ASSESSING THERMAL PERFORMANCE OF OFFICE BUILDING ENVELOPES; A CASE STUDY ON ENERGY EFFICIENCY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY

BY

AYŞE NEŞEN SÜRMELİ

IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF ARCHITECTURE

IN

THE DEPARTMENT OF ARCHITECTURE

APRIL 2004

Approval of the Graduate School of Natural and Applied Sciences

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ABSTRACT

ASSESSING THERMAL PERFORMANCE OF OFFICE BUILDING ENVELOPES; A CASE STUDY ON ENERGY EFFICIENCY

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April 2004, 93 Pages

In this study, the energy conservation potential of selected retrofitting interventions on an office building were investigated, on the basis of which some rational strategies for the improvement of building envelopes in terms of energy, environment and comfort design were proposed. Examined were various measures on envelope constructions that can be retrofitted to existing buildings. By using simulation techniques, the effectiveness of such measures in reducing energy consumption and environmental threat were also assessed.

Effects of glazing types, effect of insulation and thermal mass were analyzed as energy efficient retrofit measures to the Engineering Building (MM building) situated on Middle East Technical University Campus, Ankara. The Energy-10 computer program was used for the modeling and simulation of the energy flows through the envelope to examine measures for reducing thermal load.

Within this framework, the energy conservation potential of single and combined retrofitting actions was investigated. Based on results from the evaluation model, it was found that a saving of 161.20 MWh in the annual heating load could result, depending on the glazing type. The evaluation showed that thermal insulation is the most effective factor in thermal performance when placed as an exterior layer on walls. The study showed thermal mass has significant impact on increasing the duration, where highest temperatures were achieved, under passive mode. The study also revealed that applying a combination of retrofitting measures which responded to the challenges and opportunities presented by different façade orientations, a saving of 52.41% can be achieved in annual heating energy use in case study building.

Keywords: building envelope, retrofitting office building, energy saving, sustainability, Energy-10.

ÖZ

Ofis Binalarında Yapı Kabuğunun Isıl Performansının Değerlendirilmesi; Enerji Etkin Kullanım Üzerine Örnek Çalışma

Sürmeli, Ayşe Neşen
Yüksek Lisans, Yapı Bilimleri, Mimarlık Bölümü
Tez Yöneticisi: Y. Doç. Dr. Soofia Tahira Elias Özkan

Nisan 2004, 93 Sayfa

Bu çalışmada mevcut bir ofis binasına uygulanacak belli yenileme müdahalelerinin enerji konservasyonu potansiyelleri, binalarda enerji, çevre ve termal konfor açısından incelendi. Çalışmada mevcut binalarda enerji kullanımının azaltılması için bina kabuğuna uygulanacak önlemler analiz edildi ve simülasyon teknikleri uygulanılarak bu müdahalelerin enerji kullanımı ve çevresel zararı azaltma konularındaki etkinlikleri sınandı.

Çeşitli cam tipleri, ısı yalıtım malzemelerinin kalınlığı ve duvarda uygulanma yeri ve ısıl kütlenin etkileri Ankara, Orta Doğu Teknik Üniversitesi kampusunda kullanılan Merkez Mühendislik binasında (MM) yapının kabuğuna uygulanacak enerji etkin yenileme müdahaleleri olarak incelendi. Çalışmada yapı kabuğundaki ısı geçişleri ve yenileme müdahalelerinin termal yükü azaltmadaki etkileri Energy-10 bilgisayar programı ile modellendi.

Çalışma kapsamında incelenen enerji konservasyon önlemleri tek tek ve birleştirilmiş şekilde uygulanarak etkileri değişik durumlarda hesaplandı. Sonuçlara göre incelenen binada cam tiplerine bağlı olarak yıllık toplan ısıtma enerjisinde 161.20 MWh kazanım sağlamanın mümkün olduğu görüldü. Sonuçlara göre ısı yalıtımının duvarlarda dış çeperlere yerleştirildiğinde termal performans açısından en belirleyici faktör olduğu belirlendi. Isıl kütle ile ilgili incelemelerde bu uygulama binada ısıtmanın yapılmadığı pasif moda en yüksek sıcaklıkta kalma süresinin arttırılmasında etkili oldu. Çalışmada farklı cephelerdeki problem ve imkanlar gözetilerek tüm önlemlerin beraber uygulanmasıyla yıllık ısıtma enerjisi kullanımında %52.41 azaltma sağlanabileceğini gösterildi.

Anahtar Sözcükler: yapı kabuğu, ofis binalarının yenilenmesi, enerji kazancı, sürdürülebilirlik, Energy-10.

To my beloved family
Şencan, Nedret and Gülşen Sürmeli
for their support, education and love

ACKNOWLEDGEMENT

I express my sincere thanks and appreciation to Asst. Prof. Dr. Sofia Tahira Elias Özkan, my advisor, for her support and persistent guidance. I would like to thank for her kind approach and insight throughout the study.

I am also grateful to Mr. Uğur Yalçıner for his invaluable contributions. Starting from the first draft he has always helped me with the ideas he suggested and comments in every phase of the study. I would also like to thank him for the time he spent, for his care and continuous encouragement.

Thanks to my room mates; Gönülay Keten, Kader Şahin and Gülbahar Yılmaz for their understanding and help whenever I needed. Thanks to Oya Uslu and Ece Alagöz for their help.

I would like to thank to my faithful friends Melis Gürbüzbalaban, Tuğçe Tağmat, Cenk Çetin, Emre Altürk and Yonca Günday for their support and company.

I would like to thank to my cousin Emre Vural, for his help and for providing me the documents I needed.

Lastly but not the least I would like to express my thanks and love to my family for their continuous encouragement, patience and support during my studies.

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LIST OF ABBREVATIONS

Abbrevations

ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineers
BSP	Building Simulation Program
DOE	U.S. Department of Energy
EMCS	Building Energy Management and Control System
HVAC	Heating Ventilation and Air-conditioning
LBNL	Lawrence Berkeley Solar Group
Low-e	Low-emissivity
MM	Merkez Mühendislik Binası (Engineering Building)
NREL	U.S. National Renewable Energy Laboratory
R&D	Research and Development
R- Value	Thermal Resistance
SHGC	Solar Heat Gain Coefficient
T_{in}	Inside Temperature
T_{out}	Outside Temperature
TSE	Türk Standartları Enstitüsü (Turkish Standards Institute)
U-Value	Thermal Transmittance
UV	Ultra violet

LIST OF UNITS

Units

°C	Centigrade Degree Celsius
kg	Kilogram
kg/m^2	Kilogram per meter square
kg/m^3	Kilogram per cubic meter
m	Meter
mm	Millimeter
nm	Nanometer
Wh/m^2	Watt-hour per meter square
MWh	Megawatt-hours
W/mK	Watt per meter Kelvin
W/m^{2}K	Watt per square meter Kelvin

CHAPTER 1

INTRODUCTION

This chapter presents the argument and objectives of the study and summarizes the way the study has been conducted. It concludes with a disposition of the subject matter, covered in each subsequent chapter.

1.1. Argument

Buildings exist to give shelter, privacy and security to their occupants and equipment. Environmental comfort, economy, and energy conservation are among the major functional considerations in buildings. In most parts of the world, external conditions do not provide adequate thermal comfort for humans and for most human activities. Enclosures must therefore give basic protection from the thermal extremes of the natural environment. In most places, some form of additional energy input will also be required in order to maintain required comfort levels.

In recent years, rapid development of building materials, design procedures and thermal installations together with energy source alternatives have greatly accelerated improvements in thermal standards. This has led to a situation where nearly half of the total energy consumption is used up in providing environmental comfort in buildings. Changing economic circumstances and environmental concerns have made it very important to utilize energy with the greatest possible economy and efficiency.

The energy efficient retrofitting of existing buildings is an important tool for the reduction of energy consumption in the building sector, for the improvement of existing indoor thermal comfort conditions, and also for the improvement of environmental conditions in urban areas. With this point of view, retrofitting of office buildings has gained interest during the past few years mainly due to increasing energy and air-quality problems.

The most important elements that contribute to reduction in the heating and cooling loads of buildings are the proper size and orientation of the solar apertures, types of glazing, the amount and placement of thermal insulation, and the amount of thermal storage mass involved. From the viewpoint of the resulting thermal environment, internal comfort conditions depend on the combined effects of the building form, windows and materials of construction.

1.2. Objectives

The objective of this thesis study was to investigate the energy conservation potential of selected retrofitting interventions on an office building and to propose rational strategies for the improvement of building envelopes in terms of energy, environment and comfort design. This research examined various energy-saving measures on envelope configurations that can be retrofitted to existing buildings and, by using simulation techniques, it assessed the effectiveness of these measures in reducing energy consumption and environmental threat.

Such reductions in heat losses through the building envelope combined with optimized material configuration and the proper amount of thermal insulation in the building envelope help to reduce heating energy demands of the building and production of building related carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxide (NOx) emission into the atmosphere. In addition to these, the aim of interventions on the improvement of the building envelope was to reduce the impact of the outdoor air temperature on the thermal performance of the building.

In light of these factors, in this study various retrofit options on envelope of building have been analyzed and compared with each other for a base case building situated in Ankara. The measures examined, can be categorized under three titles; types of glazing, placement and amount of thermal insulation, and effect of thermal mass.

Effect of glazing types were examined in order to propose a better performing glazing instead of existing ones, which can improve the thermal conditions of building and reduce energy use. The interventions on thermal insulation aim to reduce the heating requirements of the building by taking advantage of the increased thermal resistance of opaque elements by use of insulation material in various thicknesses. The group of interventions on thermal mass, aim to reduce the impact of the outdoor air temperature on the thermal performance of building and minimize the heat losses.

It is hoped that a knowledge of how the case building responded within the computer program to the various energy conservation measures can provide an insight to understand how any other building may respond.

1.3. Procedure

The study was carried out on an existing building which belongs to the department of Engineering Science located on the M.E.T.U campus, by using a computer program to calculate its thermal loads and greenhouse gas emissions. By altering the computerized models of the building, new outcomes were used to determine the optimal properties of the components of the building envelope such as: thickness, conductivity, heat capacity, glazing type.

Manual methods can not explore the advantages and disadvantages of varying measures in depth, and thoroughness can be provided by using computer. Computers are able to conduct the repetitive cycles of thermal analysis and provide experimentation of alternative approaches to form material and construction properties while examining many solutions and preconditions.

Accordingly for the analysis of this study the computer software Energy10 was used.

The study procedure can be examined in three stages; the first part of building energy analysis was describing the building to the computer. The second was evaluation of various energy efficient measures separately in terms of their effect on energy loads and environmental concerns. The third step was application of retrofitting strategies which are combinations of the best performing single measures.

At first step, the building was described with information on location; total square footage and use category, and envelope materials were defined in detail such as: floor and roof constructions, wall types (material layers and thicknesses) and window configurations (area and glazing properties) corresponding to the envelope materials used in existing building. The computer model was used for the accurate description of the building and to make an accurate first assessment of the building's energy performance, indoor environmental quality, and other criteria depending on the use of the building. At this point, critical data on the thermal properties of the building were gathered and evaluated for use in further steps.

For the second step of the study the simulation program was used to assess the effectiveness of proposed retrofitting scenarios aiming to improve the energy performance of the building. The original base case description was modified by applying energy efficient retrofitting strategies to the envelope and then the resulting building scheme is simulated. Thereafter, the simulation results of the modified building were compared with the original *base case* and with the performance goals.

As the third step, properties such as glazing type, insulation placement and thickness and mass effect with the best performance were chosen for the final configuration of the building envelope through the analysis of single measures. The virtually retrofitted building was then simulated and the energy conservation and measures of environmental considerations were compared with that of the base case.

1.4. Disposition

The information covered in this research study is presented in five chapters, of which this introduction is the first.

The second chapter is a brief summary of literature on the subject matter. It covers the concept of energy efficient building design and issues related to thermal principles, elements of building, properties of transparent and opaque elements and their thermal effects. The use of simulation techniques and building renovation for energy efficiency are also described, as it is essential to have a preview on these subjects to conduct a study in this field.

In the third chapter the input data referring to examined case study building, weather data and simulation program, which are used for the analyse, are described. The method used to conduct the study is defined in detail.

The fourth chapter is the presentation of results. The data are displayed in figures and tables and the outcomes are discussed in this chapter.

The fifth and the last chapter is the conclusion in which the study and results are summarized.

CHAPTER 2

LITERATURE SURVEY

To evaluate and examine the thermal performance and energy requirement of a building one has to be aware of the concepts covered in this area. This chapter covers the relevant information in the literature regarding to the subject and methodology of this thesis study. In first three sections, energy demand in buildings, energy efficient architecture and elements of thermal comfort are discussed. Then the envelope components and their properties such as mass, thermal insulation, absorbtivity, and solar control effects are defined. The design strategies and criterias used in assessing the thermal performance of building envelopes are summarized. In the last two parts the importance and methods of retrofitting office building, use and classification of computer aided building energy simulation and previous studies on these subject matters are covered.

2.1. Thermal Performance in Architecture

The increasing concern for environmental impacts of buildings and the quality of interior environments brought into focus the role architects should play in the environmental design of buildings. With the present debates on the use of energy, not only because of cost and scarcity of fossil fuels, but also because of its implications from the view point of carbon dioxide emissions and global warming, the dynamics of thermal comfort has gained an increased importance.

Givoni (1976) defines thermal comfort as follows;

> "The maintenance of thermal equilibrium between the human body and its environment is one of the primary requirements for health, well being and comfort. It involves keeping the temperature of the core tissues of the body within a narrow range, regardless of the relatively wide variations in the external environment" (Givoni, 1976; p. 19)

Comfort is a subjective matter and varies with individuals. Straaten (1967) states that the sensation of warmth or cold are purely subjective and depend on many issues such as age, sex, state of health, type of clothing, etc. therefore the general practice is to define a range of conditions, which is called comfort zone, instead of specifying a point of optimum thermal comfort. Providing this comfort zone depends on a wide range of factors, which are classically classified as follows;

air temperature and temperature gradients
humidity
amount of clothing worn by occupant
occupants level of activity

Daniels (1997; p.36) asserts that buildings are environments for people. In the case of office and work environments, productivity levels are very important, and all steps should be taken to optimize ambient conditions and thermal comfort. In addition to physical conditions of comfort, psychological comfort must also be taken into account. Acoustic and light conditions, air quality (like existence of odour, viruses and fungi), visual comfort conditions (having outside view) are all important on maintaining comfort zones.

To be thermally comfortable one must not feel too hot or too cold. This means that the body has to have a thermal balance with the environment that surrounds it. People feel comfortable if they can maintain a thermal balance without spending much effort. Considering these factors there are certain ranges that provide these comfort levels. Watts (1999) defines these limits as follows:

> "Comfort levels will obviously fall well within these limits of shivering and sweating. The physics of heat transfer would suggest that optimal conditions

> will depend on person’s activity and clothing. In casual summer clothing- tee shirt, shorts and sandals – the optimum temperature for sedentary work at 50% relative humidity is about 25-26 °C. For more formal and winter clothing- for example suits- the optimum temperature is 20-21 °C” (Watts, 1999; p. 13).

Climate as well as season also influences comfort. Although one may be able to control the internal building environment, the external climate is beyond control but can be accommodated using the building envelope and its interaction with the exterior. The major climatic elements interact with each other and effect the sensation of thermal comfort. Busch (1996; p.115-118) lists these elements as: temperature, humidity, solar gain and wind. These elements have been combined into a graphic form known as the bioclimatic chart by Olgyay (1973). The aim of this chart is to identify the combinations of climatic elements where a human feels comfortable. Outside of this comfort zone, energy must be used to change the value of one or more of the elements to move the combination of elements back into the comfort zone.

It is important to emphasize the comfort levels in energy-efficient buildings. In any case, the occupants’ comfort is the main focus of the building’s energy consumption, so any research must reflect an understanding of the occupants’ comfort needs. The thermal comfort conditions, maintained in an inner space of a building, are directly related with the heat transfer that occurs between inner and outer environment or adjacent inner environments (Givoni, 1976; p.41-43).

2.2. Energy Efficiency

Buildings are energy intensive in their construction and operation. According to the World Watch Institute about 40 percent of the world's total energy usage is dedicated to the construction and operation of buildings. Buildings consume energy, from the mine to foundry to construction site. This energy use has serious impacts on the environment. Buildings account for about one-third of the emissions of heat-trapping carbon dioxide from fossil fuel burning and two-fifths of acid rain-causing sulfur-dioxide and nitrogen oxides. Construction and operation of buildings also contribute to other side effects of energy use, including oil spills, nuclear waste generation, river damming, toxic run-off from coal mines, and mercury emissions from coal burning (World Watch Institute, 1992, 1995).

In addition to conserving the environment, there are also commercial benefits of energy efficiency which are being recognized by both designers and clients. Kreith (1997) states that by applying energy efficient building design principles, developers can build cheaper and simpler buildings, owners pay lower running and maintenance costs, and users are more productive and healthier in the better indoor environments which can accompany energy efficiency in buildings.

In the period between 1973 and 1985, as a result of two oil crises, the ratio of final energy consumption to gross domestic product improved by more than 20 precent in Europe (Roaf and Hancock, 1992). In this case these reductions were largely due to high energy prices but later environmental concerns and reaction to global pollution followed this interest. Energy efficiency is now also recognized as a primary mechanism to limit environmental damage caused to our planet by energy use. With this perspective, environmentally benign buildings are the ones that do not harm the people who make them, nor the occupants, and use a minimum of energy in their manufacture and maintenance.

Wigginton and Harris (2001; p.14) state that the ecological goal in building design should be to strive for a reduction in the total primary energy needs to a minimum, and ideally down to zero, by using renewable resources and incidental heat gains to drive a building’s comfort system, and with the minimal use of continual importing of energy to maintain comfort.

Buildings offer enormous scope for energy savings, especially by applying technical aids and using all passive meanings provided by building’s fabric. For a building as a whole, however, a precise definition of efficiency remains elusive as it covers a wide variety of input and output parameters. Kreider and Rabl (1994) define efficiency as follows;

> “An efficient building is one that provides the required conditions of comfort, convenience, etc., under the specified conditions of utilization for the lowest life cycle cost” (Kreider and Rabl, 1994, p. 696).

To achieve these specifications, buildings must be designed by considering the external conditions and their environment that surround them. In that means environment is a parameter which is mostly related with the site of the building. Climatic conditions, wind patterns which affect infiltration and heat transfer coefficients are important to evaluate in energy use of buildings. Shading must also be taken into account as it effects not only heating and cooling loads but also day lighting. The amount and the quality of solar radiation and its exploitation for lowering the energy consumption of buildings are also directly related with environment and orientation of a building. (Kreider and Rabl, 1994)

Choice of materials, the structure of building and the air conditioning equipment are other factors to design an energy efficient building. Hawkes (1996; p.41) emphasizes that the structure and the envelope of the building carry great importance in energy efficient design as these are the elements to mediate between internal and external environment. The main effects of the structure on the thermal behavior of a building can be characterized by the following variables; total heat transmission coefficient, air exchange rate due to infiltration and/or ventilation, thermal mass and solar heat gains. (Givoni, 1976; p.120-121)

Choosing air conditioning equipment with high efficiency is the basic strategy to follow in an energy conscious building design. The efficiency of heat pumps and chillers depends not only on the machine itself but also on the method of extracting and rejecting the heat. The smaller the temperature difference across which heat is to be pumped, the higher the performance of the equipment. The design and placement of air diffusers must not also be neglected. (Hyde, 2000; p.77)

2.3. Energy Demand in Building

Mainly man-made environments consume energy during two processes. The first occurs during the construction period where raw materials; stone, wood, clay, steel, concrete etc. are transformed into building elements. The energy consumed through this process is also called embodied energy. This energy which is used for construction is reflected in the initial building cost and represents a large expenditure (Smith, 2001). Stein (1977) indicates that embodied energy may be as much as 20-30 precent of the energy required to operate the building over a 30-year life time.

