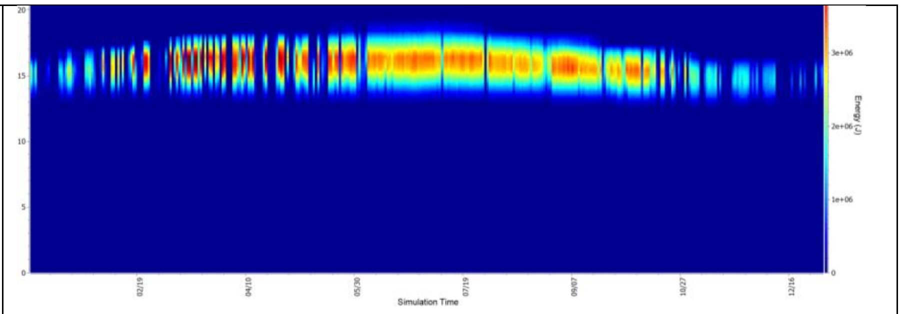
APPENDIX X- Case 2; Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy Flood Graphics (Annual)

THERMAL ZONE 19- Eastern Façade	CASE 1	
	CASE 2	
	CASE 3	
	CASE 4	
	CASE 5	

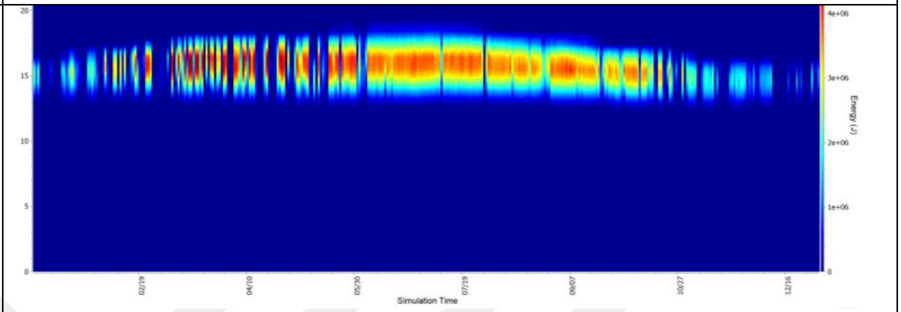
THERMAL ZONE 21- Southern Façade				
CASE 5	CASE 4	CASE 3	CASE 2	CASE 1
				