The second energy consuming process is the environmental control of built environment. This is called operational energy that is used to maintain thermal, acoustical and security functions of the building. Vandenberg (1980) states that the method and technology for environmental control in buildings have evolved in history. Primitive and agricultural societies were using fire for heating and lighting purposes whereas with industrialization and spread of urban settlements, use of fossil fuels and electricity became the means of energy supply for interior environments.

The energy used during the operation of buildings can be expressed in terms of building loads. Busch describes building loads as follows;

> “A building load is an effect imposed on a piece of equipment, as in a heating or cooling load, or imposed on the electrical system, as in a direct electrical load….a space-heating or –cooling load is defined as the net heat loss or gain resulting from a set of conditions. Heating and cooling loads result from external climatic factors, internal occupancy characteristics, and the building design” (Busch, 1996, p. 127).

Space heating and cooling loads have two components; sensible heat and latent heat. Sensible heat transfer is associated with a change in dry-bulb temperature, which means the heat gain is felt when there is a direct exchange of heat by any or all of the mechanisms of radiation, convection or conduction. Latent heat transfer is associated with a change in humidity ratio or moisture content of air (Hunn, 1996).

Busch (1996; p.129) refers to four major components of space heating and cooling loads; solar heat gain through apertures, heat conduction, ventilation/infiltration and internal loads. The first three of the space heating and cooling load components are determined by characteristics of the building envelope. The load types affecting the building envelope, most often associated with energy consumption is the climate driven load imposed externally on the building, which is the result of the time-series driving functions of ambient temperature, solar radiation, humidity and wind. Climate driven loads are dynamic in that they change from hour to hour and are approximately periodic in that they tend to repeat themselves on a diurnal cycle. The principal part of the envelope load is proportional to the difference in dry bulb temperatures between outdoors and indoors.

The variation of temperature, solar radiation, and activities during a day, as influenced by thermal mass in the building structure and the response of the heating, ventilating and air conditioning (HVAC) system all interact to affect thermal comfort. This complex interaction of the envelope loads also affects the load timing, which in turn determines the peak load imposed on the HVAC system; these peak loads have a major impact on energy use (Hunn, 1996; p.83).

2.4. Properties of Envelope Elements

> “The envelope of a building separates the indoor space from the external environment and in this way modifies or prevents the direct effect of climatic variables such a outdoor air temperature, humidity, wind, solar radiation, rain, snow, etc. this envelope is usually composed of two types of material, opaque and transparent, although translucent materials are sometimes included” (Givoni, 1976, p. 120)

The building envelope may be defined as the totality of building elements made up of components which separate the indoor environment of the building from the outdoor environment. The building envelope is designed with respect to various determinants such as environmental, technological, socio-cultural, functional or aesthetic factors (Vandenberg, 1980).

When we consider the energy problem, another objective must be the reduction of energy consumption and energy expenses to a minimum. This requires a design of the building envelope as an element of a passive system with optimal performance with respect to control of heat, light and sound. Such a design of the building envelope will result in an increased performance of its passive system, which in turn will reduce the load of the active systems (Oral, Yener and Bayazit, 2004).

The envelope, which represents only about 10-20 percent of initial building construction costs, modifies or prevents the direct effect of climatic variables and by the way it has an important influence on the operational and maintenance costs throughout the life of building to maintain internal comfort conditions. The rising concern for thermal performance has made the design of the envelope more important with energy conservation measures and rapid technological evolution of building materials (Rivard, H., C. Bedard, K.H. Ha, P. Fazio, 1999).

Vandenberg (1980) states that in his efforts to achieve environmental control, man has always had two kinds of resources that he could manipulate to modify the aspects of the natural environment which did not suit to him: physical barriers and energy. The first and simplest form of barrier between man and climate is clothing. Analogous to clothing buildings form physical shelter for human. But in addition to fabric’s properties the significant substance of mass of building enclosure gives it important thermal characteristic of heat storage capacity. However, physical barriers cannot provide light, although they can control it, and while they can conserve heat, they cannot generate it.

> “In the architectural context, proliferation of new building types and new inadequately understood materials and methods, building ever

> faster to keep up with population and economic growth, substitution of formal controls (eg codes, regulations and zoning rules) for the previous informal controls which expressed a consensus of opinion on the way buildings ought to be built, and satisfying the modern craving for novelty and change, have all combined to disorder the previous underlying unity of purpose, and competence of execution, in creating a built environment." (Vandenberg, 1980; p.14)

Moore (1993) reports that prior to 1800s, architecture was characterized by abundant resources and limited technology. Architects had to utilize the building envelope as the principal mediator between exterior and interior environmental conditions. The building envelope was the principal means of controlling the thermal environment, with the fireplace providing supplemental heat. Architects simply could not afford to ignore the existing conditions of site and, by necessity, depend on the building envelope to admit light and control other environmental variables. This approach has changed with industrial revolution. With the innovations developed during this period, designers were offered the means to free their buildings from the constraints that had forever determined their form.

As a consequence elaborate and expensive air conditioning systems take the place of climate sensitive energy effective control through building fabric.

> 'Economy of structure, space, ornament, labor and construction cost were characteristic of the new international style. This concern for economy did not extend to energy. To the contrary, virtually every technical development that characterized the movement was possible only through a greater use of energy in every phase of the life of building, including component manufacturing, transportation, construction, and particularly operation. In every case, increased energy usage was the price of these developments that freed architecture from the constraints of climate and site.'(Moore, 1993, p.2)

Givoni (1976) states that when the indoor thermal conditions are not controlled by mechanical means, the materials affect the indoor air and surface temperatures and as a result have a direct effect on the occupants' comfort. Even when mechanical control is used, the thermophysical properties of the materials used determine the amount of heating or cooling provided, and the temperature of internal surfaces.

In a cold or cool climate the greater part of the energy consumption in building is due to heat loss during the heating season. The heat loss is transmitted through the perimeter of buildings, partly by conduction and partly by air infiltration and leakage. Simultaneously the outer skin also transmits radiation energy from sun and sky into the buildings, both through opaque surfaces and windows. The situation has a positive and negative side. Dubin and Long (1978) reports that thermal properties of the envelope, which can be used to control these effects, are determined by the combination of wall mass, thermal resistance, insulation location, exterior surface colour and texture, and the type and location of glazing.

In the light of these factors the following sections examine the properties of a building envelope components and their effect on building energy consumption. The search covers thermal performances of opaque and transparent building components and their effect on thermal behavior of interior environment.

2.4.1. Properties of Opaque Components

> "All external heat impacts must pass through the building shell before they affect indoor temperature conditions. As heat flows into the shell material the process is comparable to the absorption of moisture by a porous material; successive layers of the structure become 'saturated' with heat until finally the effect is felt on the inside surface" (Olgyay, 1973, p. 113).

The opaque surfaces of a building are, in general, more benign in their energy impact on the building than are glazed surfaces. The heat transfer through the building envelope is not instantaneous as all opaque surfaces have some qualities of thermal resistance and capacitance. The opaque surfaces occupy a much larger percentage of the total surface than the glazed surfaces, it is appropriate to review the qualities of opaque surfaces and their interactions on energy use of buildings. As a main determinant of the transmission of the physical factors, in order to design an opaque component, decisions must be taken with respect to; the surface properties of the opaque elements (sound absorption coefficient, construction, solar radiation absorption coefficient, etc.), the cross-section properties of the opaque elements (single or multiple layer, total mass, heat conduction coefficients of the materials, etc.), the properties of the different components (door and window area, density, number of layers, total heat conduction coefficient of the component, etc.), the total weight of the opaque element (Oral, Yener and Bayazit, 2004).

a. Thermal Resistance Measures

The insulation properties of a material is related to its overall heat transfer resistance which is characterized by 'R' value, and other physical properties such as airflow resistance, water vapor permeability, and fire characteristics. As a general rule the higher the R value, the better insulation effect. In terms of airflow resistance, the movement of air through an insulation material will decrease its insulation value. Similarly, the presence of water in an insulation material will decrease its insulation value and cause deterioration of material. The desired insulation magnitude is directly related to the difference between outside thermal conditions and comfort requirements (Olgyay, 1973; p.104).

Givoni (1976; p.114) defines the R-value as the resistance of one square meter of the component to heat transfer for a given temperature difference across it. The R-value is often used as a quantifier of the efficiency of building envelope components. In fact the R-value alone is not sufficient to assess the thermal property of overall building envelope. The U-value (W/m^2K) is the reciprocal of resistance, commonly used to express the ability of a building assembly to conduct heat. It is more generally used as more than one material is used to fabricate walls and roofs.

Busch (1996) reports that the U-value of an assembly can be calculated if the following are known: the conductivity and thickness of homogenous materials, the conductance of nonhomogenous materials, the surface conductance of both sides of the construction, and finally the conductance of enclosed air spaces. Thus one can calculate the heat flow through each component of the building envelope as the product of its area A, its conductance U, and the difference T_{in}-T_{out} between the interior and outdoor temperatures (Kreider and Rabl, 1994).

The major concern in use of insulation materials is the decrement factor. It is the reduction of the peak heat flow through the envelope. The amplitude of the heat wave on the outer surface of the wall is based on solar radiation and convection in-between the outer surface of the wall and ambient air. During the propagation of the heat wave through the wall, its amplitude will decrease depending on the thermophysical properties of wall materials. When this wave reaches the inner surface, it will have amplitude that is considerably smaller than the value it had at the outer surface. The decreasing ratio of its amplitude during this process is named as 'decrement factor' (Smith, 2001)

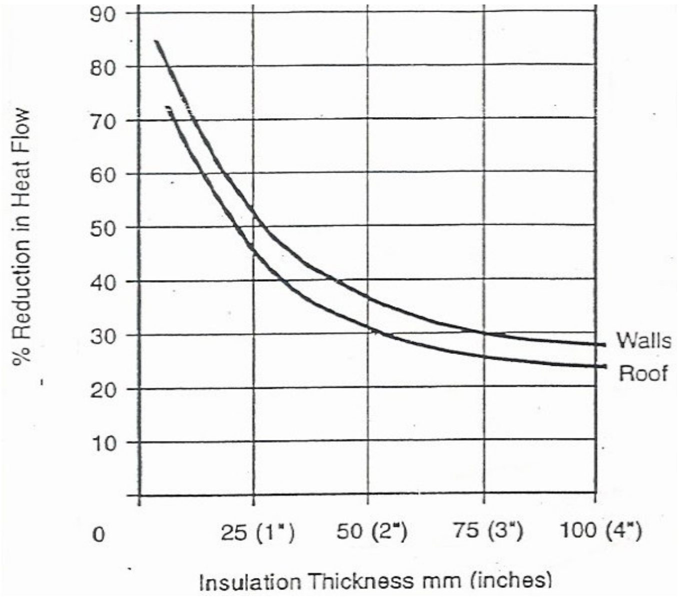


Figure 2.1. Percentage of heat flow reduction with added insulation. (Source: Hunn, 1996; p. 365)

Ritellmann (1996; p.365) maintains that the conception that the impact of R and U values causes a linear change in percentage of heat flow is not true. Figure 2.1 shows that the reduction in percentage of heat flow is not directly proportional to the quantity of insulating material. Granum (1976) adds that there is also an economic limit over which it is not feasible to increase the thickness of insulation. A reasonable optimization criterion may be to select the insulation which will give the lowest sum of annual cost in the expected life-time of the building.

Floridesa, Tassou, Kalogirau and Wrobell (2002) claim that where the heating of the building is the major concern, insulation is the predominant effective envelope factor. In climates where cooling is of primary importance, thermal mass can reduce energy consumption; provided the building is not occupied during the evening hours and the stored heat can be dissipated during the night. In this case, either natural or mechanical ventilation can be used during the night, to introduce cool outdoor air into the space and remove heat from the massive walls and roof.

Vandenberg (1980) states that standards of thermal insulation have been rising, partly because of the accompanying saving in fuel costs, and partly because increased availability of effective thermal insulators and partly because of people's increased expectations of comfort. The comparative performances of some insulation materials are listed in Table 2.1 derived from Smith (2001).

Table 2.1. Comparative performance of insulation materials.
(Source: Smith, 2001; p. 60)

	Thermal Conductivity (W/mK)
Extruded polystyrene	0.030
Glass fibre quilt	0.040
Phenolic foam	0.020
Polyurethane board	0.025
Cellulose fibre	0.035

In addition to generally used opaque insulation elements there are transparent and translucent elements that show highly insulating properties. Transparent insulation converts one or more walls of the building into solar collectors. Initially, a single glazing was used as the transparent cover of a wall, this was known as a Trombe wall system (Athienitis and Ramadan, 1999). Transparent insulation materials, are a class of product which enhance the solar heat gain while simultaneously reducing the heat loss by conduction and radiation. The insulation allows transmission of the incoming solar radiation but acts as a barrier to conductive and radiative heat loss, by retaining absorbed heat effectively (Daniels, 1997).

b. Thermal Capacitance Measures

Heat can be stored in the structural materials of the building in order to reduce the cooling-load peaks and shift the time that the maximum load occurs. The storage material is referred to as thermal mass. It is an essential component in the effective use of solar energy in buildings. It acts like a reservoir that absorbs and releases interminent sources of energy.

The amount of thermal mass in buildings is an early design question. Thermal mass of the building fabric is important as it determines the thermal response of the building and the ways of storing heat. Olgyay (1973; p.113) mentions the effect of mass on thermal properties of buildings by exemplifying the conditions of a stone church or a pyramid. Both of the examples demonstrate thermally stable interior environments, independent from outdoor temperature variations.

Previous findings by Fathy (1973) described a highly original approach to rural mass housing in Egypt through the use of mud-bricks. He observed that even when the local climate is extreme, the right application of building materials, and controlling air movement could passively modify conditions for comfort.

Busch (1996; p.132) claims that mass has two basic thermal characteristics. First it imposes time delays and dampens the magnitude of fluctuations in external climatic variables, such as temperature and solar radiation. Second, it provides resistance to heat flow based on its U value. As Givoni (1976, p. 137) states; for high mass materials, “the indoor temperature is closely related to the thickness of the walls and internal partitions.”

Rittelman (1996; p.365) defines the term ‘thermal inertia’ to represent the amount of mass in the walls and the roof of the building. In addition to this Givoni (1976; p.141-142) claims that thermal mass effect of building materials depends on some basic thermo-physical properties. These properties can be listed as; thickness of the materials, density of the materials, and heat capacity of the materials. The heat capacity of a building material is the product of the mass per unit area (kg/m²) and the specific heat of the material (j/kg Cº) whereas, specific heat is the amount of heat a material can hold per unit mass.

Thermal capacity does not influence the heat flow through the wall under steady state conditions, so there is no capacitive insulation effect. However the steady state conditions rarely exist because even if the indoor temperature is relatively constant, the outdoor temperature is always typically changing. As the thermal mass dampens and shifts the time of peak value of heat flow, the thermal resistance of insulating material only dampens the amplitude of peak heat flow. Figure 2.2 shows the graphical illustration of the different effects of thermal resistance and capacitance.

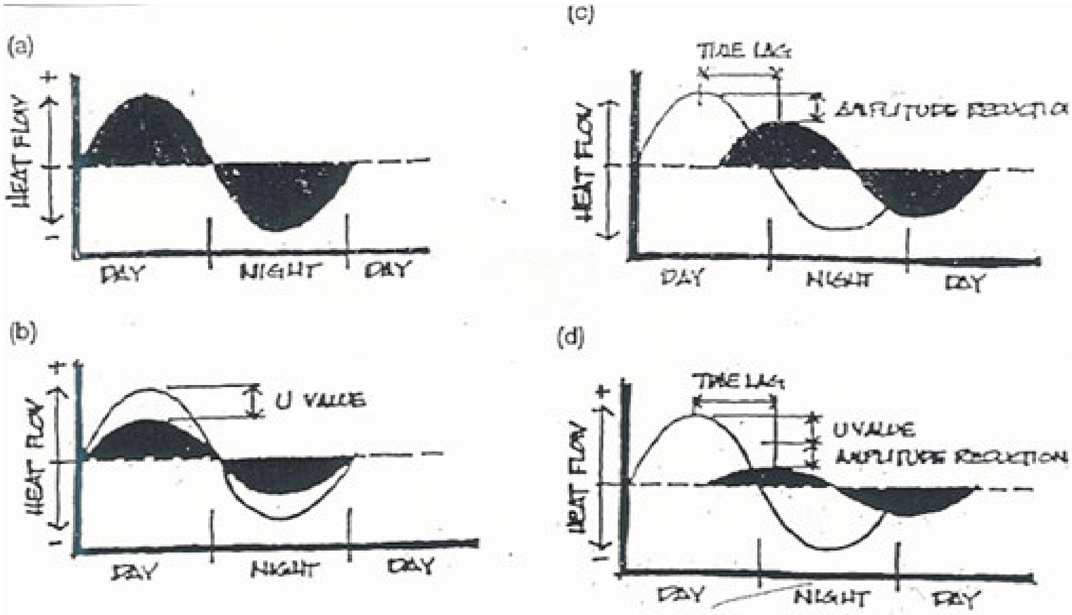


Figure 2.2. Effects of thermal mass and thermal insulation (a) perfectly conductive wall. (b) effect of insulation value. (c) effect of thermal mass. (d) compound effect (Source: Hunn, 1996; p. 366)

Givoni (1976) states that under periodic variations in outdoor conditions and with given conditions of temperature difference and thermal resistance, heat flow into a building decreases as the heat capacity of its structure increases. Heat capacity is the determinant of the ratio between the heat absorbed and heat stored by the material during the day. In winter, during periods of high solar-gain, energy is stored in the thermal mass so avoiding overheating. In summer, the thermal mass acts in a similar way as in winter reducing the cooling load peaks. In this way the heat capacity moderates the rates of heat flow in and out of the building interior. The delay that mass causes in the timing of the heating and cooling periods of the temperature and heat flow cycles is called time lag effect (Goulding, Lewis, and Steemers, 1993). Kreider and Rabl (1994) state that the time lag effect is particularly important in commercial buildings, as a time lag of several hours can shift much of the load past the hours of occupancy, to a time when temperature control is no longer critical.

Much research has been conducted to maximize energy saving by using thermal mass. Brown (1990) monitored an office building and compared data with simulations using variable levels of thermal mass in similar buildings, and found that an increase of the thermal mass in closed and in ventilated buildings, can reduce the peak indoor temperature by approximately 1°C to 2 °C.

Hyde (2000; p.11) adds that an energy efficient building employing solar design principles can use the sun's heat, taking advantage of the thermal mass to store heat and releasing this heat. Alternatively cooler temperatures at night can cool the thermal mass and assist keeping the building cooler during the day. The main strategy with this approach is to manipulate the building structure to activate high-density elements in the building in an appropriate manner to create an acceptable thermal regime.

Six test buildings were investigated by Burch, Malcolm and Davis (1984) to test the effects of wall mass on summer space cooling. The buildings were located at the US National Bureau of Standards in Gaithersburg. They found that for indoor temperature set at 24° C, high mass buildings consumed less cooling energy than similar lightweight buildings that have similar thermal resistance. They also found that thermal mass was more effective when positioned on the interior side of the insulation.

Yalçıner (1983) examined the thermal performance of adobe trombe walls in passive solar applications. Through an experimental investigation he proved that adobe, with its high specific heat capacity, can be used as an advantageous material since it collects heat and transfers it to the indoor space within a desired duration and regulates the indoor air temperature. The author claims that by using both mathematical models and simulation techniques, the effect of direct solar heat gain and use of thermal mass has significant effect on thermal performance of test buildings.

Yohanis (1999) introduced a utilization factor for building solar heat gain for use in a simplified energy model. The utilization factor, which is a function of weather and building thermal response, is determined by using data obtained from a dynamic hour-by- hour thermal analysis of solar energy absorption in a generic office building. The researcher found that this factor depends mainly on zoning and the time constant.

c. Solar Energy Absorption Measures

The thermal forces acting on the outside of a structure are combinations of radiation and convection impacts. The properties of materials with respect to convective heat transfer have been discussed in previous sections. A third factor, after thermal mass and thermal insulation, to be considered is solar heat gain when thinking about internal temperatures. The radiation component consists of incident solar radiation and of radiant heat exchange with outdoor surrounding and with the sky.

The solar radiation consists of visible (wavelength 0.3 to 0.7 microns) and short infrared radiations (1.7 to 2.5 microns). As this energy is concentrated near the visible part of the spectrum, the criterion of reflectivity is related to colour values. White material may reflect 90 precent or more, black materials 15 percent or less of radiation. On the other hand, the thermal exchange with the surroundings consists of longer infrared wavelengths (over 2.5 microns) the characteristics of materials in regard to reflectivity of longwave infrared heat depends more on the density of the surface and on molecular composition (Olgyay, 1973). Calculations of solar effects on opaque surfaces involve the concept of sol-air temperature. Busch (1996, p. 141) defines this factor as follows;

> "Sol-air temperature is the temperature of the outdoor air that, in the absebce of all radiation exchanges, would give the same rate of heat transfer to the surface as would arise from the actual combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air."

According to Olgyay (1973; p.53-54), the sol–air temperature includes the effects of solar radiation combined with outside air temperature and changes periodically. The author states that this temperature is assumed to show sinusoidal variations during a 24-hour period and that the sol-air approach to orientation recognizes that air temperature and solar radiation act together to produce one sensation of heat. The author continues to state that the selective absorptivity and emissivity characteristics of materials are other effective defenses against radiation impacts and are especially important in overheated conditions.

2.4.2. Properties of Transparent Components

The transparent components of building envelope generally provide a desired amenity in the form of view and contact with the outdoors with a cost of lack of privacy, potential problems with thermal and visual discomfort, and potential increases in energy consumption, peak electric demand, and chiller size. The use of effective strategies with present and forthcoming technologies and the answer to the question of how to design windows to improve their energy performance, which is vital not only for passive solar but for all building designers, is covered in this section of the study.

The transparent component of the envelope has certain objectives, like maximization of the daylight entrance, controlling the direct sunlight, minimizing the heat gain during overheated period, providing glare control and view to the outdoor environment. According to Brown and Ruberg (1988) the primary function of a window has been to provide the building occupants with light and view. This function is related with the transmission characteristics of glazing. The part of the electro-magnetic field our eyes are sensitive to lights between 400 and 760 nm. This constitutes light. Clear glass transmits most of the visible radiation falling on its surface while absorbing or reflecting the rest. Heavily tinted and reflective glazing transmits as little as 8 percent of the radiation. Both the amount of natural light available in a room and its colour can be affected by the choice of glazing (Brown and Ruberg, 1988).

Window dimensions are generally given as transparency ratio, which equals to the ratio between the window area and the window to wall area. The lower limit of the transparency ratio is to be accepted as 20 percent in order to satisfy the psychological human needs and visual communication with the surrounding environment (Lynes, 1979). The upper limit of this value depends on aspects such as heat conservation and noise control, as well as on structural properties of the room, its function and the arrangement of the settlement (Oral, Yener and Bayazit, 2004).

The methods to improve the performance of the window can best be addressed by first considering their six possible energy control functions. These are to provide: passive solar heating, day lighting, shading, insulation, air tightness and natural ventilation. (Givoni, 1976) The first four of these significantly determines the energy requirement of the building as well as the thermal and visual comfort. They can be controlled by appropriate choices of glazing.

About 3 percent of the sun's energy reaching the earth's surface is found in the ultraviolet (UV) region of the spectrum. Clear glass transmits about 80 % of the incident UV energy. About the half of sun's energy is found in the near infrared (shortwave) region of the solar spectrum. Clear glass transmits 80 percent to 90 percent of this radiation. It must be selectively absorbed or reflected, for solar heat gain is to be reduced. Clear glass absorbs 80 percent to 90 % of the far infrared (longwave) radiation emitted by bodies at terrestrial temperatures but reemits the heat at the same rate.

Givoni (1976) states that the thermal effect of a glazed wall section is dependent on the shading provided and the spectral properties of glass. Brown and Ruberg (1988) add that by changing the characteristics of the glazing or the transparent portion of a window different 'types' of energy can be selectively transmitted or reflected.

> "On impinging on a transparent or a translucent surface, radiant energy is divided into three components: a part is reflected, having no thermal effect on the material; a further component is absorbed by the material,

> subsequently to be dissipated to either side by convection and longwave radiation; the third component is directly transmitted through the material. The relative proportions of the three components are determined by the angle of incidence with the surface and the spectral properties of the glass."
> (Givoni, 1976, p. 232)

a. Types of Glazing

The word glazing described by Brown and Ruberg (1988) includes any material which allows sunlight to pass through it while retaining a certain amount of heat. Glazing materials include glass acrylics, fiber glass and many other materials. Although different glazing materials have very specific applications, the use of glass has proven the most diverse and to be the best all-around solar glazing material.

The glazing type to be used for the windows is determined with respect to its transmission, absorption and reflection for heat, light and sound, as well as aspects such as function, aesthetic impression and price, among others. Since the window frames are manufactured from different materials with different thicknesses, their specific construction has an influence on heat loss or conservation, on the amount of daylight and the noise level. With a market research of the available products with respect to their heat, light and sound transmission values, their thickness, structural properties, functionality, aesthetic appeal and price, a choice of appropriate windows can be determined (Oral, Yener and Bayazit, 2004).

Lampert (1990; p.22) states that glass selection will influence total transmittance, spectral properties and directional properties and adds a vast array of window accessories can be added to glazing to alter its properties in response to changing external conditions and internal needs. There are three ways of heat losses through windows; conduction, convection and radiation. Elmadhy and Comick (1988) state that among these, radiation accounts for 2/3 of the total while conduction and convection heat transfer account for the remaining 1/3.

One method for improving the thermal performance of windows is to control the thermal radiation losses. The use of transparent films decreases the amount of heat transferred by conduction and radiation while heat loss due to convection can be decreased by the use of gases. Argon and Krypton store and therefore transport less heat than air, hence glazing units filled with inert gases lose less heat through convection and random molecular movement (Tuluca, 1997)

Until recently, clear glass was the primary glazing material used in windows. Although glass has good structural properties and allows a high percentage of sunlight to enter buildings, it has very little resistance to heat flow. During the past two decades glazing technology has changed greatly. Research and development into types of glazing have created a new generation of materials that offer improved windows efficiency and performance for consumers. Amstock (1997) emphasizes the process of development of glazing products, he states that in the evolution of flat glass products for glazing, regular clear glass is referred as ‘first generation’ glass. By the mid 1930s, hermetically sealed double glazed insulation glass unit was offered on the market.

The ‘second generation’ glass products evolved since the late 1930s as heat absorbing and glare reducing tinted glass. Their shading coefficients are lower than the ‘first generation’ glass products and they reduce excessive solar brightness (Amstock, 1997). Author goes on to report that, from the period of 1940s and 1950s some special low absorbtance glass was produced for high solar energy transmission with opposite characteristics to the ones defined above. He defines ‘third generation’ glass products as those with reflective characteristics as an important factor in controlling solar energy transmission.

Today many commercial fenestration products use films and coatings to reduce heating and cooling loads while admitting high levels of light. Low-e glazings have special coatings that reduce heat transfer through windows. The coatings are thin, almost invisible metal oxide or semiconductor films that are placed directly on one or more surfaces of glass or on plastic films between two or more panes.

The coatings typically face air spaces within windows and reduce heat flow between the panes of glass. When applied inside a double-pane window, the low-e coating is placed on the outer surface of the inner pane of glass to reflect heat back into the living space during the heating season. This same coating will slightly reduce heat gain during the cooling season. (Tuluca, 1997)

Heat-absorbing glazing with tinted coatings is used to absorb solar heat gain. Some heat, however, continues to pass through tinted windows by conduction and re-radiation. But inner layers of clear glass or spectrally selective coatings can be applied with tinted glass to further reduce this heat transfer. Heat-absorbing glass reflects only a small percentage of light and therefore does not have the mirror-like appearance of reflective glass (Smith, 2001). Figure 2.2 shows over a range of thermal efficiencies, (U-value) windows vary considerably in their spectral selectivity. Figure 2.2 plots the coolness factor as a function of the U-value, showing that, for example, in the U-value range of 2 to 3, the coolness factor ranges from 0.2 with low visible transmittance in relation to solar gain, to 1.4 which gives very well-managed solar heat gain and good visible transmittance.

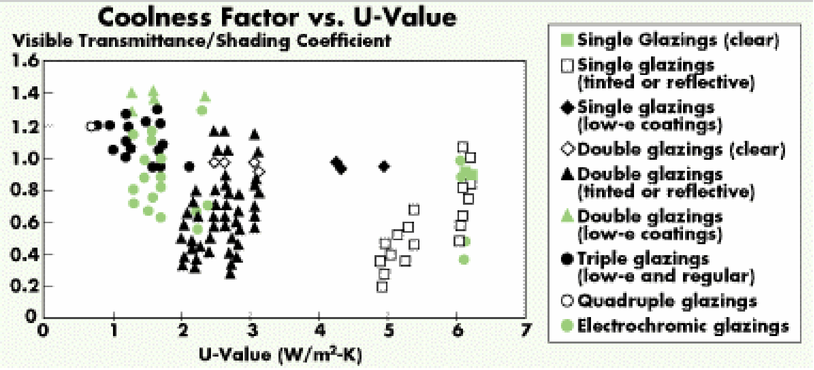


Figure 2.3. U value and spectral selectivity of glazing types
(Source: Window Library in the DOE-2 building energy simulation program)

Amstock (1997; p.357-361) states that reflective coatings greatly reduce the transmission of daylight through clear glass. Although they typically block more light than heat, reflective coatings, when applied to tinted or clear glass, can also slow the transmission of heat. Reflective glazings are commonly applied in hot climates in which solar control is critical; however, the reduced cooling energy demands they achieve can be offset by the resulting need for additional electrical lighting.

Switchable or smart glazings, which have optical properties that vary in response to some control condition, are expected to improve building energy efficiency by modifying window energy flows to match building demands. Using glazings that have variable solar or visible transmittance will allow the rejection of solar energy when its effect would be produce unwanted air conditioning loads or glare, while accepting it when its effect is to provide useful daylight (Klems, 2001).

Luminuous, solar and thermal radiation are confined to specific and well defined wavelength intervals. According to Granqvist (1991; p.2) a key concept for energy efficiency is spectral selectivity, implying that the radiative properties should be qualitatievely different for different wavelength ranges solar radiation that it is possible to combine transmittance of luminous radiation with reflectance of thermal radiation. Switchable coatings filter out from 40 percent to 70 percent of the heat normally transmitted through clear glass, while allowing the full amount of light.

The amount of heat transferred through the window determines the thermal comfort conditions of the interior environment in many ways. The amount and character of heat transfer is related with the principle properties of glazing products. The light transmission, total solar energy transmission, shading coefficient and thermal transmittances are the parameters used to measure the efficiency (Daniels, 1997).

Choosing glazing materials to optimize energy use and electric demand may be viewed as a trade-off between lowering the solar heat gain coefficient to reduce cooling while maintaining visual transmission of glass to capture daylight savings.

> "...to facilitate the comparison between different glazings the ratio between light transmittance and shading coefficient can be used. This ratio is called efficacy factor or the coolness index. A high coolness index indicates that the glazing is effective in admitting daylight and in stopping solar heat. Such glazings are well suited for energy saving and daylighting strategies" (Tuluca, 1997).

High performance films and surface coatings aim to reduce heat transfer by modifying the shading coefficient and daylighting transmittance of the glazing The static control systems result with lower shading coefficient and reduce heat gain by blocking visible portion of solar spectrum, with the cost of decrease in daylighting. Consequently the use of electricity for lighting may increase or at minimum daylighting control systems become less effective (Amstock, 1997; p.341-344).

The ineffectiveness of low-emittance coatings is that they reduce heat transfer both in heating and cooling by impeding the longwave radiation. In heating the effect of low-e glass is always beneficial whereas in cooling, it may not be effective depending on climate and building use (Amstock, 1997; p.367-368). Achieving higher energy savings under such conditions requires looking beyond static systems to dynamic systems that respond to changing climatic or occupant condition and getting real time control of cooling and lighting energy balance while addressing glare and thermal comfort.

b. Shading Devices and Solar Control

Givoni (1976) claims that windows may have a profound effect on the indoor thermal conditions. Heat gain through a sunlit glass area is higher than through an equal area of opaque surface, and this effect is felt almost immediately without any time lag. But when shading devices are applied, the thermal effect of windows is modified.

Shading the glass affects the quantity of incident radiation and modifies the heat flow to the interior. In the development of simple design methods for sun control there are two basic types of sun controls: vertical and horizontal shading elements. At the smallest scale they may be made up of tiny louver assembled in to a window screen or at larger scale the fins and overhangs may become important architectural elements in the design of façade (Givoni, 1976; p.237).

The process of sustaining solar control depends on the location of shading with respect to glass, internal or external. Exterior appendages have the distinct advantage of intercepting adverse climatic forces on the outside of the window. Consequently residual forces such as heat from absorbed sunlight are dissipated to the outside air rather than to the room air.The size and shape of device is affected by the amount of diffuse vs. direct radiation and the window orientation. (Givoni, 1976; p.238)

When shading is internal in the form of curtains, roller shades, venetian blinds, solar radiation is transmitted through the glass before interception. Strategies occuring on the indoor side of window offer one distinct advantage which is accessibility. This feature can be used by depending upon occupant management of the system as outdoor conditions or indoor requirements change (Givoni, 1976; p.240-241).

The complexity of solar heat gain makes it impossible to fully meet competing goals while using fixed devices. Movable types such as external louvers, blinds and awnings are adjustable to accommodate changing sun angle weather and building use and are employed to modulate solar gains for a long time, but operating difficulties prevent their widespread use. The controls of this type range from manual to automatic. The best of the automated systems are connected to building energy management or daylight dimming systems for maximum efficiency (Tuluca, 1997).

Fixed shading devices lack to fulfill the changing goals of solar control. A high degree of summer shading will result in reduced daylighting in winter. Problems also occur in spring and fall months resulting in decrease in cooling and increase in heating loads. Mechanical shading devices can track changes in weather yet they have the disadvantage of increased level of complexity, with high cost and low durability (Georg, Graf, Schweiger, Wittwer, Nitz and Wilson, 1998).

2.5. Assessment of Envelope Performance

Building design does not follow an analytical pattern where a progressive series of calculations leads to a specific answer. It is necessary to conceive possible answers to the problem which are then checked in many ways to see whether they offer acceptable performance. One possible way of maintaining optimum thermal performance is to adopt design strategies that lead to minimum total heating and cooling load. Another strategy is to consider the cost and lifecycle environmental properties of materials. The following sections cover these performance assessment factors.

2.5.1. Heat and Mass

Thermal performance of the building fabric is not merely a problem of the rate of heat transfer form one side of the enclosing element to the other side. An additional factor of great importance is the timing of the transfer. A building enclosure of low thermal capacity, for example a lightweight construction, will allow external temperature changes to be reflected internally with almost no time lag. This will necessitate a cooling or heating equipment which can respond rapidly to changing conditions. On the other hand building enclosure with high thermal capacity, like a massive construction, will tend to delay temperature changes and reduce the capacity and rapidity of response of required HVAC equipment (Vandenberg, 1980).

Hyde (2000; p.162-163) states that the evaluation of thermal performance of building fabric must be done by dividing enclosures into categories of short, medium and long thermal responses. Daniels (1997; p.124-126) explains the effect of thermal storage on the amount of heating and cooling loads with an experimental study. In the study Daniels categorizes the rooms according to their thermal storage capacity as very low, low, medium and high thermal mass. Then he demonstrates in conditions where rooms having the same geometry and insulation and only varying in wall design and layouts have different room temperatures after five days of clear weather in summer for a room facing south, due to their storage factor in external walls, amount of solar incidence they receive, and the thermal storage capacity of the room itself.

Practical experience of storage behavior in buildings has sufficed for more than 2,000 years to create a comfortable environment with the help of climate and cooling systems. High storage buildings not only improve thermal comfort, they also considerably reduce energy requirements (Daniels, 1997).

2.5.2. Cost

The cost analysis method takes into account the time value of money and allows detailed consideration of the complete range of costs. Energy conservation measures such as use of insulation in buildings is generally characterized by high initial cost and low operating costs, due to either the improved thermal resistance of the building envelope or reduction in the conventional fuel used. Thus, the basic economic problem is that of comparing an initial known investment with the estimated future operating costs.

Hunn (1996; p.15-22) states that to place a net value on energy efficiency, the benefit of improved energy efficiency should be compared with the cost of achieving that benefit. He reports that present worth, payback period and rate of return analyses are often used to identify cost effective measures and to determine implementation priorities for multiple strategies under consideration. The author further claims that as these methods depend on assumed energy prices, they do not lead to explicit and clear comparison.

One way of achieving this comparison can be calculating the cost of conserved energy. Typically, the cost of conserved energy is compared to the average cost of electricity or natural gas. By this method, the cost of conserved energy can be compared to the cost of supplying energy from a new source and the cost of reduced energy demand can be compared to the cost of a utility of building new generating capacity (Hunn, 1996).

2.5.3. Sustainability

Past years have seen a significant increase in interest and research activity on development of environmental assessment methods for buildings. Suzuki and Oka (1998) claim that modern buildings are typically large-scale projects utilizing different kinds of building materials so their constructions have great impact on may other sectors.

The purpose of sustainability analyses is to quantify the total amount of energy consumption and CO_2 emission caused during the lifecycle of a building. Cole and Kernan (1996) maintain that an important art of this activity centers on the development of more comprehensive and reliable information on the environmental attributes of building materials.

This performance is linked to the building's energy in- and outputs evaluated from cradle to grave. Typically, life cycle phases are considered to be manufacture, construction, occupancy, including repair and maintenance, refurbishment, demolition and recycle) (Aygun, 2003). More specifically, it is useful to examine four distinct categories of a building's life-cycle energy use;
Energy used to, initially, produce the building.
The embodied energy required to refurbish the building over its life time.
Energy to operate the building
Energy to demolish and dispose the building at the end of its effective life.

Life-cycle cost is the sum of all the costs associated with an energy delivery system over its lifetime in today's money, and takes into account the time value of money. The life-cycle savings, for an insulated building, is defined as the difference between the life-cycle cost of a non-insulated building and the life-cycle cost of an insulated one. This is equivalent to the total present worth of the gains from the reduced fuel and electricity costs for an insulated building, compared to the fuel and electricity costs for a non-insulated one (Floridesa, G.A., S.A Tassou, S.A. Kalogirou, L.C. Wrobell, 2002).

According to Cole and Kernan (1996) operating energy represents the largest component of life cycle energy use. Whereas authors claim that as environmental issues continue to become significant building design priority, designers can anticipate improved energy standards, which leads to increase in the energy needed to produce the buildings.