THERMAL ZONE 23- Western Façade

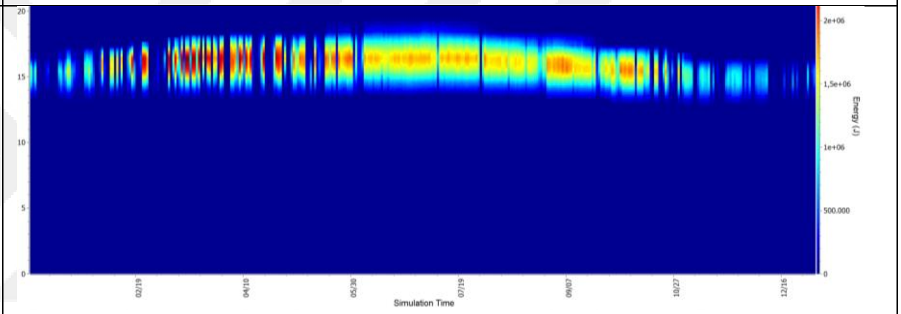
CASE 1



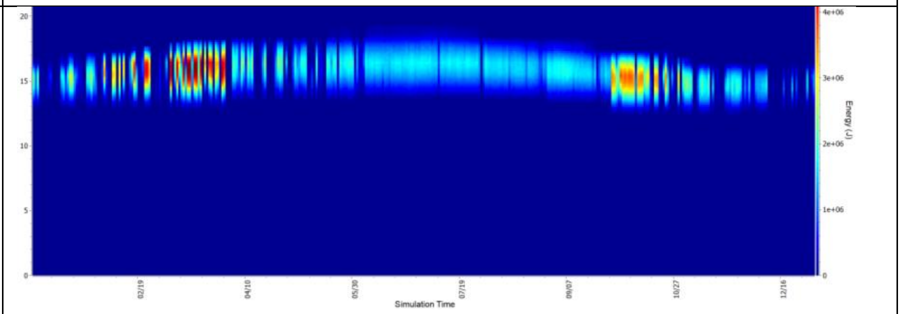
CASE 2



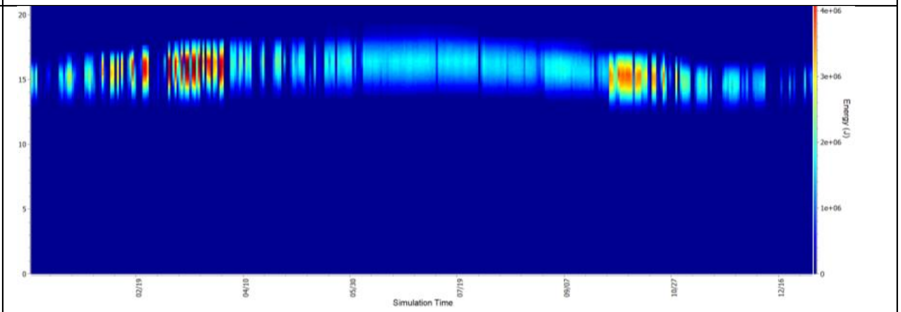
CASE 3

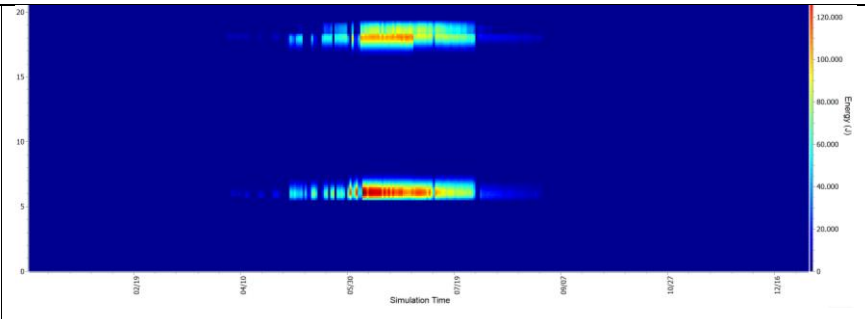
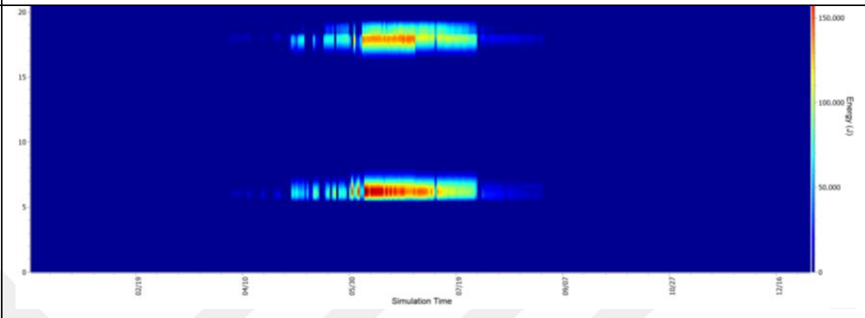