2.6. Retrofitting of Office Buildings

All office buildings need to be renovated during their life time, often more than once. Nilsson, Aronsson, Jagemar (1994) state that the nature of many retrofitting is a response to a number of factors, including the normal ageing process of the building and its equipment, changes in the requirements of building occupants, and the development of new technologies which offer advantages and make the replacement of already existing ones necessary. One of the most important retrofitting measures that determine the operative characteristics of building are the energy efficient issues which compose the subject of this thesis study.

From an energy point of view, building performance is complex. Nilsson *et al.* (1994) emphasize that this is mostly clear in office buildings where the thermal interactions between the building structures, internal heat loads and solar radiation result in continuous fluctuations in heat surplus or heat deficit. The energy efficient retrofitting measures depend on two important issues: levels of current energy use and estimates of likely future savings.

Papadopoulos, Theodosiou and Karatzas (2002) claim that it has been established those buildings which were constructed before 1980 cause excessive energy consumption. On the other hand, the energy saving potential in these buildings is significant. This evidence is even stronger for buildings which exceed the age of 30 and 40 years. At the same time the conventionally accepted useful life time of a building is 70 years, raising serious doubts on whether it is worth considering 30-40 year old building for modernization. However, with the rapidly growing demand for buildings in the urban areas, it is more likely that even older buildings will remain in use, provided that they are refurbished and upgraded.

In addition Balaras, Dascalaki, Droutsa, and Kontoyiannidis (2002) report, retrofitting a building costs much less than demolition and reconstruction (about half to one-third of the cost). The refurbishment or retrofit of existing buildings can also play a determinant role in the effort to reduce the energy consumption in the building sector that currently represents about 35-40 percent of the final energy consumed in the member states of the European Union, and contributes about 40-45 percent of the CO_2 emissions released to the atmosphere.

Considering the fact that operational costs of a building grow with time and that problems get worse unless some actions are taken, there is a clear need for proper maintenance, refurbishment or retrofitting i.e. upgrading of the building. Such actions should focus on the structural building elements and its installations that can also improve the energy performance and the indoor environmental quality. In any refurbishment / retrofitting project, the preparation phase is of utmost importance since the building exists and has to be studied in order to diagnose its condition, assess the potential for interventions and estimate the relevant cost (Dascalaki and Santamouris, 2002).

Retrofitting actions involve combined interventions in the main energy-related aspects of the building, including its outer envelope and installed systems for heating, cooling, ventilation and lighting with a simultaneous incorporation of passive systems and techniques. The objective of such retrofitting actions is to optimize the energy performance of the building, while maintaining thermal and visual comfort as well as acceptable air quality for the occupants. The

effectiveness of retrofitting scenarios on the energy performance of an office building depends on specific characteristics related to its architectural structure, its operational features and relation to the surrounding environment (Dascalaki and Santamouris, 2002).
Dascalaki and Santamouris (2002) conducted a study which was based on the analysis of the energy-saving potential of retrofitting strategies proposed for 10 buildings that were classified into different types according to four criteria: degree of exposure, thermal mass, skin dependence and internal structure. Results show that cost-effective energy savings up to 20–30 percent can be achieved in office buildings. The method and degree of energy saving differ according to building typology.

Energy use in core dependent buildings, which have high volume-to envelope surface ratio and massive floors and ceilings, was mostly effected by the HVAC type and lighting systems. For heavyweight and skin dependent buildings, by taking advantage of the building's skin dependence, the scenario on the envelope improvement was found to achieve impressive reduction of the total energy and further improvement was achieved through application of a better HVAC system. For lightweight and skin dependent buildings application of measures for the improvement of the building envelope combined with measures aiming to reduce the cooling requirements and application of the 'passive systems and techniques' scenario have an outstanding effect on energy savings (Dascalaki and Santamouris, 2002).

Bennet, Barnes, Gibson (1985) examined four buildings in London to determine the potential energy savings in commercial office buildings by using THERM computer program. The emphasis was on heating and determining the payback periods of various energy conservation measures. These measures include; roof insulation, using double glazing, low-e glazing and wall insulation. The study presented that in general the main sources of heat loss was through windows and draught stripping of doors and windows was cost effective with short payback period to reduce heat loss by ventilation. Roof insulation with 25 mm was more cost effective than 50 mm layer and provided energy savings up to 15 percent. Internal wall insulation had a shorter payback period than exterior wall insulation because of high insulation cost of external insulation. Double glazing, as a retrofit measure found to be the least financially attractive item due to very long payback periods.

2.7. Energy Simulation in Building Design

Before the advent of computer-aided building simulation, architects and building services engineers relied heavily on manual calculations using pre-selected design conditions and often extrapolations in extending beyond conventional design concepts. This approach had frequently led to oversized plant and system capacities and poor energy performance. For large or complex buildings, it would be unrealistic to expect that energy-efficient designs could be attempted without resorting to computer-aided detailed building simulation programs (Hong T., S.K. Chou, T.Y. Bong, 2000).

Building simulation began in the 1960s and became the hot topic of the 1970s within the energy research community. During these two decades, most of the research activities were devoted to studies of fundamental theory and algorithms of load and energy estimation. The studies had resulted in the many refinements of the transfer function technique and well-known simplified methods such as the degree-day method, equivalent full load hour method, and the bin method, to predict the energy consumption of buildings. During this period, building simulation was regarded as the key to turning energy consuming buildings into energy-efficient thermally conducive built environments (Hong *et al.*, 2000).

The passing of the oil crisis lessened the incentive for achieving energy efficiency. Just as attention on energy conservation began to wane in the late seventies and early eighties, building simulation began to receive renewed interest brought about largely by advancements in desk-top personal computing. During that same period, the US Department of Energy (DOE) granted more than $1 billion to research and development (R&D) projects related to energy conservation and renewable energy. The result of the sponsorship is a series of popular detailed building and energy systems simulation programs like DOE-2 and TRNSYS. However, despite the availability of building simulation programs (BSP), they remained mostly in research laboratories after 1990's (Hong *et. al.*, 2000).

Hong *et al.*, (2000) state that the beginning of the 1990s saw the growing global concern to protect the environment. Wasteful consumption of fossil fuels and the use of harmful fluorocarbon based refrigerants are being blamed for global warming and the thinning of the protective ozone layer. In the building sector, the challenge to professionals is to create a healthy and comfortable built environment with less energy consumption and reduced negative impact on the environment. The demand for green buildings has made the application of building simulation a must, rather than a need. Thus, BSPs have gained acceptance as routine analysis and design tools.

The analysis of the overall performance of a building should take into account the ecological cost of providing comfort in buildings. As mentioned in previous sections the energy crisis of the 70s has resulted in the use of building energy consumption as a performance measure. Furthermore, the Rio Conference in 1992, where the environmental impact of human activities was officially recognized, has introduced limitations in the use of specific materials in the building industry (Citherlet S., J.A. Clarke, J. Hand, 2001).

Even if there are no green standards which define the maximum allowed impacts, the environmental impacts of a building during its lifetime can already be estimated, and could be included as a new domain requiring performance assessment at the design stage. Therefore, a holistic approach should include building performance indicators as well as comfort and energy and environmental impact indicators, each relating to the building's life cycle (Citherlet *et al.*, 2001).

2.7.1. Energy Modeling Techniques

Citherlet *et al*. (2001) claim that a holistic approach in building design requires a method to estimate the performance that will result from the interactions between the different technical domains. Table 2.2 shows real scale experimentation and numerical simulation are suitable methods because they each can integrate the complex physical processes. However, since the experimental approach is time consuming and expensive, it can be argued that computer simulation is the preferred option for the holistic approach to design options.

Table 2.2 Comparison of building physics simulation approaches. (Source: Citherlet *et al.*, 2001)

Approach	Type	Advantage	Disadvantage
Experimental	Small scale	Reproductive experiment Low cost Compare variants	Scale effects Model errors Measurement errors
	Full scale	Complex phenomenon Global analysis	Time consuming expensive
Mathematical	Analytical Numerical	Ease to use Complex model Fast calculation Compare variants	Measurement errors Simplified model Validation Model error

Hong *et al*. (2000) group building simulation programs into two categories, namely, design tools and detailed simulation programs. Design tools are more purpose-specific and are often used at the early design phases because they require less and simpler input data. They are very useful in checking prescriptive building standards. On the other hand, detailed simulation programs often incorporate computational techniques such as finite difference, finite element, state space, and transfer function for building load and energy calculations. To account for the dynamic interactions among all thermal-based elements associated with comfort and energy consumption, including the building envelope, HVAC systems, lighting, and control devices, detailed simulation programs often have to perform the computations on an hour by-hour and zone-by-zone basis. Thus, optimal design and operation of a building and its facilities can be achieved. Besides design, detailed simulation programs are also useful in the compliance checking of performance-based building energy standards.

According to the purpose of design, simulation programs use different mathematical methods. Clarke (1985) defines these mathematical models as follows:

> "From a thermal point of view, a building is a complex network of thermal resistances and capacitances linking different regions and representing conductive, convective, radiative and heat storage processes. The manner in which this network is treated mathematically – some portion may be neglected, fixed values may be assigned of simplifying boundary condition assumptions might be made-will determine the flexibility of the modeling technique to one of five categories: steady-state; simple dynamic; response function; numerical and electrical analogue." (Clarke, 1985, p.18)

Steady state models have no mechanism for calculation of the effects of solar gains, longwave radiation exchanges or plant operational strategies, etc. and typically address only fabric heat flow under special boundary conditions. Simple dynamic models address dynamic performance and are applied to multiple parametric runs. Response function models use dynamic performance and combine it with varying system boundary conditions and overcome the problems of steady state models. Finite difference and finite element are two ways used in numerical techniques. Finite difference is the one which commonly applied to problem of energy modeling (Clarke, 1985; p.19).

Of the models above, electrical analogue model provides the most accurate material definition and parametric analysis. The analogy that exists between electrical flow and heat flow has led to the construction of electrical analogue devices useful in the study of complex heat flow phenomena. The technique is commonly used as a research tool, allowing long term simulations to be completed in a short time (Clarke, 1985; p.22).

2.7.2. Material Description and Simulation

Hong *et al*. (2000), in a systemic approach classify the basic applications of building simulations as follows:

> Building heating/cooling load calculation; the peak values and load profiles of heating/cooling loads of buildings are the basis for the sizing and selection of HVAC equipment, systems, and plants.
>
> Energy performance analysis for design and retrofitting; by analyzing the annual building energy demand profile and part-load performance of major energy-consuming equipment, an energy-efficient building design can be realized, and the energy budget of the building can be accurately estimated for energy planning and management.
>
> Building Energy Management and Control System (EMCS) design; plays the role of monitoring, controlling and reporting the operation of the building systems and plants so as to ensure that thermal comfort and energy efficiency is maintained. EMCS can include strategies like enthalpy control, night setback and optimal start/stop control and can help to exploit the full potential for energy saving of a good building design. EMCS has concentrated on providing guidelines for selecting appropriate systems, the development of management rules, and the evaluation of emulation methods.
>
> Complying with building regulations, codes, and standards; Building simulation can be employed to design the building to the requirements of local building regulations, codes or standards.
>
> Cost analysis; Some BSPs are able to perform a cost analysis of the various options being simulated, thus presenting the designer with cost-effective energy-saving alternatives. BSPs of this type are best used in conjunction with codes of practice and energy standards.

Studying passive energy saving options; BSPs can be used to investigate the technical and economic feasibility of passive design options such as sunshading, daylighting, evaporative and earth cooling, night ventilation, radiative cooling, movable insulation, roof ponds, refective roof, and various heat storage, release and buffer systems.

Computational Fluid Dynamics; Computational Fluid Dynamics tools are widely used in the study of global warming, urban climate, microclimate, building ventilation, indoor air quality, indoor and outdoor thermal comfort, fire safety, and smoke extraction. Software is used for technical and design applications covering: pipework design (hot and cold services, pipework sizing, fluid dynamics, and heat emissions), drainage (design of drainage systems, soakaway design, stormwater flow, manhole and pipeline schedules), other pipework (sprinkler systems and rainwater gutter sizing) and energy consumption (U-value calculation and envelope analysis, analysis of domestic fuel use, thermal and comfort analysis and analysis of energy consumption and cost).

An important issue in integrated simulation is to determine the physical measures that will cause an impact on the performance issue to be addressed. Each material must include the physical characteristics of any domain that is likely to be simulated.

These material properties required for the model depend on the measures which could possibly be simulated and on the methodologies used to assess the performance in specific measures. It should be noted that according to the subject of simulation, not all properties are necessary for the calculation. Only the relevant material properties for a specific calculation method can be extracted from the model and used during the simulation. Summary of the material properties required to perform an integrated simulation using the main calculation methods in building physics is given in Table2.3

Computer-based simulation often requires the use of engineering tools to calculate envelope heat gains and space heat loads, predict the energy performance of the building, and provide diagnostics to enable automatic control of system and plant operation.

Table 2.3 Summary of the material properties required to perform an integrated simulation using the main calculation methods in building physics. (Source:Citherlet *et al.* 2001)

Properties	Methods
Material level:	Thermal
Density	Thermal transmittance
Solar absorption	Dynamic characteristics
Conductivity	Thermal bridge
Heat capacity	Steady state energy consumption
IR emmisivity	Dynamic behavior: nodal network, response factor
Vapour diffusion resistance	Thermo-optic properties
Visible, solar, IR and UV trans.	Ventilation
Visible, solar, IR and UV ref./abs.	BSI
Dynamic viscosity (for gas)	ASHRAE
Surface roughness	Hybrid
Reflection index	Flow/system network
Chromatic co-ordinates	Zonal
Acoustical absorption coefficients	CFD
Environmental impacts	Lighting
	Lumen
	Split-flux method
	DIN
Construction level	Radiocity
	Ray-tracing
U-value	
Visible transmittance	
Sound reduction index	Room acoustics
Linear thermal transmittance	Image source model
Point thermal transmittance	Radiosity
	Ray-tracing
Environmental impacts	Cone/pyramid tracing
	Hybrid
	LCA
	Eco-indicator
	Ecopoints
	Critical surface-time
	EPS

CHAPTER 3

MATERIAL AND METHOD

This chapter gives the details of the materials and methodology that are used to conduct the study. The section on material describes the case study building and the weather data for Ankara, which were used as inputs, and the ENERGY-10 simulation program which was used for thermal simulations. The procedure of the study is presented in steps consisting of definition of the case study building on the simulation program, determination of the critical façade in the existing building scheme, and data processing and evaluation.

3.1. Material

The study was carried on an existing building which is situated in Ankara. In this section the case study building, the weather data of Ankara that wass used as input through the simulations and the simulation program ENERGY-10 is defined.

3.1.1. The Base Case Building

Within the framework of the thesis study the effects of retrofitting actions were investigated on an existing case building. The building that was chosen for the case study is situated in the Middle East Technical University (M.E.T.U.) Campus in Ankara. The ten storey building is a part of (A block) the Engineering Building, known as MM Building, and was constructed in early 1970s. It accommodates the offices for administrative facilities of M.E.T.U. and represents the typical construction over the last half century with a regular arrangement of windows and envelope design with tile cladding and shear wall.

The building layout and orientation is shown in Figure 3.1. The ten floors have a total floor area of 2077.5 m². The building receives energy in two forms; thermal and electrical. Thermal energy is supplied as high –temperature saturated steam, generated in the central heating plant building on the campus. Natural gas is the primary fuel for steam generation. Figure 3.2 shows a general view of the case study building looking to the northeast and northwest facades.

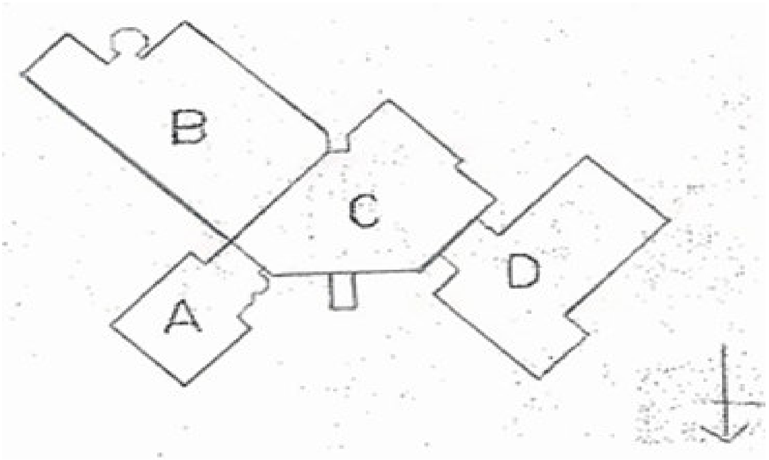


Figure 3.1. Plan layout and orientation of MM building

The roof of the building is flat without heat insulation. It is covered with 1 cm water insulation, 7 cm concrete with perlite and 5 cm pebbles and has an overall U value of 0.68 W/m²K. Intermediate floors are 20 cm concrete covered with 2 cm plaster on ceilings with an overall U value of 0.52 W/m²K.

Figure 3.2 General view of case study MM building

All the windows are single glazed with a U value of 6.82 W/m²K and shading coefficient of 1.0. The ratio of glazing to wall area is not equal for all facades. The amount of window area and the corresponding glazing to wall ratio is given in Table 3.1. The Northeast façade has the maximum glazed area, windows accounting for 31% of the wall area, where southwest façade has no openings in the concrete wall. The building, from a heat storage point of view, can be regarded as medium to heavyweight construction, when window ratios and wall compositions are considered.

Table 3.1 Wall-window ratios.

	Northeast Facade	Southeast Facade	Southwest Facade	Northwest Facade
Total Area (m²)	451.84	668.23	451.84	668.23
Window Area (m²)	142	170.4	0	540.4
% of Window Area	31	25	0	19

External walls of the building can be classified in two groups. The shear walls are uncladded in all of the four facades with varying ratios. Cladded walls are composed of 2 cm mosaic tiling on exterior surface, 10 cm concrete, and 3 cm plaster in the interior. The ratio and overall U value of wall compositions for all four facades are given in Table 3.2.

Table 3.2. Wall Ratios and U values in four facades.

	Northeast Facade	Southeast Facade	Southwest Facade	Northwest Facade
Total Area (m²)	451.84	668.23	451.84	668.23
Opaque Area (m²)	309.8	497.83	451.84	540.4
% of Uncladed Wall Area	51.2	63.56	100	74.84
% of Claded Wall Area	48.8	36.44	0	25.16
Overall U-value (W/m²K)	3.12	3.12	2.77	2.94

Although the materials used for all four facades are identical the U values are not same. This change is due to the difference of cladded and uncladded wall ratios and the different thicknesses of concrete used in shear walls. Northeast, southeast and southwest facades have 240 mm thick walls whereas this thickness is 280 mm in northwest façade.

3.1.2 Weather Data

As climate is one of the main parameters affecting the energy loads of a building, the effectiveness of an energy efficient intervention is strongly dependent on the climatic region of reference. The *base case* building is situated in Ankara, Turkey. Ankara is described to be in the third climatic region according to Turkish Code (TSE 825). The location design parameters and climate properties of Ankara are described in Table 3.3 and Table 3.4 respectively.

Table 3.3 Location design parameters (Weather Maker Version 1.0)

Location	Location latitude (deg)	Location longitude (deg)	Location atitude (m)
Ankara, Turkey	39.4°	33.1°	850.087

Ankara's climate is moderate with low precipitation-cold winters and dry-hot summers. Big differences in temperature from one day to another occur in spring and autumn.

Table 3.4 Climate design parameters (Weather Maker Version 1.0)

Heating design dry bulb temperature temperature (°C) (°C)	Cooling design dry bulb temperature (°C)	Average annual dry bulb temperature (°C)	Average annual wet bulb
-22.2	32.2	11	8.2

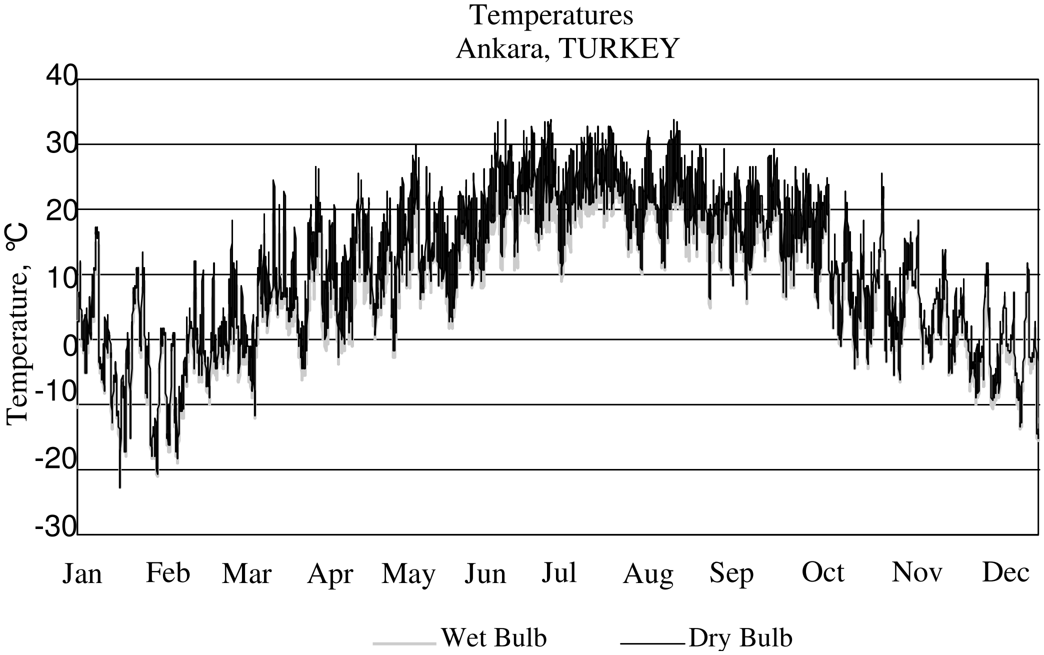


Figure 3.3 Average monthly dry bulb and wet bulb outdoor air temperatures

Most of the precipitation is in spring time, there are high differences in temperature between day and night, winter and summer. Hottest months are July (average 33.1 °C) and August (average 33.3 °C); coldest months are January (average 0.3 °C) and February (average 1 °C). Figure 3.3 shows average monthly dry bulb and wet bulb outdoor air temperatures in Ankara. The variations in annual beam and direct solar radiation also follow a similar pattern with outdoor temperature values. The highest solar radiation is obtained in June and July while the lowest values are in January and December.

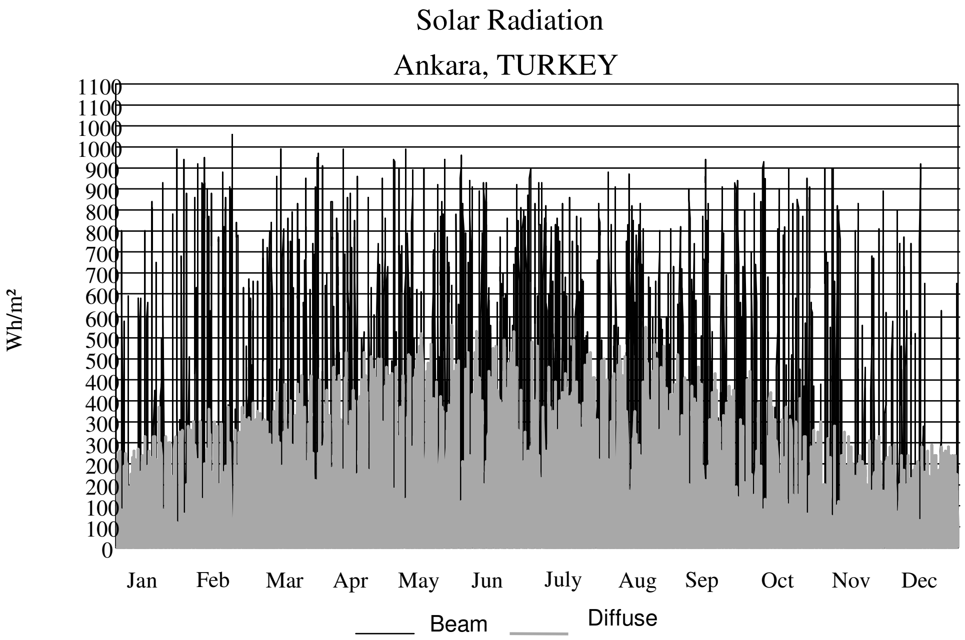


Figure 3.4 Beam (direct) and Diffuse Solar Radiation Data for Ankara.

3.1.3. Thermal Analysis Program; ENERGY-10

The ENERGY-10 software was developed at National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and Berkeley Solar Group. Lawrence Berkeley National Laboratory is responsible for the daylighting portions of the program, including the daylighting simulation engine, and provided technical advice on all aspects. Berkeley Solar Group provides the thermal simulation engine, develops the HVAC interfaces, and programmed the original output graphics (Balcomb, 2002).

ENERGY-10 uses California Nonresidential Simulation Engine which performs whole-building energy analyses for 8760 hours per year that include both day lighting and dynamic thermal calculations. The software is applicable to both residential and nonresidential buildings. Version 1 simulates one or two thermal zones, which limits its application to smaller buildings. While the biggest share of projects designed using ENERGY-10 are residential in nature (70%), half of the software users (47.6%) are also using it to design energy and resource efficient offices. Also other use areas include educational facilities (29.4%), manufacturing and assembly plants (14%), warehouses (12%), mercantile/service industries and grocery stores (16.8%), lodging (7.7%), and restaurants (5.6%) (Balcomb and Beeler, 1997).

ENERGY-10 gives comprehensive evaluations of energy use with a technique called simulation, the most widely accepted method for doing building energy analysis. Simulation predicts conditions in the building, based on assumed occupancy characteristics. In ENERGY-10 this is done by calculating heat transfer from point to point within the building each hour throughout a simulated year. Weather data consists of site-specific, hour-by-hour values such as temperatures, solar radiation, humidity, and wind speed. Each month of data is from a different year, selected to be typical of the long-term average for that particular month (Wilcox, Barnaby, and Niles, 1992).

The graphs generated by ENERGY-10 show typical simulation results. The advantage of simulation analysis is that it provides a reasonably realistic picture of how an actual building would perform. The simulation analysis in ENERGY-10 accounts for a detailed evaluation of solar gains through windows, heat flowing into and out of walls, thermal storage in all building materials, and HVAC performance. The simulation is performed for an entire year, summing hourly energy consumption into monthly totals, determining monthly costs, and then annual totals (Balcomb, 2002).

ENERGY-10 weather data files can be made from data provided in either of two formats: a standard TMY2 format or an ENERGY-10 ASCII-text format. In either case, the user must provide the hourly data required: global solar radiation, beam solar radiation, diffuse global solar radiation, dry-bulb temperature, dew-point temperature, wind direction, wind speed, and cloud cover (Marion and Urban, 1995).

ENERGY-10 evaluates one or two thermal zones. The buildings that can be simulated with the program include commercial and institutional buildings such as schools, libraries, small banks, stores, restaurants, offices, and low-rise residential buildings. The target audience for the program is building designers, architects, HVAC engineers, utility officials, and architecture and engineering students and professors (Balcomb, 2002).

The alpha test version of ENERGY-10 was released in 1994, the beta test version in 1995, and Version 1.0 in June 1996. The first upgrade to the original program, Version 1.1, was released in February 1997. ENERGY-10's accuracy has been demonstrated using the BESTEST procedure developed by NREL’s Center for Buildings and Thermal Systems within the International Energy Agency Solar Heating and Cooling Program Task 12. BESTEST has been adopted by the DOE and the international community as the accepted basis for verifying the credibility of computer simulation programs (Judkoff, and Neymark, 1995).

ENERGY -10 uses the approach called thermal network to calculate heat flow in walls and roofs with the analogy to electrical networks as shown in Figure 3.5. Here the resistors represent resistance to heat flow between points within the wall and the capacitors represent the heat capacity of materials located at the points.

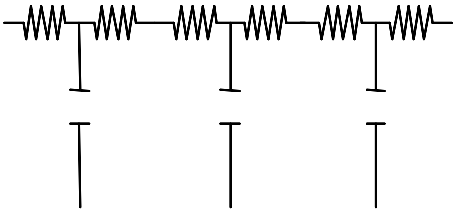


Figure 3.5 Thermal network method

The thermal simulation engine transforms the building description into a thermal network model. It converts the wall description from the layered description to values in the network and iterates to find an energy balance at every step, accounting for heat storage in each material layer. By this way, modeling converts a homogenous wall material into a series of discrete elements. The thermal network approach to modeling is well accepted and is accurate. Numerous tests have confirmed the accuracy of simulation reports including BESTEST. (Balcomb, 2002)

3.2. Method

In this study, an optimization approach was proposed where the evaluation criteria is related to the environmental performance of the building, in terms of energy efficiency and sustainability. For this purpose, the study was conducted as a parametric study to be able to identify the contributions of individual energy efficient retrofitting strategies. In parametric study one parameter was varied at a time and the effect on annual heating energy use (MWh) and amount of CO_2, SO_2, NOx emissions (kg) were displayed. In this part, the method and process of the parametric study is explained.

3.2.1 Defining the Building

The first part of building energy analysis was describing the building to the computer. Through this procedure, the building was described in terms of its location (Ankara) total square footage (207.75 m²) and use category (office). Additionally, the number of stories (10) and type of HVAC system (Gas-Fired Unit Heater) were set according to properties of MM building.

The next step was to define envelope materials in detail, according to the data gathered from architectural drawings of the MM building and on-site visual inspections. Floor and roof constructions, wall types (material layers and thicknesses) and window configurations (area and glazing properties) were defined from the material library of the program corresponding to the envelope materials used in existing building. As wall types and window area differ on four facades of the existing building, description of façade elements regarding to thermal properties and areas were done separately for Northeast, Southeast, Northwest and Southwest facades.

Completing all the relevant data, the properties of the building were defined in the computer program. This is called the ‘Base Case Building’ that has all the attributes of the building such as appropriate internal gain schedules, orientation, HVAC controls, the glazing-to-wall ratio, and constructions. The next step was to perform an energy analysis on the *base case.*

Internal temperatures were calculated inside the space by taking into account external climatic conditions, the characteristics of the building fabric wall, roof and window materials, solar gains through the windows, internal gains from occupants, equipment and artificial lighting, etc by simulation engine. Those temperatures were compared to set points defined at the beginning of the simulation, and heating was provided if required to compensate for the difference between calculated temperatures and predefined set points.

The energy spent for heating was determined, and added to lighting energy to determine total annual energy consumption in the building. These calculations were further carried out for gas emissions produced during the use of building. In this way the thermal behavior and heating loads of the *base case* was determined which was then used for parametric study and comparative evaluations of various energy efficient strategies.

3.2.2 Determining the Critical Façade

At this step of the study the four facades of the *base case* facing different directions, namely; Northeast, Southeast, Northwest and Southwest, have been compared in terms of their relative contribution to the heating load of the building. The aim was to determine the façade that has the biggest impact on the energy that is required for heating the building.

To be able to conduct a relative comparison, a new *base case* building was created, called the *modified case*. *Modified case* was assigned to have totally identical properties with *base case* building except the wall and window U values. *Modified case* represents the *base case building* that provides wall and window U values according to Turkish Code (TSE 825) and has a U value of 0.5 W/m²K for walls and U value of 2.80 W/m²K for windows. In this way *modified case* showed the thermal behavior of the *base case* when Northeast, Southeast, Northwest and Southwest facades have identical U values without changing the glazing-to-wall ratio and envelope materials in climatic region of Ankara. Table 3.5 gives the envelope U values of the *base* and *modified case*, for each of the four facades.

Table 3.5 Envelope U values for the Base and Modified Case

	Northeast Facade	Southeast Facade	Southwest Facade	Northwest Facade
Base Case U Value (W/m²K)				
Wall	3.12	3.12	2.77	2.94
Window	6.81	6.81	6.81	6.81
Modified Case U Value (W/m²K)				
Wall	0.5	0.5	0.5	0.5
Window	2.80	2.80	2.80	2.80

After calculating the total annual and heating energy requirements of the *modified case*, envelope properties of each façades was analyzed one by one. Through this process the analyzed façade was assigned to have its original wall and window U values as that of the *base case*. This systematic modification on envelopes was done to evaluate the effect of each façade on heating load independently. For example, to see the effect of Northeast façade on the energy use of building, wall and window U values of Northeast façade was set as it is in the *base case* (wall U value 3.12 W/m²K, window U value 6. 81 W/m²K), and the wall and window U values of the remaining three facades were set according to TSE 825 (wall U value 0.5 W/m²K, window U value 2.80 W/m²K).

Table 3.6 Data used to determine effect of different facades.

	Northeast Facade	Southeast Facade	Southwest Facade	Northwest Facade
Northeast Facade Effect				
Wall U Value	3.12	0.5	0.5	0.5
Window U Value	6.81	2.80	2.80	2.80
Southeast Facade Effect				
Wall U Value	0.5	3.12	0.5	0.5
Window U Value	2.80	6.81	2.80	2.80
Southwest Facade Effect				
Wall U Value	0.5	0.5	2.77	0.5
Window U Value	2.80	2.80	6.81	2.80
Northwest Facade Effect				
Wall U Value	0.5	0.5	0.5	2.94
Window U Value	2.80	2.80	2.80	6.81

Table 3.6 shows the data used in the study. For the purpose of the study the critical façade is defined to be the façade whose annual energy requirement deviates most from the annual energy requirement of the *modified case*.

3.2.3 Data Processing and Evaluation

At this stage of the study, the *base case* was modified to incorporate a set of energy-efficient strategies. To evaluate effects of each strategy independently, only one variable was changed at a time and all other elements were kept constant. For each strategy evaluated, a new building scheme which was named according to modifications it carries was created. For example a process analyzing effect of double glazing was created by altering only its glazing type without any change in wall properties and called as 'double glazing' in displaying results. The effect of each variable was evaluated, according to their influence on the output measures that change only due to the modifications applied to the *base case* building.

During the study, the original *base case* description was modified by applying energy efficient retrofitting strategies to the envelope and then the resulting building scheme was simulated. In the next step, the result of the simulations of the modified building was compared with the original *base case* and with the performance goals. This requires manually computing the wall surface and window properties of the building and entering the values in appropriate places in the building-description dialog boxes of ENERGY-10 simulation program. New envelope compositions were created to describe multiple material choices and configurations. The evolving building descriptions were called the 'current design' named by the applied retrofitting strategy. This was a repetitive process including design, adjusting the model, review, design, adjusting the building description, evaluation, etc.

In this thesis study three distinct energy efficient retrofitting scenarios were evaluated;

- type of glazing,
- use of thermal insulation, and
- application of thermal mass.

Each step represents a different design layout. The retrofitting scenaros were applied only to the vertical elements aof the envelope. In other words construction type and material configurations of roof and the ground floor were kept throughout the study. This is because they have small surface area and consequently relatively insignificant effect on thermal performance of building when compared to that of external walls. This section explains the process used to evaluate the variables. In addition, the data that is used to evaluate the performance of these variables i.e. constant and output measures, are described in this section.

a. Constant Measures

Constant measures are those that were kept unchanged for all cases that are analyzed throughout the study. Two of these measures are the orientation and façade layout that are impossible to modify when working on an existing building on a real case. Although it is not impossible to change the HVAC system and control, they were also kept constant as it is not a considered retrofitting scenario for this study. HVAC System of the MM building is Gas-Fired Unit Heater.

Thermostat setpoints were defined to be 21.6 °C for heating and 23.8 for cooling. The occupancy schedule for HVAC controls were from 8 a.m to 7 p.m in working days.

b. Variable measures

The variable measures of the parametric study are the elements that were analyzed according to their effect on the energy efficiency and sustainability measures. The analyzed variables were glazing type, thermal insulation thickness and configuration and thermal mass of the building envelope. After detailed evaluation of each single measure the combination of best performing ones were applied to *base case building* to form a new building scheme called *retrofitted case*.

- Glazing Type

In this study different types of glazing were examined in order to compare and evaluate their effects on building energy loads and sustainability measures. The selected types of glazing differ from each other in terms of their; thermal conductivities, solar heat gain coefficient (SHGC), and visible transmittance and shading coefficients.

The glazing material used for this study was double glazing, triple glazing and low-emissivity film coated double and triple glazing. Table 3.7 summarizes physical and thermal properties of glazing materials used in the study.

Table 3.7 Physical and thermopysical properties of analyzed glazing materials. (Material Library, ENERGY-10)

Glazing Type	**U-Value (W/m²K)**	**Shading Coefficient**	**SHGC**	**Visible Transmittance**
Single glazing	6.30	1.0	0.86	0.90
Double glazing	2.78	0.89	0.77	0.81
Triple glazing	1.82	0.79	0.68	0.74
Double glazing with low-e coating	1.48	0.65	0.56	0.75
Triple glazing with low-e coating	1.31	0.67	0.58	0.71

Through the study the changes made on the glazing materials were applied to all facades at the same time by taking the walls properties as that of the *base case*. After the evaluations the building scheme that gives the minimum energy loads was determined to be later applied to the critical facade.

- Thermal Insulation

The basic aim of applying thermal insulation can simply be stated as altering the thermal conductivity of walls. In practice the desired reduction in U value was achieved by increasing the wall insulation. This study analyzed the effect of thermal insulation on wall U value and consequently building heating load in two ways. In the first step the influence of insulation configuration in the wall was compared; external or internal insulation, and in the second step the use of various thicknesses of insulation was examined. The thermal properties of materials used throughout the calculations are given in Table 3.8.

Table 3.8 Thermophysical properties of thermal insulating and thermal mass (Source: Material Library, ENERGY-10)

Material	**Thermal Conductivity (W/mK)**	**Density (kg/m^3)**	**Specific Heat (kJ/kgK)**
Concrete	1.730	2242	0.837
Insulating Foam	0.029	40	1.214

For analysis of insulation configuration, two types of walls were proposed to be generated for energy simulation in the study. *Wall type1* represents the wall configuration with external insulation of various thicknesses where *wall type2* being the wall configuration with internal insulation. Table 3.9 shows the material layers of these two wall compositions. To calculate how these applications affect on heating energy use and sustainability measures the program created a complete new building scheme by modifying *base case* building according to prescription of wall to represent *wall type1* and *wall type2* compositions systematically. The results of the simulations were evaluated and compared with each other and with the *base case* building.