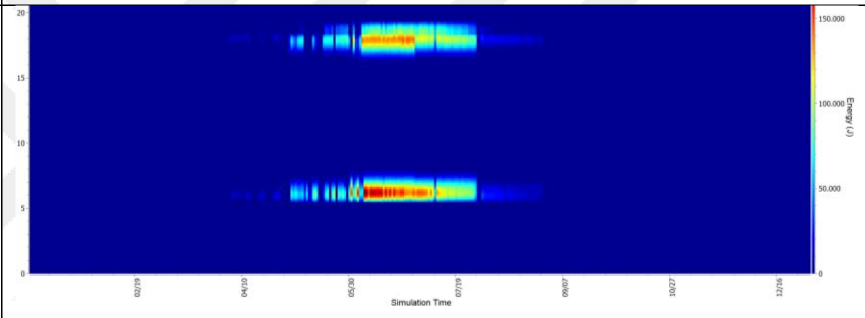
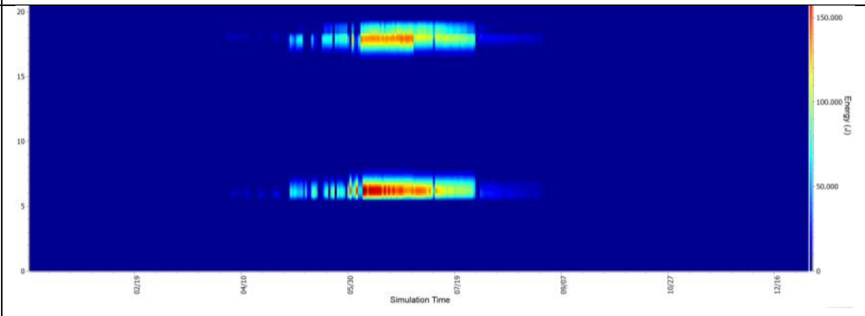
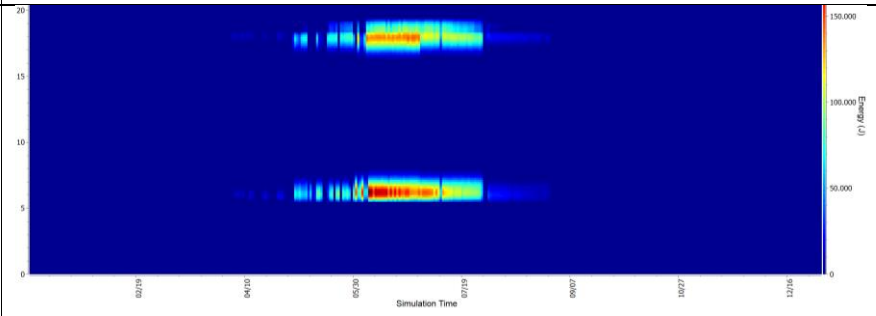


CASE 4



CASE 5



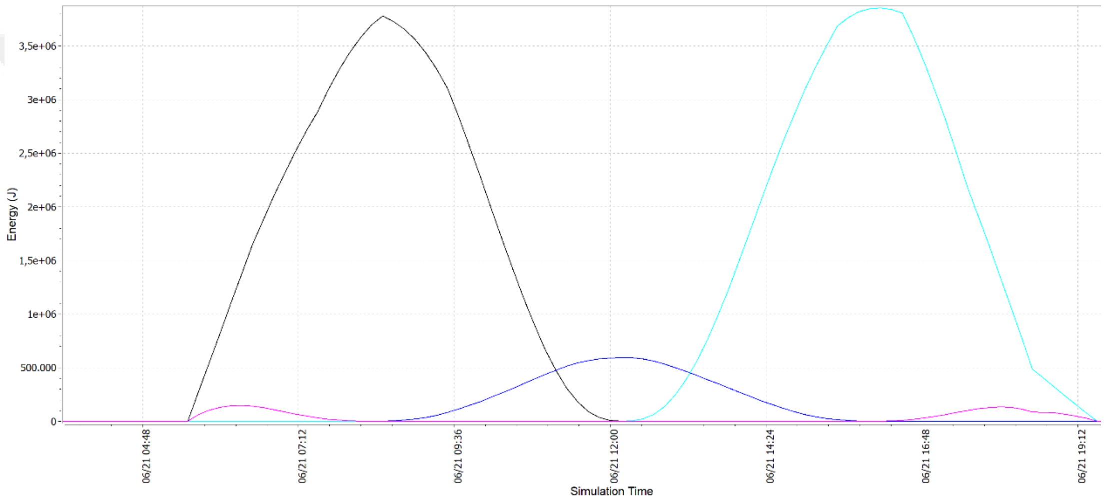
THERMAL ZONE 25- Southern Façade		
	CASE 1	
	CASE 2	
	CASE 3	
	CASE 4	
	CASE 5	

APPENDIX XI- Case 2; Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy Line Graphics (Summer and Winter Solstice Days)

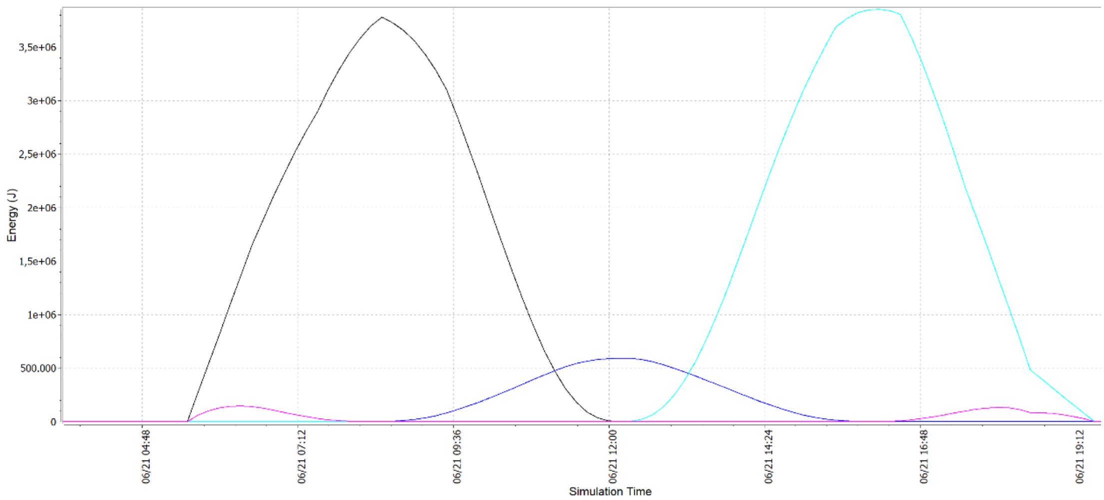
(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 19
(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 21
(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 23
(6-EnergyPlus-0) Zone Exterior Windows Total Transmitted Beam Solar Radiation Energy,THERMAL ZONE 25

SUMMER SOLSTICE (21st of June)