Table 3.9 Wall compositons used in insulation analysis

	Material layers	
	Uncladded walls	**Cladded Walls**
Base Case	2 cm mosaic tiling, 10 cm concrete, 3 cm plaster	24 cm concrete
Wall Type-1	2 cm mosaic tiling, thermal insulation, 10 cm concrete, 3 cm plaster	3 cm plaster, thermal insulation, 24 cm concrete
Wall Type-2	2 cm mosaic tiling, 10 cm concrete, thermal insulation, 3 cm plaster	24 cm concrete, thermal insulation, 3 cm plaster

The second problem was to find the optimum thickness of the insulation material. For this various thicknesses of insulation were applied to walls by manually modifying the values in the computer program. This alters the overall U value of the wall and affects the heating load of the new building scheme. Table 3.10 shows the various thicknesses analyzed in the study and resulting wall U values for external and internal insulation

Table 3.10 Insulation thicknesses and calculated overall U values of walls

Insulation Thickness	**10 mm**	**25 mm**	**50 mm**	**75 mm**	**100 mm**
Northeast Wall U value (W/ m²K)					
Wall type1	1.53	0.86	0.49	0.34	0.26
Wall type2	1.51	0.85	0.49	0.34	0.26
Southeast Wall U value (W/ m²K)					
Wall type1	1.49	0.84	0.49	0.34	0.26
Wall type2	1.51	0.85	0.49	0.34	0.26
Southwest Wall U value (W/ m²K)					
Wall type1	1.29	0.78	0.46	0.33	0.26
Wall type2	1.32	0.82	0.48	0.34	0.26
Northwest Wall U value (W/ m²K)					
Wall type1	1.42	0.82	0.48	0.34	0.26
Wall type2	1.47	0.84	0.49	0.34	0.26

- Thermal Mass

The building shell can act as a buffer to exterior heat pulse. In the climate of Ankara, where daily temperature variations are high, massive walls can help to maintain comfort limits within the building.

To evaluate the influence of mass, various thicknesses of concrete layer was added to wall configuration to create a new building scheme. The change on the energy efficiency measures and internal temperature fluctuations in the interior of the building was compared for each scheme. The material used as the added thermal mass is concrete panels with a density of 2242 kg/m³, thermal conductivity of 1.730 W/mK and specific heat 0.837 kJ/kgK as shown in Table 3.8.

For the purpose of the study the effect of thermal mass was shown in terms of equivalent insulation in the next step. The aim was to calculate the necessary thickness of thermal mass that decreases approximately the same amount of annual energy use supplied by optimum insulation. During this process a matrix of wall U values for different amounts of thermal mass and thermal insulation was generated and used for comparative evaluation.

c. Output measures

Output measures are the evaluation criteria that depend on the properties of variable measures applied to *base case* building. They were used to assess the relative impact created by each energy efficient retrofitting scenario.

In the framework of this study annual heating energy use (MWh) was used to evaluate energy efficiency of each variable measure. The amount (kg) of CO_2, SO_2 and NOx gas emissions that are produced by each building scheme was taken to be the representative for sustainability. These measures were calculated by ENERGY-10 according to building properties defined in the *base case* and retrofitting scenarios.

CHAPTER 4

RESULTS AND DISCUSSION

A number of energy efficient retrofitting scenarios were defined for the *base case* building. As first stage the existing situation of the building and thermal performance was defined, then the energy efficient modifications were applied. Each of the scenarios applied addresses one of the main energy related aspects of the building mentioned in section 3.1. The effectiveness of the modifications on the energy performance of the building and the sustainability measures were assessed through the thermal energy simulations of the building.

Interventions vary from individual actions affecting a specific building component (single measures), to combinations of actions (combined measures). Despite the importance of understanding the impact of an individual action on the building energy behavior, the complexity of the phenomena affecting the latter requires an application of combined actions in order to achieve a successful overall retrofit. In the following sections, detailed results of various strategies are discussed and overall effect of the most successful intervention is presented.

4.1 Critical Facade

As the four facades of the *base case* building display approximately the same thermal properties in terms of solid-void ratio and overall thermal conductivity but differ in orientation, their respective contribution to the building heating load was not equal. In order to calculate these differences a *modified case* was created which represents *base case* that provided wall and window U values according to TSE 825. This *modified case* was calculated to have an annual heating energy requirement of 322.99 MWh.

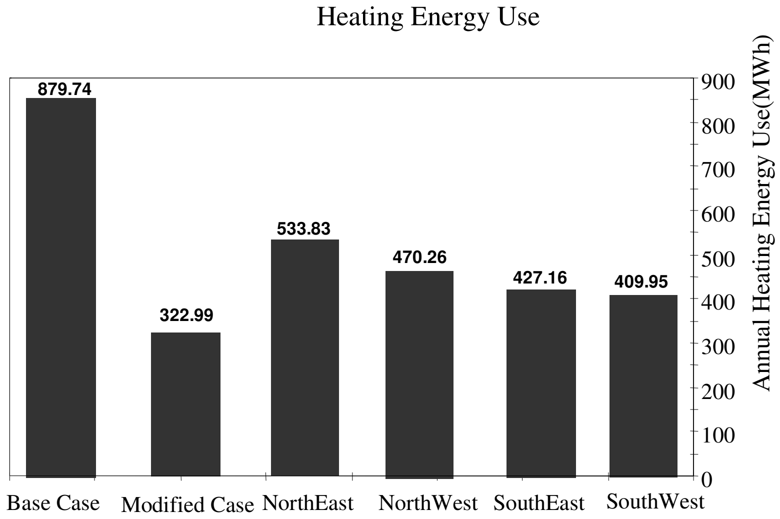


Figure 4.1 Effect of different facades on annual heating energy use

As given in Figure 4.1 the NorthEast façade has the biggest deviation from the heating energy use of the *modified case*. In accordance with its orientation, this façade has the minimum solar heat gain and maximum heat loss. Consequently, it makes the biggest contribution towards the heating load of the building.

4.2 Single measures

The simulated energy consumption data given in this section presents terms of certain comparison between major design variables. This section summarizes the predicted results, which show how the yearly heating load would be affected by changing types of glazing, adding insulation to the external walls in different configurations, thickness of the thermal insulation layer and by varying the thickness of concrete. The charts and figures show the general overall trends of how changes in single energy efficient retrofitting scenarios can affect the energy use in building.

4.2.1 Analysis of Glazing Type

In this section, an analysis of the impact of window glazing on the annual heating load and annual gas emissions are presented. A number of cases were investigated where only the glazing type is modified from that of the *base case*. These cases and thermophysical properties of analyzed glazing types are presented in Table 3.7

The results of the simulations are presented in Figure 4.2. As observed, a saving in annual heating load between 83.85 MWh and 161.20 MWh can result, when compared to the corresponding construction with clear single-glazing windows as in the *base case*. The result of this simulation showed an improvement in energy saving from 7.54% for ordinary double glazing to 13.7% for double glazing with low-e coating.

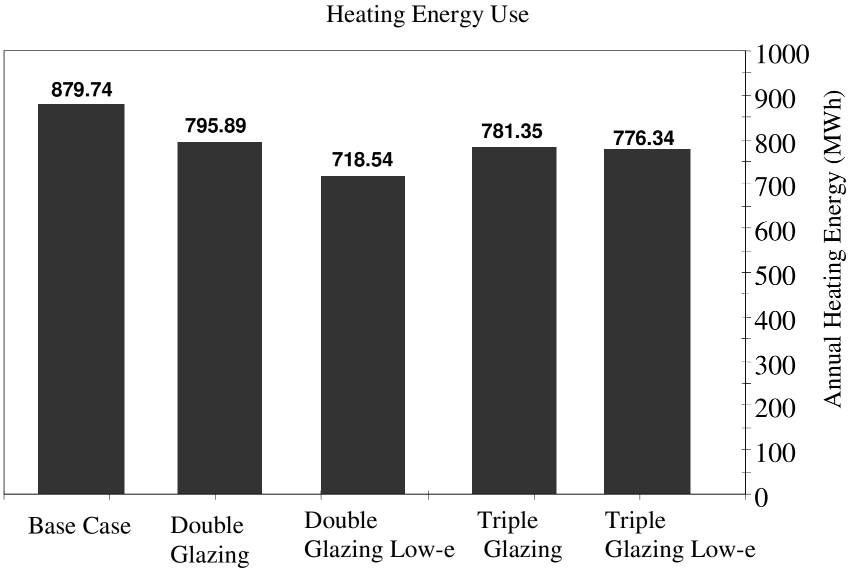
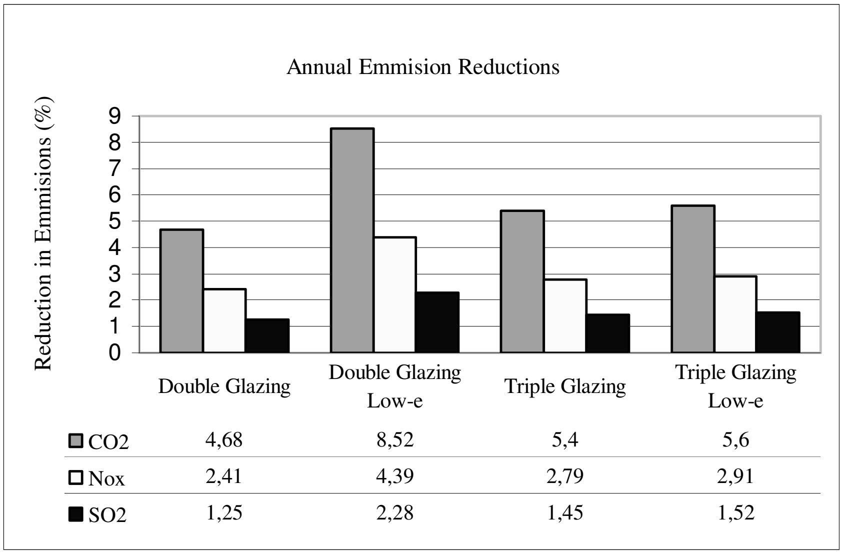


Figure 4.2 Effect of window glazing types on annual heating energy use

Triple window glazings were less beneficial than double glazing in terms of heating energy requirements. The decrease in energy use is 8.71% for triple glazing where it is 9.11 % for triple glazing with low-e coating. So it is seen that although significant energy savings were achieved with double glazing and low-e coated double glazing the expected results were not achieved with triple glazing. It is thought that this was due to the reduction in solar radiation transmission into the building due to higher shading coefficient of glazing in three layers, which would have been beneficial in cold days.

Figure 4.3 shows the annual emission results for different glazing types. It can be seen that the reduction in emission amounts for CO_2, NOx and SO_2 gases were best achieved by use of double glazing with low-e coating. This chart also maintains the rate of decrease in production of gas emmisions is coherent with the rate of decrease in heating energy use according to glazing types.



	Double Glazing	Double Glazing Low-e	Triple Glazing	Triple Glazing Low-e
▨ CO2	4,68	8,52	5,4	5,6
☐ Nox	2,41	4,39	2,79	2,91
■ SO2	1,25	2,28	1,45	1,52

Figure 4.3 Annual reductions in CO_2, NOx and SO_2 gas emissions according to glazing types

From the simulations for energy demand and gas emissions produced, double glazing low-e was proved to be the most energy efficient and sustainable choice for glazing type. The comparison of thermal energy use by months for *base case* and *double glazing low-e case* is displayed in Figure 4.4.

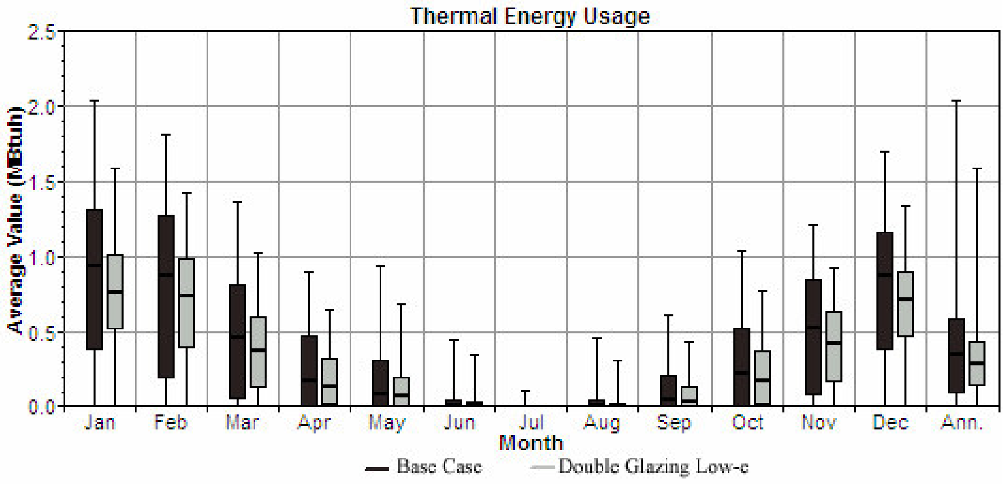


Figure 4.4 Total thermal energy usage for space heating monthly averages *base case* and *double glazing low-e*

4.2.2 Analysis of Thermal Insulation

Overall heat transfer coefficient values of the opaque components must be revised in order to achieve minimum heat loss for an alternative building scheme which is different from the *base case* building, without changing other design parameters. This part of the study examines the effects of insulation configuration and varying the thickness of the insulation layer. The thermal insulation alternatives were achieved by setting the external walls U-values range between 1.53 and 0.26 W/m²K with 10, 25, 50, 75 and 100 mm of insulation thicknesses.

In analyzing the impact of the insulation configuration in walls two building schemes are examined. Figure 4.5 displays the annual heating loads where *wall type1* represents exterior insulation and *wall type2* represents interior insulation. The results of the computer simulation lead to the conclusion that the material configuration of the exterior wall can significantly affect the annual thermal performance of the whole building.

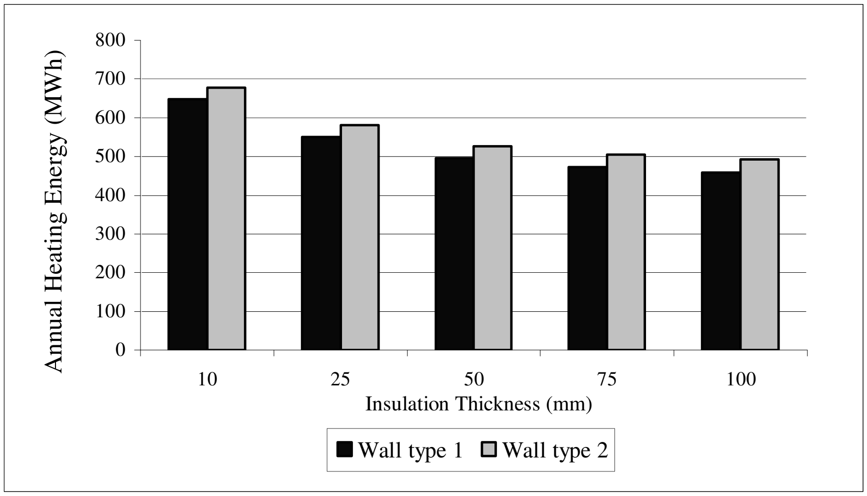


Figure 4.5 Annual heating energy usage according to insulation configuration

The results of extensive parametric analysis showed that, walls with insulation outside always perform better than those with the insulation inside. In comparing *type1* and *type2* walls with the same insulation thickness and the same U-value, it can be observed that *wall type1* configurations were thermally more effective than others. Differences in heating energy demand between the configuration 'all insulation inside' and the most effective configuration from the point of view of energy savings 'all insulation outside' may exceed 3.4 % for the simulated office building.

Figure 4.6 shows how effective wall insulation is in reducing heat energy consumption through the walls. It can be seen that increasing thickness of the insulation layer from 25 to 50 mm would lead to a decrease in the yearly heating load of up to 4.4%. Although the simulation results showed that increased insulation thickness did not demonstrate a constant rate of decrease in energy demand. The amount of reduction in energy use started to diminish when the thickness of insulation was increased beyond 75 mm.

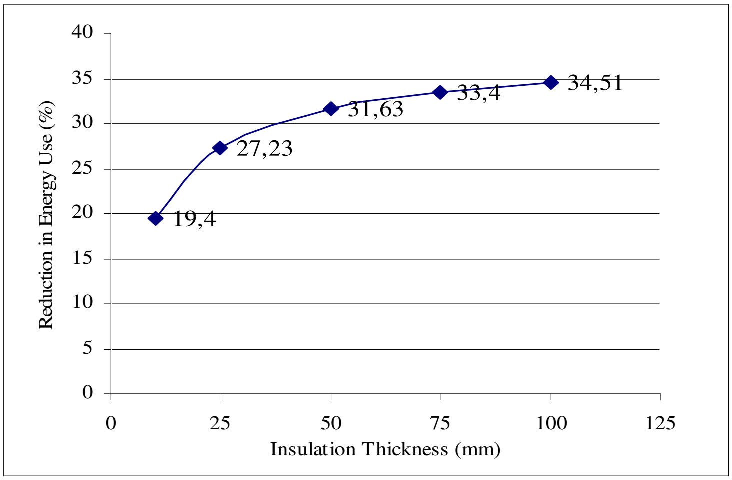


Figure 4.6 Effect of insulation thickness on energy usage

75 mm of insulating foam was able to reduce the annual heating load by 33.4% although a thickness of 50 mm is nearly effective with a U value of 0.49 W/m²K and 31.63 % reduction in energy use according to TSE 825. Figure 4.7 and Figure 4.8 summarize the monthly averages for total thermal energy use and annual emission amounts for *base case* and *75mm thermal insulated case* respectively.

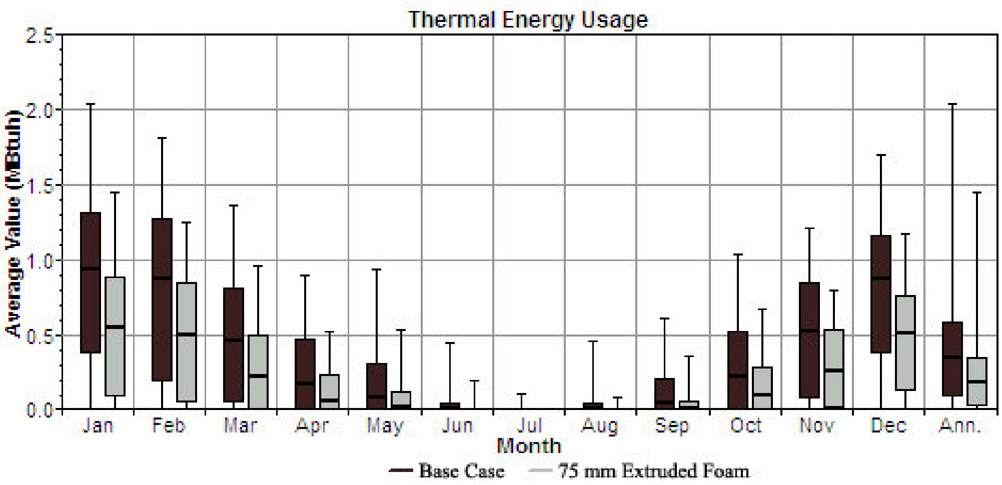


Figure 4.7 Monthly averages of total thermal energy usages for space heating Base Case and 75 mm Extruded Foam

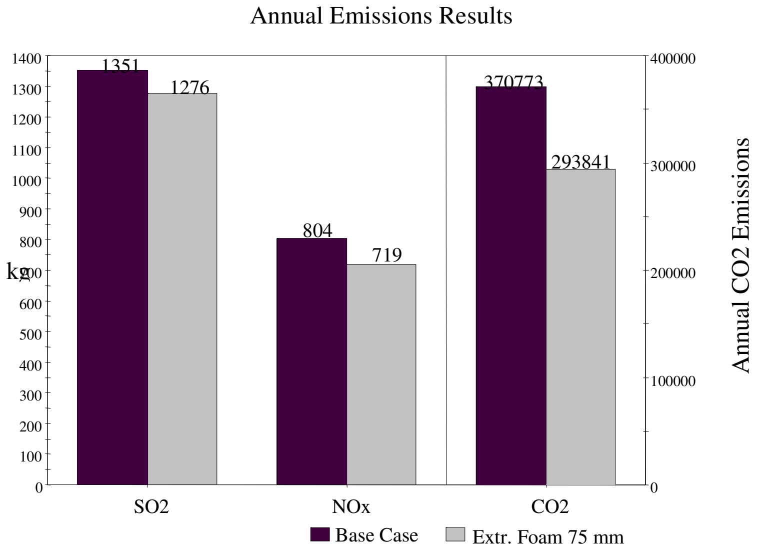


Figure 4.8. Annual CO_2, NOx, and SO_2 results for Base Case and Extruded foam 75mm

4.2.3 Analysis of Thermal Mass

To check how the use of thermal mass can influence the performance of the base case building the study was extended to examine the effect of the concrete thickness of walls on the yearly heating energy demand. Thermal mass alternatives were designed by applying an additional layer of concrete to exterior walls with thickness ranging between 50 and 2000 mm. The predicted results are shown in Figure 4.9 as a function of concrete thickness.