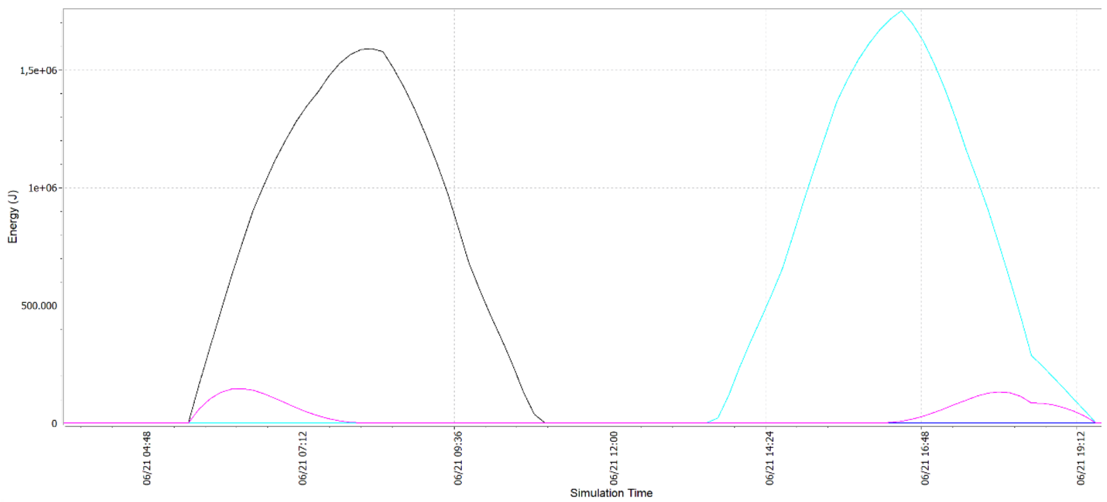
CASE 1



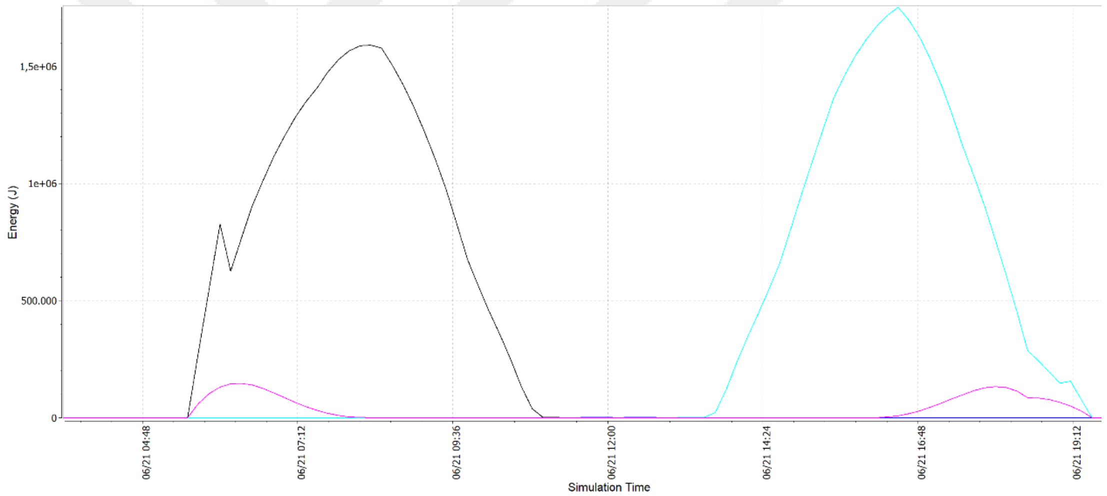
CASE 2



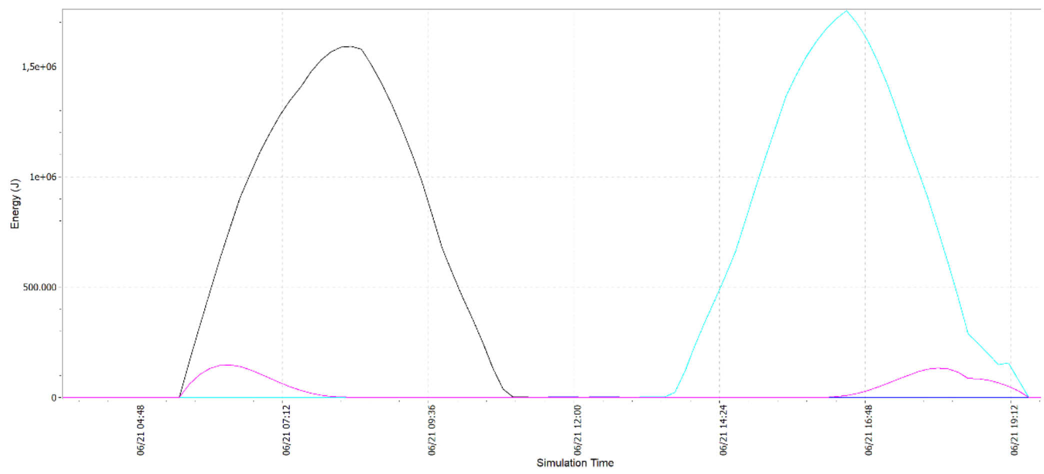