Heating Energy Use

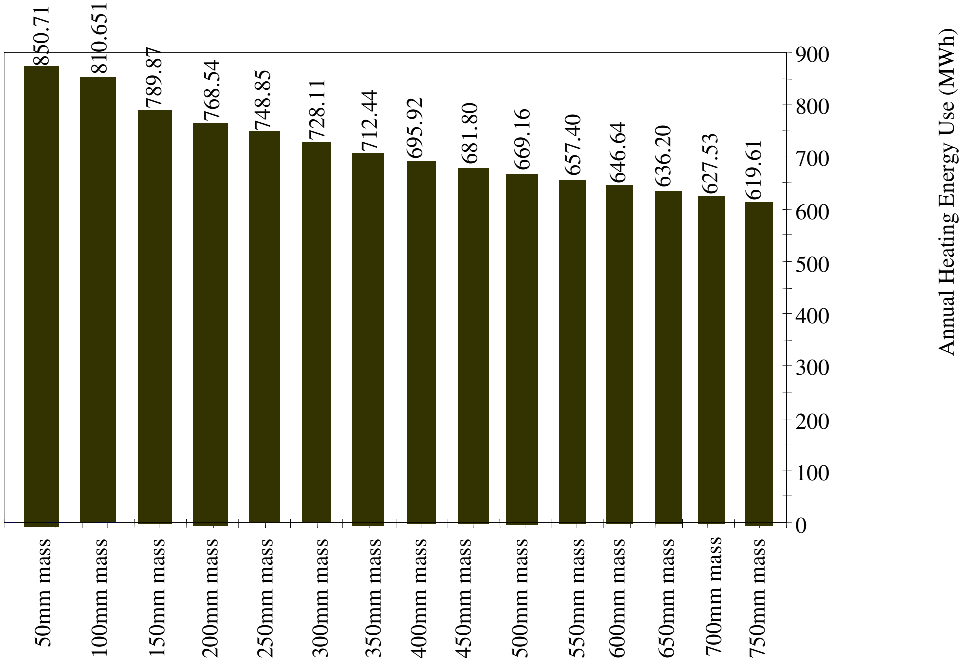


Figure 4.9 Annual heating energy use according to added mass ive layer thickness

The simulations showed that increasing the concrete thickness by 50mm would yield a slightly lower heating load. The change in heating energy use was examined by incrementally increasing the building's concrete thickness by 50 mm for each step from 50 to 2000mm. Figure 4.10 depicts the results from 50mm to 750 as adding mass after this point was not reasonable in terms of economy and applicability.

The trend of the results is consistent with that of insulation thickness. There is a fall in the proportion of decrease in the amount of energy reduction for the same amount of mass increase. In other words, the effect increasing thickness from 250mm to 500mm is significantly higher than the effect of increasing thickness from 1750 to 2000mm. Adding a 500mm concrete layer to base case would reduce the thermal load of the building by 17.71% whereas this was 21.68% for 750mm and 24.54% for 1000mm. The trend showed that there was a critical value where increase in mass amount would not cause any effective change on the heating energy use.

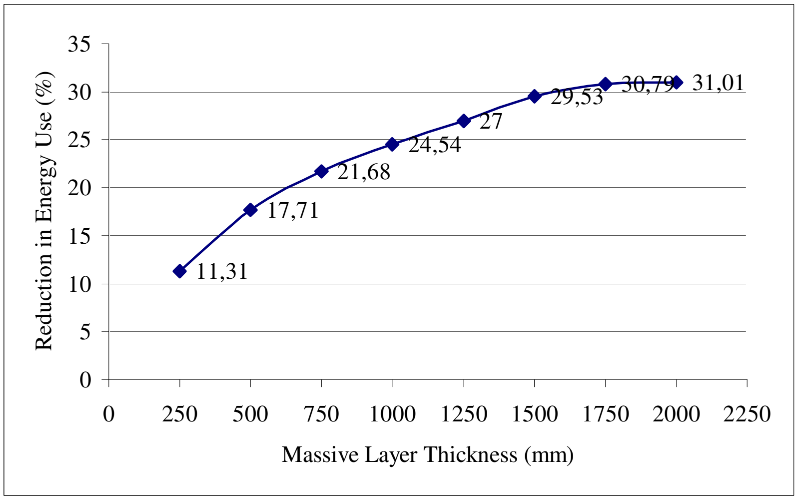


Figure 4.10. Reduction in heating energy use as a function of massive layer thickness

To be able to evaluate the effectiveness of thermal mass for varying thicknesses the results were compared with the results of insulated building schemes in terms of U value. Table 4.1 summarizes that 500mm of added massive layer can decrease the wall thermal conductivity equal to the 10mm extruded foam. In fact 2000mm of additional concrete layer, which can be considered as an extreme case from the point of applicability, can approximately reach to the U value of 40mm extruded foam.

Table 4.1 Mass equivalent of insulation thickness in terms of U value

	Massive Layer Thickness			
	50-500mm	500-1000mm	1000-1500mm	1500-2000mm
U value (W/m²K)	2.94-1.53	1.53-1.04	1.04-0.81	0.81-0.65
U equivalent of insulation thickness	0-10mm	10-20mm	20-30mm	20-40mm

Figure 4.11 compares the annual thermal energy use for base case and 500mm mass added case. These results suggest that energy saving which is accomplished as a result of the thermal mass was not effective.

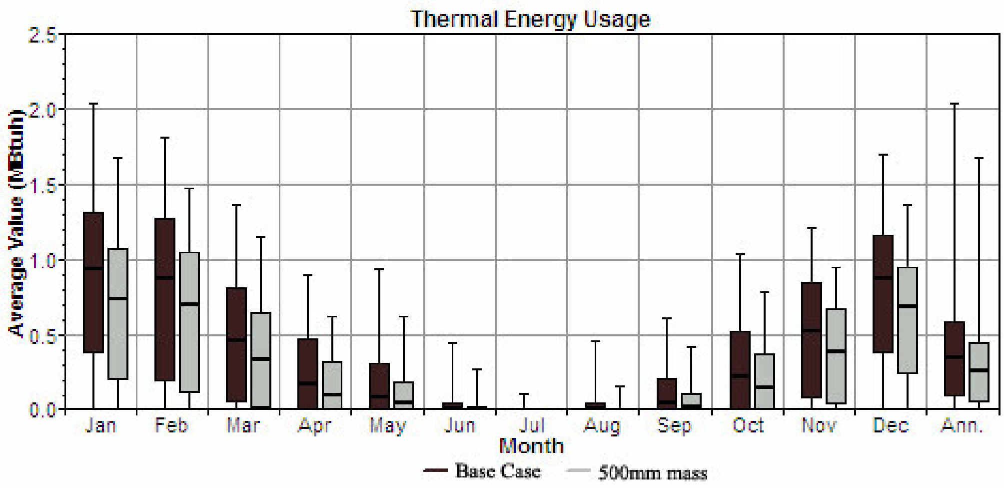


Figure 4.11. Monthly averages of total thermal energy usages for space heating *base case* and *500mm mass added case*

Although the thermal mass has little effect on the thermal load it has considerable impact on internal temperature fluctuations. The annual energy demand of a building for heating is affected to some extent by the thermal stability of the building itself. Building thermal stability is understood as the ability to hold the internal temperature within a certain interval, given normal external temperature oscillations without any plant action. This building thermal stability depends on the dynamic thermal responses of all building envelope components to external and internal temperature variations.

To see the effect of thermal mass on the internal temperature fluctuations, the building schemes were simulated without any HVAC use which is called the free run mode. This mode provides to examine the time lag and the decrement caused by addition of thermal mass. The main strategy with this approach was to manipulate the building structure to activate high-density elements in the building in an appropriate manner to create an acceptable thermal regime. The simulations were carried for two dates on which the thermal energy use of building had its maximum value during the year.

Figure 4.12 , Figure 4.13 and Figure 4.14 show the results of heat flows for a 24 hour period of the *base case*, *250mm mass added case* and *500mm mass added case* on 21st of December respectively. Figure 4.15, Figure 4.16 and Figure 4.17 show the performances of same building schemes on 21st of January. These figures indicate that thermal mass caused a time delay in the heat flow and shifts the time that the maximum heating demand occurs. In this way the heat capacity moderates the rates of heat flow in and out of the building interior

Comparisons of Figure 4.12 and 4.14 show that the *base case* reaches a minimum temperature of 1 °C between 1to 9 a.m. where the minimum temperature for *500mm mass added case* is 2 °C and between 1 to 10 a.m. A more important result was obtained in time interval when maximum temperature was reached.

The *base case* reached a maximum temperature of 4.5 °C between 5-6 p.m., whereas the *500mm mass added case* reached a temperature of 5 °C and maintained this between 3 to 6 p.m. *250mm mass added case* had slightly smaller temperature value for maximum and minimum point but the time interval was close to that of *500 mm mass added case*. When the function of the building as an office is considered, the 2 hours time shift to reach to maximum temperature in work hours is a significant advantage from the view point of thermal performance.

On 21st of January the effect of thermal mass was more clearly displayed. Adding mass has shifted the duration of minimum temperature from 7 to 9 a.m. in base case to 6 to 8 a.m. and decreased it from -7 °C to -5.5 °C. The *500mm mass added case* maintained a 4 hour duration between 12 to 16 p.m. to reach to maximum temperature value of base case which occured between 13 to 14 p.m. *250mm mass added case* provided a slightly weaker performance than *500 mm mass added case*

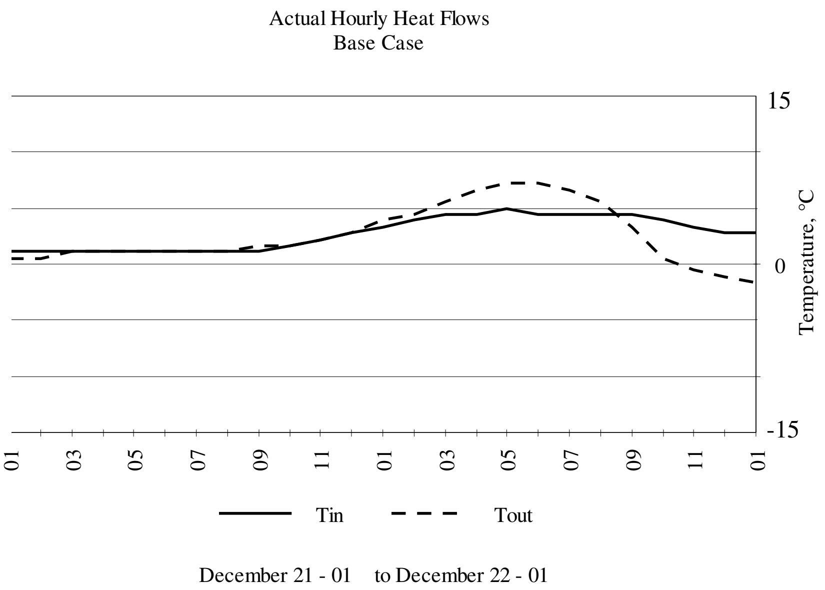


Figure 4.12 Actual hourly heat flow for base case on December 21st .

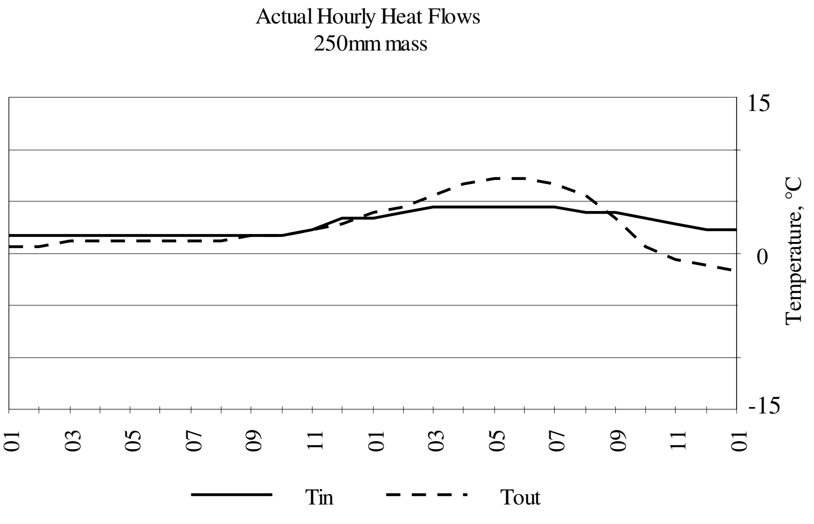


Figure 4.13 Actual hourly heat flow for 250mm mass added case on December 21st

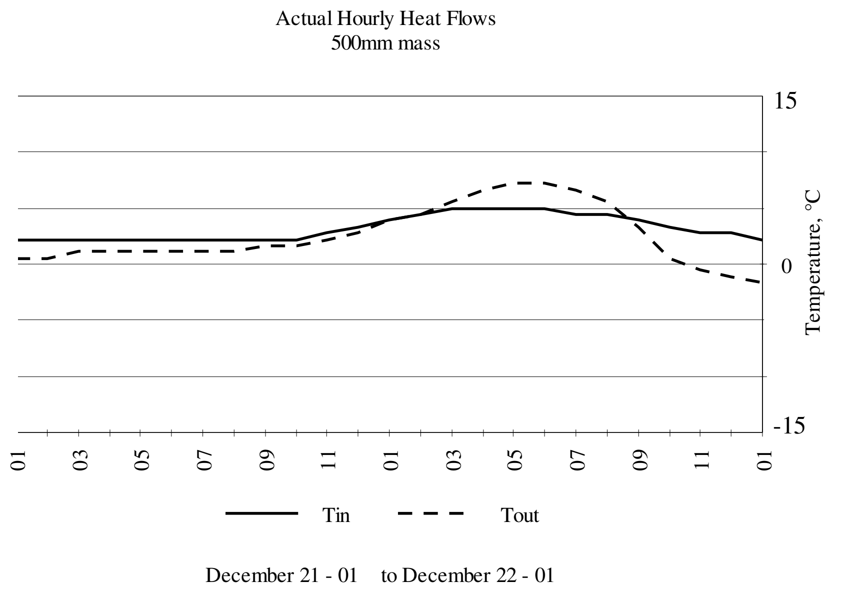


Figure 4.14 Actual hourly heat flow for 500mm mass added case on December 21st

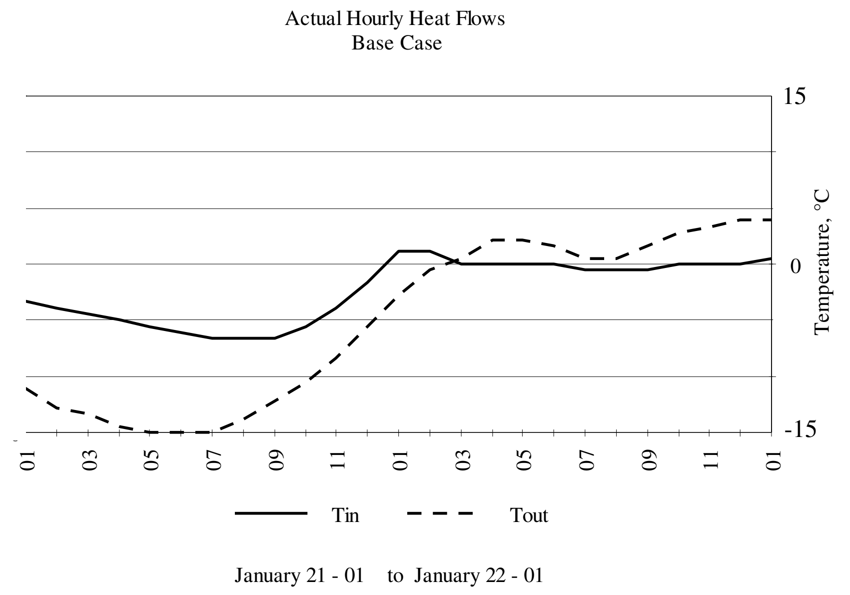


Figure 4.15 Actual hourly heat flow for base case on January 21st

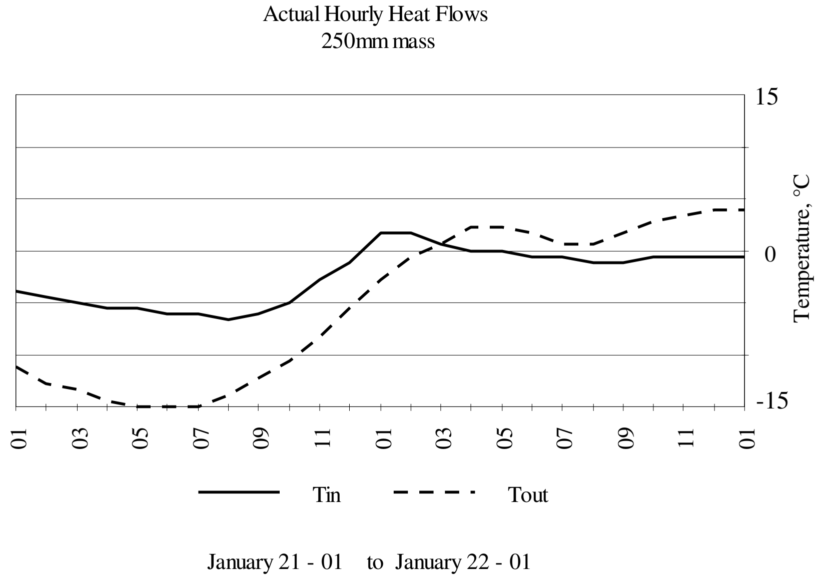


Figure 4.16 Actual hourly heat flow for 250mm mass added case on January 21st

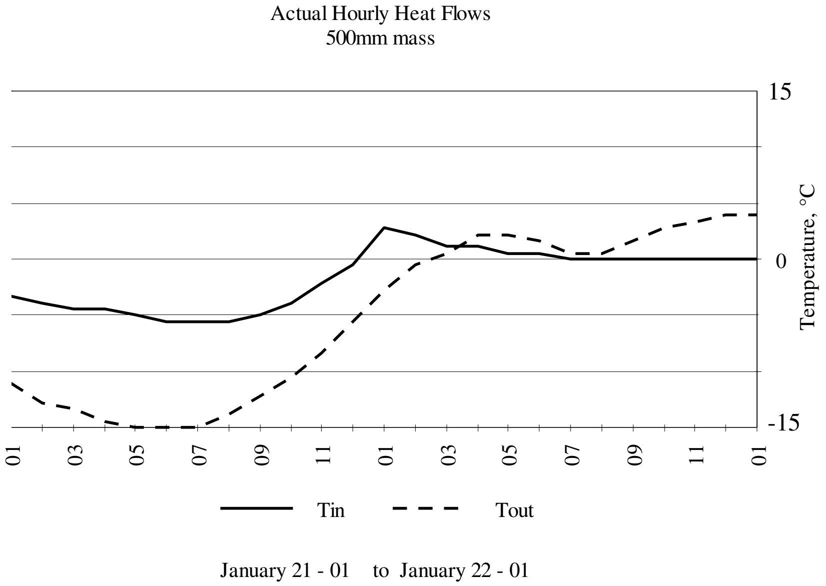


Figure 4.17Actual hourly heat flow for 500mm mass added case on January 21st

4.3 Combined Measures

Combined measures applied to the base case building involve the combination of the most effective retrofitting measures. Based on the single evaluation results, the thermal mass, thermal insulation, and type of glazing were modified in the MM building to improve its thermal performance. In all of the combined scenarios glazings were assigned to be double glazing low-e coating. The exterior insulation was applied as 50 mm or 75mm on the walls, and the added thermal mass was also increased to 250mm.