CASE 3



CASE 4

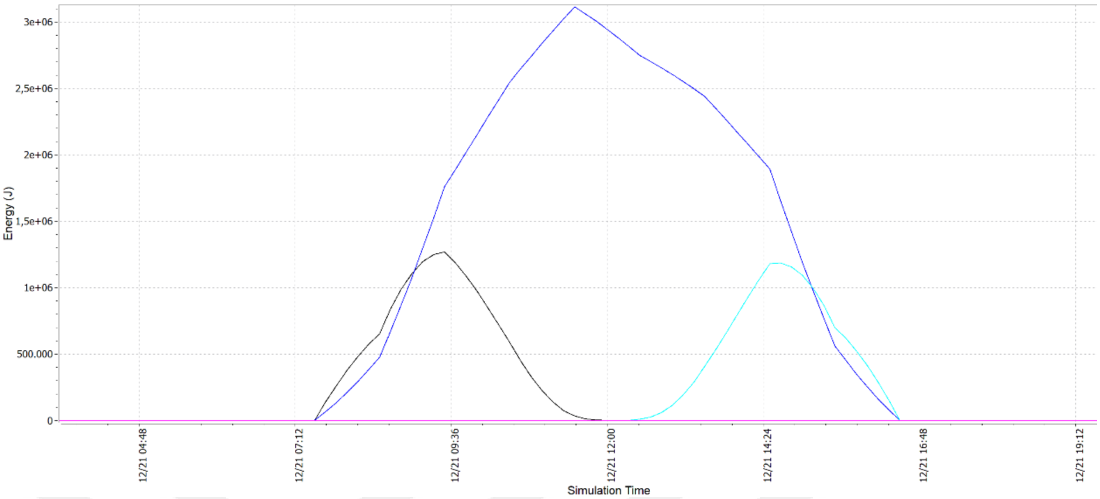


CASE 5

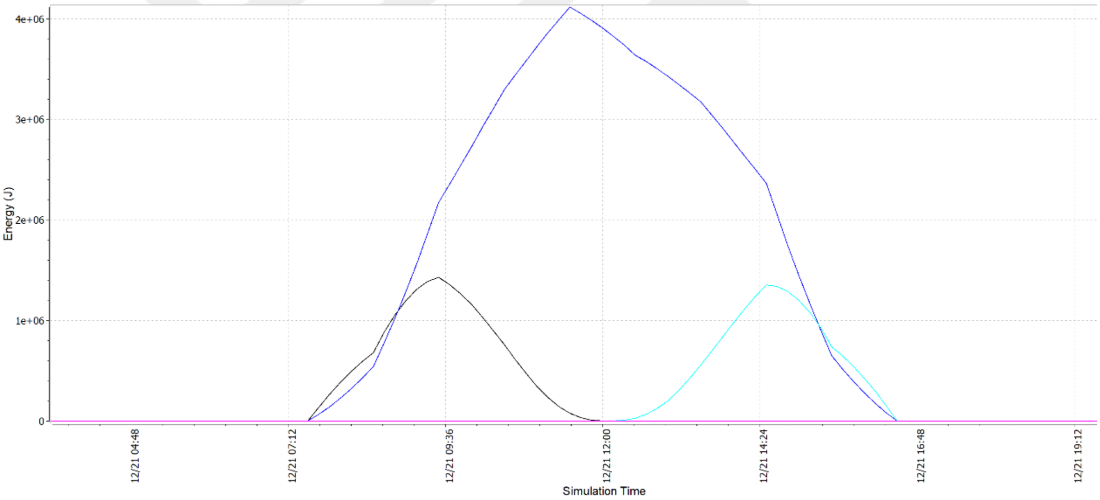


WINTER SOLSTICE (21st of December)

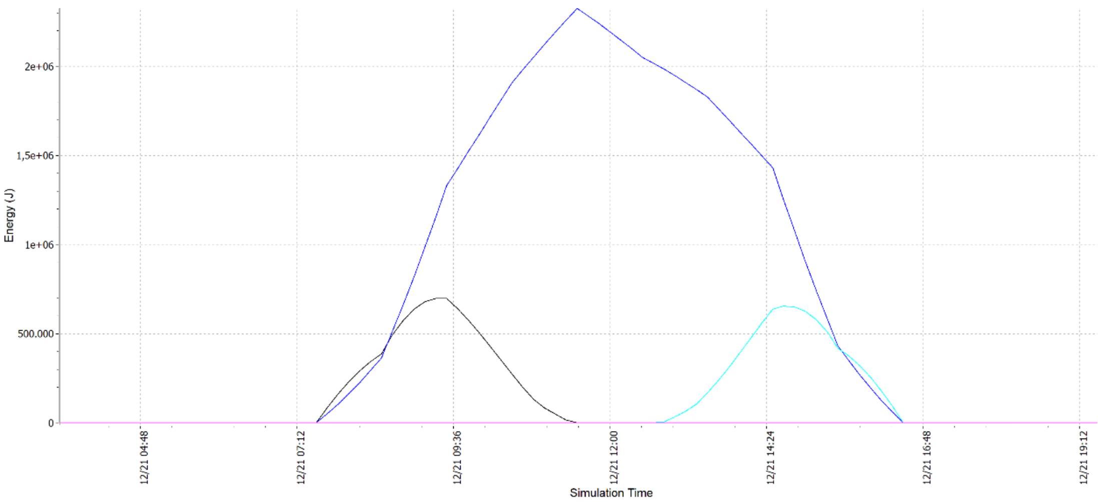
CASE 1



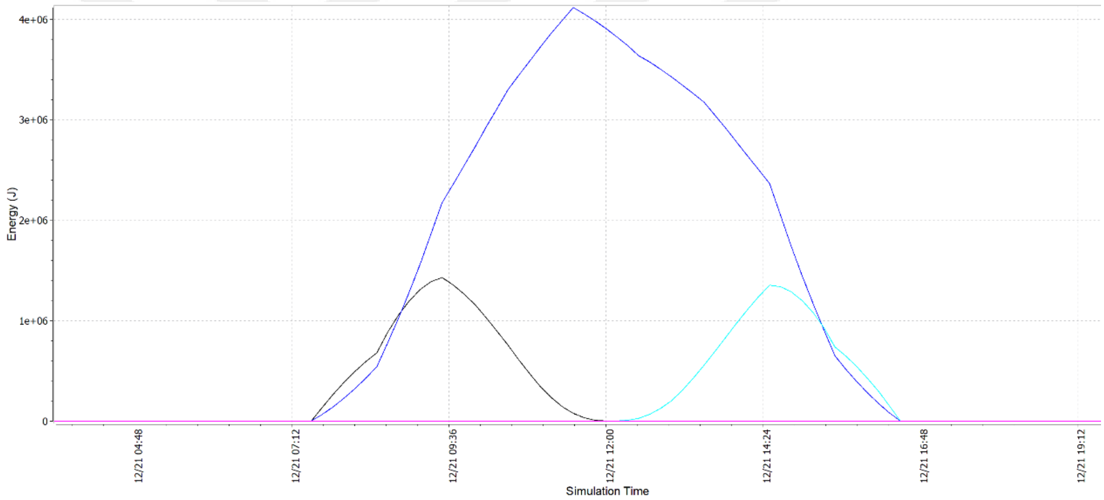
CASE 2



CASE 3



CASE 4



CASE 5