In the first stage, the energy efficient envelope measures were applied only to the critical façade with a set of 75 mm insulation, 250 mm added thermal mass and double low-e glazing. According to this, the Northeast façade had a U value of 0.31 W/m²K after retrofitting and the remaining three facades were left with their base case properties. This building scheme is named as *retrofitted case1*. The comparison of thermal energy use of *base case* and *retrofitted case1* is given in Figure 4.18.

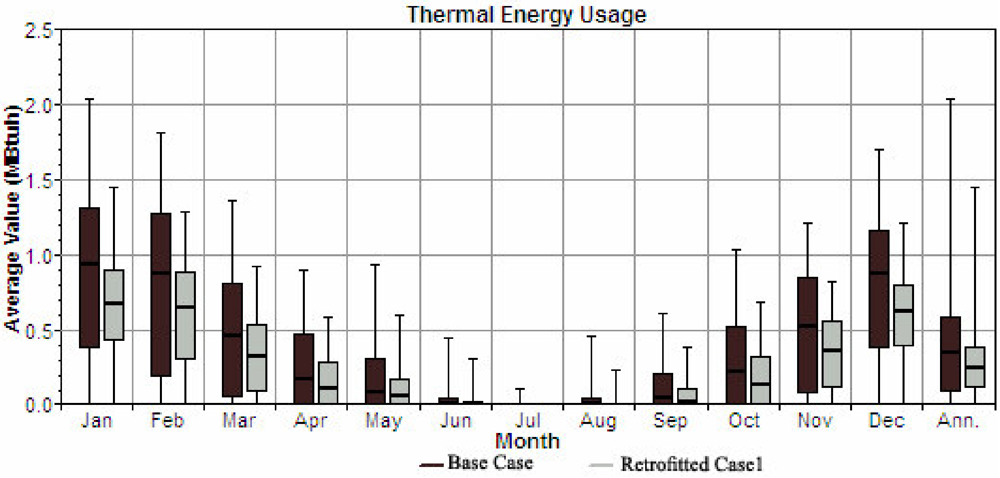


Figure 4.18. Monthly averages of total thermal energy usages for space heating *base case* and *retrofitted case1*

According to simulation results, applying combined retrofitting measures to the critical façade provided 21.76% decrease in energy use of the building and reduced the annual heating energy use to 618.58 MWh from 879.74 MWh of the *base case.* Figure 4.19 gives the annual emission results for the *base case* and the *retrofitted case1.* According to this new building scheme the annual production of greenhouse gasses were reduced by 13.49% for CO_2, 3.61% for SO_2 and 6.95% for NOx.

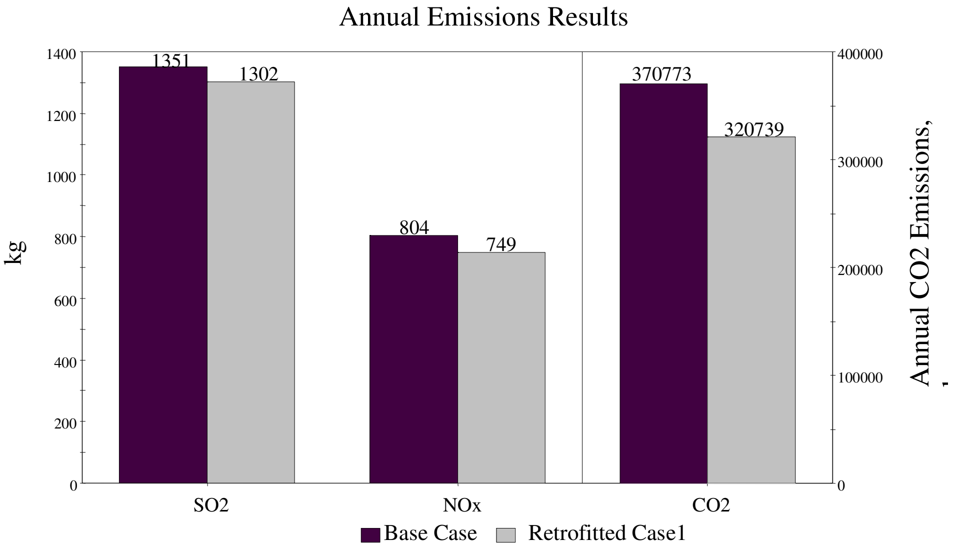


Figure 4.19 Annual CO_2, NOx, and SO_2 results for *base case* and *retrofitted case1*

As the next step a combined set of energy efficient retrofitting scenarios were applied to all four facades of the *base case* building with respond to orientation of facades. This new building scheme was called *retrofitted case2*. The aim of these interventions was to reconfigure the overall building envelope so that it incorporates energy efficient strategies in a way to provide minimum heat loss and maximum use of solar heat gain. The applied energy efficient measures and the resulting U values are depicted in Table 4.2. The intention was to modify the envelope to respond to the challenges and opportunities presented by different façade orientations. The distribution of thermal mass and the amount of thermal insulation depends on the orientation of the given surface in building scheme for the *retrofitted case2*.

Table 4.2 Wall configuration for retrofitting scenarios

		Applied retrofitting Measures	Derived U value
NorthEast Façade			
	Walls	75mm insulation, 250mm added mass	0.33
	Glazing	Double Glazing Low-e	
NorthWest Façade			
	Walls	75mm insulation	0.34
	Glazing	Double Glazing Low-e	
SouthEast Façade			
	Walls	50mm insulation, 250mm mass	0.46
	Glazing	Double Glazing Low-e	
SouthWest Façade			
	Walls	50mm mass, 250mm insulation	0.44
	Glazing	Double Glazing Low-e	

With this view, the NorthEast façade was assigned to have 75mm insulation and 250mm added massive layer where this retrofitting scenario represent the largest amounts for both measures. The aim was to alter the thermal properties of the NorthEast facade to have minimum thermal conductivity and maximum thermal capacity as it was calculated to be the critical façade through which maximum heat loss occurs.

Increasing thermal resistance of NorthWest Façade was maintained by applying 75 mm insulation. No thermal mass was added to this façade as a surface with north orientation can provide little use of thermal capacity, since it only exhibits small heat gains due to low solar radiation it gets.

Retrofitting measures for Southeast and SouthWest Façades include identical applications for thermal insulation and mass. As these two facades display relatively low impact on building heating energy demand they were assigned to have 50 mm insulation layer which can provide necessary value for thermal resistance according to TSE 825. 250 mm concrete layer was added to both surfaces as south orientations can operate effective use of thermal mass with biggest solar heat gains.

The simulations showed that the building performance improved significantly. A 52.41% of decrease was achieved in building energy use and annual heating energy use was calculated as 236.55 MWh for *retrofitted case2*. Figure 4.20 displays the thermal energy use of the building before and after retrofitting scenarios are applied and clearly demonstrates the difference monthly.

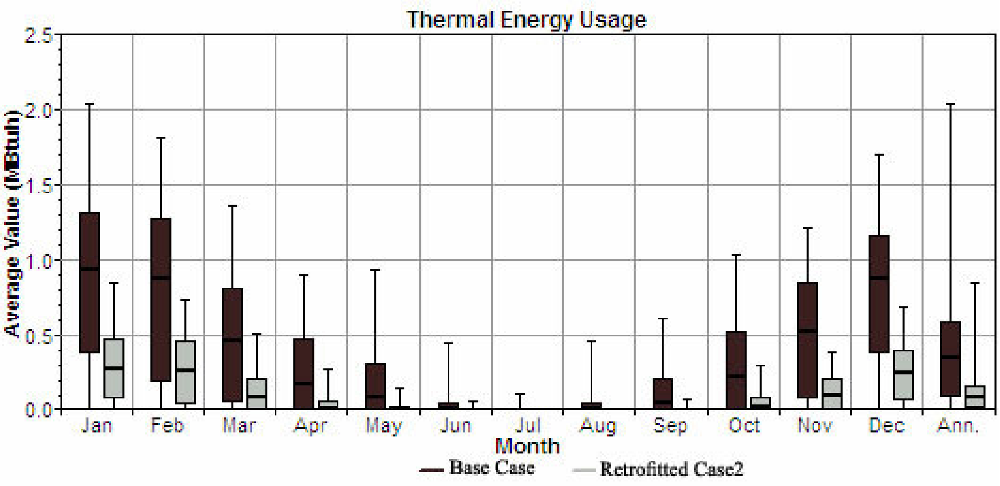


Figure 4.20 Monthly averages of total thermal energy usages for space heating *base case* and *retrofitted case2*

Figure 4.21 displays the performance of *retrofitted case2* in terms of annual emission production. There was a 32.49% decrease in CO_2 production, 8.69% decrease for SO_2 and 16.74% decrease for NOx gasses.

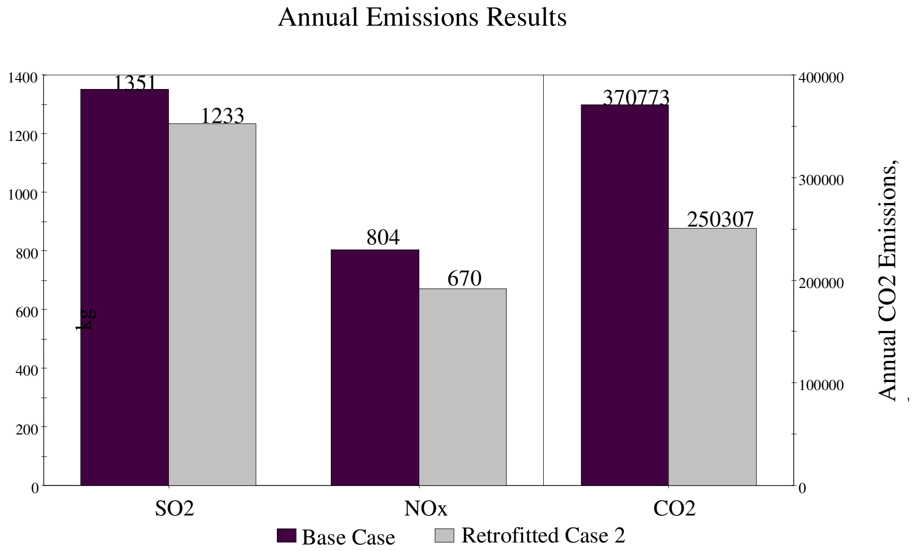


Figure 4.21. Annual CO_2, NOx, and SO_2 results for Base Case and Retrofitted Case2

To be able to asses the effectiveness of the scenarios adapted in *retrofitted case2* the analysis was carried one step further. As a new step, *base case* building scheme was modified to incorporate the maximum values for thermal insulation and thermal mass measures in all four facades.

The resulting new building, *retrofitted case3*, was assigned to have 75mm insulation and 250 mm mass for all orientations. The analysis showed that the *retrofitted case3* provided 53.83 % decrease in annual heating use which is a slightly better than *retrofitted case2*. Comparison of annual heating energy use and annual emission reductions are given in Figure 4.22 and 4.23 respectively. The scenarios applied in *retrofitted case2* prove to be most effective alternative for energy efficiency by providing a significant amount of energy saving and by maintaining to stay within the ranges of applicability and economy.

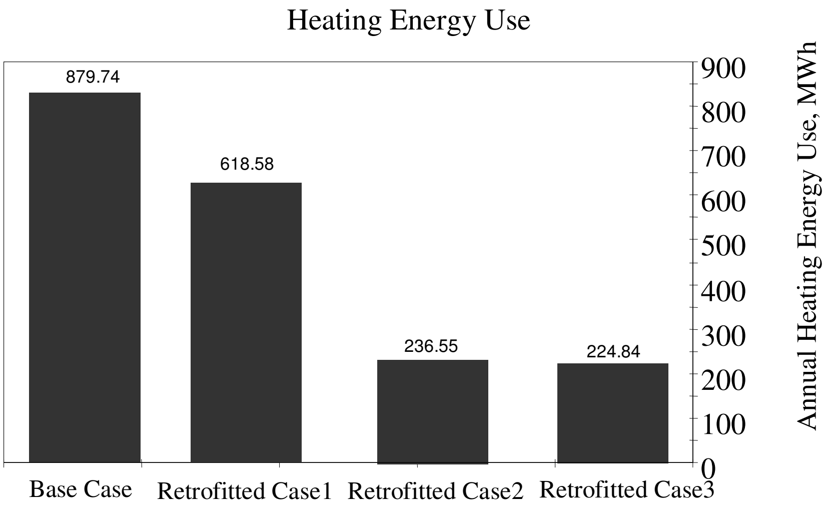


Figure 4. 22. Annual heating energy use after retrofitting scenarios

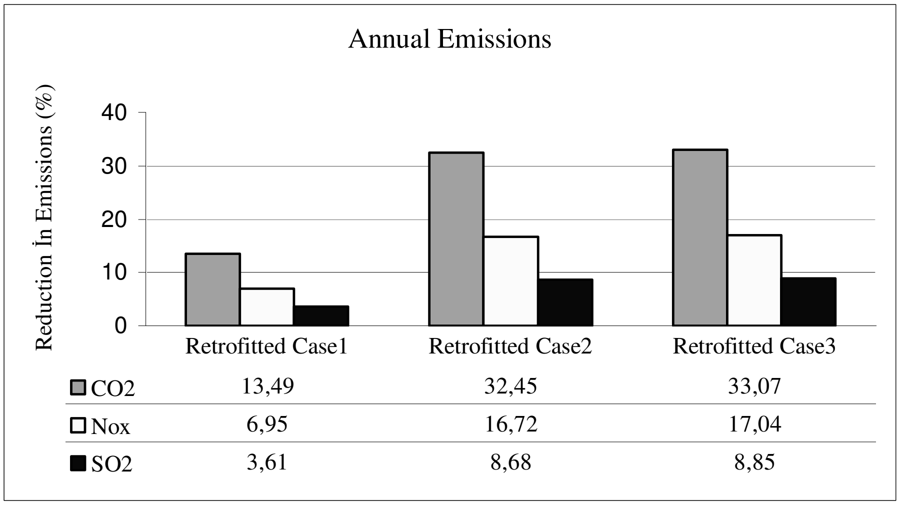


Figure 4.23. Annual reductions in CO_2, NOx and SO_2 gas emissions after retrofitting scenarios

It is important to understand that dependence on the physical enclosure is reliable, and often more effective than the application of energy; where the skin of the building has been badly designed, and fails to play its part in reducing the undesirable characteristics of the local climate. Therefore it is essential that the physical enclosure be exploited to the maximum, leaving the experimental services to cope with as small change as possible, to produce effective, energy efficient and economical buildings.

CHAPTER 5

CONCLUSION

Environmental comfort, energy conservation and sustainability are among the major functional considerations in buildings. The most important elements that contribute to the reduction of heating load and greenhouse gas emissions in buildings are the proper choice of glazing material, amount and wall placement of thermal insulation, and the amount and placement of the thermal storage mass within the envelope of the building.

This thesis describes the investigations performed on the thermal behavior of MM building situated on the Middle East Technical University Campus in Ankara. These investigations were based on envelope characteristics such as; the thermophysical properties of materials, material thicknesses and configurations. Successful energy efficient retrofitting strategies evaluated single measures or combination of measures related to special energy related characteristics of the building in order to improve its energy performance.

Due to the large number of variables considered in the analysis of several alternatives, computer assistance was essential to achieve minimum energy conservation. In this study the impact created on the yearly heating load and annual greenhouse gas emissions were predicted by using the detailed building heat transfer simulation program ENERGY-10. The computer model was used for accurate description of the building and to create a first assessment of the building’s existing thermal condition, energy performance, indoor environmental quality, and other criteria depending on the use of the building, with an estimate of the total heating energy use of 879.74 MWh.

During the study, the original *base case* description was modified by applying energy efficient retrofitting strategies to the envelope. In the next step alternative solutions with different thermal mass, thermal insulation and glazing type were generated with the simulation program. The results of the simulations of the modified building schemes were compared with the original *base case* and with the performance goals.

Window gains were proved to be an important factor in thermal performance and significant savings could result with proper choice of window glazing. This research study examined effects of four types of glazing; double glazing, triple glazing and low-e coated double and triple glazing. Analyses of this research showed that a saving in the annual heating load between 83.85 and 161.20 MWh can result depending on the glazing type for the examined case study building. The lowest annual heating with an energy saving was reached when low-emissivity double glazing windows were used when compared to the corresponding construction with clear single-glazing windows in *base case*.

The results of the simulation of this study have shown that where the heating of the building was the major concern, insulation was the predominant effective envelope factor. Thermal insulation had the highest effect on the heating load, within the practical range of thermal insulation that has been established in evaluating case study building; increasing thermal insulation was shown to have significant effect on reducing heating load.

This study revealed that in analyzing the impact of the insulation configuration, walls with insulation outside always perform better than those with the insulation inside. Differences in heating energy demand between the configuration ‘all insulation inside’ and the most effective configuration from the point of view of energy savings ‘all insulation outside’ may exceed 3.4 % for the simulated office building.

The evaluation showed that although thermal insulation was the most determining factor in building thermal performance, predicting the appropriate amount of thermal insulation was rather complex. According to the calculations carried the amount of reduction in energy use started to diminish when the thickness of insulation was increased beyond 75 mm.

With respect to thermal mass, the analysis showed that this property had the third major effect on heating load. The principal part of the envelope load is proportional to the difference in dry bulb temperatures between outdoors and indoors. This complex interaction of the envelope loads also affects the load timing, which in turn determines the peak load imposed on the HVAC system; these peak loads have a major impact on energy use. Thermal mass plays a major role in balancing the temperature fluctuations in the interiors. Although energy saving which was accomplished as a result of the thermal mass was not great, thermal mass had significant impact on increasing the hours where highest temperature was achieved under passive mode. By this property of thermal mass, heat is released into the building, satisfying part of the heating load when energy is needed.

The research study showed that the best thermal performance was achieved when a combination of energy efficient retrofitting scenarios were adapted. Energy efficient modifications that applied only to the critical façade, which was defined to be the façade that had the maximum contribution to energy use, can decrease the energy use by 21.76%. When modifications were carried on all four facades with the distribution of thermal mass and the amount of thermal insulation depending on the orientation of the given surface in building scheme, this decrease was calculated to be 52.41 %.

These result show the importance of envelope strategies as the benefit were significantly high when considered that the evaluations were carried out on the envelope properties only. These findings reveal that by expanding the strategies to further energy related aspects of construction it is possible to create higher energy savings. The future researches can therefore analyze the aspects related to control of HVAC size and type and moveable elements of envelope. As economical features were not analyzed throughout this study another aspect can be investigating the cost related properties of energy efficient retrofitting of this study.

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