Investigation of passive retrofitting techniques to improve the energy efficiency and indoor thermal comfort of an office building.

by

Katerina A. Stroponiati

Submitted to the Department of Production Engineering and Management at the

TECHNICAL UNIVERSITY OF CRETE

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Dimitrios V.Rovas

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ABSTRACT

Building design is a high complex task, part art and part science, in which architects and engineers need to address a number of often conflicting requirements ranging from the pure aesthetic to the very practical, with important considerations being construction and operational costs. A particularly important functional consideration is conditioning of the building spaces to achieve comfort conditions for the building occupants. Depending on the building's modus operandi, this involves: planning of the building envelope, appropriate selection of active and passive climate control systems and lighting design. In concordance with stricter government regulations, the building has to be designed, and its subsystems have to be selected, so as to operate in an energy efficient manner. Energy efficiency is particularly important in view of rising energy costs and concerns over environmental effects. For example, in the selection of HVAC systems, proper selection, sizing and integration of the system with the building envelope can result in significant energy savings with a concomitant decrease in operational costs. In the present work we investigated passive retrofitting techniques to improve energy efficiency and indoor thermal comfort that can be applied to new or existing buildings.

We selected an office building situated in Crete, the southernmost island of Greece, as an archetypical example of building in Mediterranean region. A computer model of the building was created using the DesignBuilder software, and then a numerical simulation using the EnergyPlus integrated building simulation environment was used to estimate the energy requirements. Four different retrofitting scenarios were investigated: controlled natural ventilation; use of shading devices; and addition of a thermal mass using a floor concrete slab. For each of these scenarios the energy savings were evaluated and thermal comfort indices were calculated. A critical evaluation regarding energy savings for each of these methods was performed, providing guidelines for buildings designers and facility managers on how to operate and renovate existing buildings in the Mediterranean region.

Έρευνα για την εφαρμογή παθητικών τεχνικών σε ένα υπάρχων κτίριο γραφείων με σκοπό την εξοικονόμηση ενέργειας και την βελτίωση της εσωτερικής θερμικής άνεσης.

από

Κατερίνα Α. Στροπωνιάτη

Υποβλήθηκε στο τμήμα Μηχανικών Παραγωγής και Διοίκησης

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ΠΕΡΙΛΗΨΗ

Ο κτιριακός τομέας είναι υπεύθυνος για το 48% περίπου της συνολικής τελικής κατανάλωσης ενέργειας σε παγκόσμιο επίπεδο. Η κατανάλωση αυτή, κυρίως σε μορφή πετρελαίου και ηλεκτρισμού εκτός της σημαντικής οικονομικής επιβάρυνσης λόγω του υψηλού κόστους της ενέργειας, ευθύνεται σημαντικά για τη μεγάλη επιβάρυνση της ατμόσφαιρας με ρύπους, κυρίως διοξείδιο του άνθρακα (CO_2), που ευθύνεται για το φαινόμενο του θερμοκηπίου. Προβλέπεται ότι θα υπάρξει σημαντική αύξηση της κατανάλωσης στην προσεχή δεκαετία. Προκύπτει επομένως επιτακτικά η ανάγκη παρέμβασης, μειώνοντας την κατανάλωση κυρίως στη θέρμανση και την ψύξη του κτιρίου. Η μείωση της κατανάλωσης ενέργειας με παράλληλη βελτίωση των συνθηκών διαβίωσης και της ποιότητας ζωής τόσο μέσα όσο και έξω από τα κτίρια εξασφαλίζεται εν μέρει με τον κατάλληλο σχεδιασμό του κτιρίου και τη χρήση ενεργειακά αποδοτικών δομικών στοιχείων και συστημάτων (παθητικός σχεδιασμός) και εν μέρει μέσω της υψηλής αποδοτικότητας των εγκατεστημένων ενεργειακών συστημάτων (ενεργητικός σχεδιασμός) η οποία προϋποθέτει την άριστη ποιότητα του σχετικού εξοπλισμού και της εγκατάστασής του. Στην παρούσα εργασία μελετήσαμε παθητικές

τεχνικές με σκοπό την εξοικονόμηση ενέργειας και την βελτίωση της θερμικής άνεσης των εργαζομένων. Το κτίριο που επιλέχθηκε για την εφαρμογή των τεχνικών αυτών έγινε σε ένα υπάρχων κτίριο γραφείων που βρίσκεται στην Κρήτη. Ο σχεδιασμός και ο υπολογισμός της ενεργειακής αποδοτικότητας του κτιρίου πραγματοποιήθηκε μέσω του υπολογιστικού εργαλείου ενέργειας για κτίρια, EnergyPlus. Μελετήθηκαν τρείς διαφορετικές τεχνικές παθητικού σχεδιασμού και οι συνδυασμοί τους : φυσικός αερισμός, βελτιωμένα παράθυρα, θερμική μάζα. Για κάθε μια από τις τεχνικές υπολογίστηκε η εξοικονόμηση ενέργειας και η βελτίωση της θερμικής άνεσης, παρέχοντας οδηγίες στους μηχανικούς-σχεδιαστές κτηρίων σχετικά με την αποτελεσματικότητα μεθόδων ανακαίνισης υπαρχόντων κτηρίων στην περιοχή της Μεσογείου.

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Chapter 1

Introduction

1.1 General problem description

Since the beginning of the industrial revolution in the late 18th century, there has been an increasing need for energy — see Figure 1-1. Initially, carbon-based energy sources were used exclusively: wood, peat, coal, oil, and natural gas. Today, however, as needs increase, new alternative energy sources are also being utilized. Although a shift towards renewable energy sources is indeed taking place, it is happening at a much slower rate than desired. As Figure 1-2 illustrates, oil is still the most important energy source, with renewable and nuclear energy gaining ground as more environmentally-friendly alternatives. At present, demand for energy is increasing at a much faster rate than available supplies can meet. The industrialization of emerging countries, increases in human population, rising demand for consumer goods, use of energy-intensive domestic appliances and means of transport, all suggest that demand for energy will grow even faster in the near future. This increasing demand drives energy prices up, and the socio-economic impacts are already apparent. While it can be argued that the use of better technologies can increase supply and help control energy prices, this will be, at best, a short-term solution to the energy problem. The world still relies too much on naturally-occurring energy sources like fossil fuels. The concern is that, on the one hand, available supplies are fast dwindling and the time when these will be exhausted is not too far in the future and, on the other hand, that "unscrupulous" use of energy will have dire environmental consequences: the burning of fossil fuels creates atmospheric, water and land pollution, and the use of nuclear fuels produces byproduct toxic wastes that have to be carefully stored. As human activities lead to increased emissions of CO_2 and greenhouse gases, global warming is no longer "a theoretical possibility advocated by environmentalists and other groups". Its effects are real and we are already seeing them: climate changes, melting of the polar ice-caps and increased incidence of natural disasters. The efficient use of energy is the only way to mitigate and reverse these environmental effects. Otherwise, the bet against nature is lost and the price for humanity to pay is too high — survival itself.

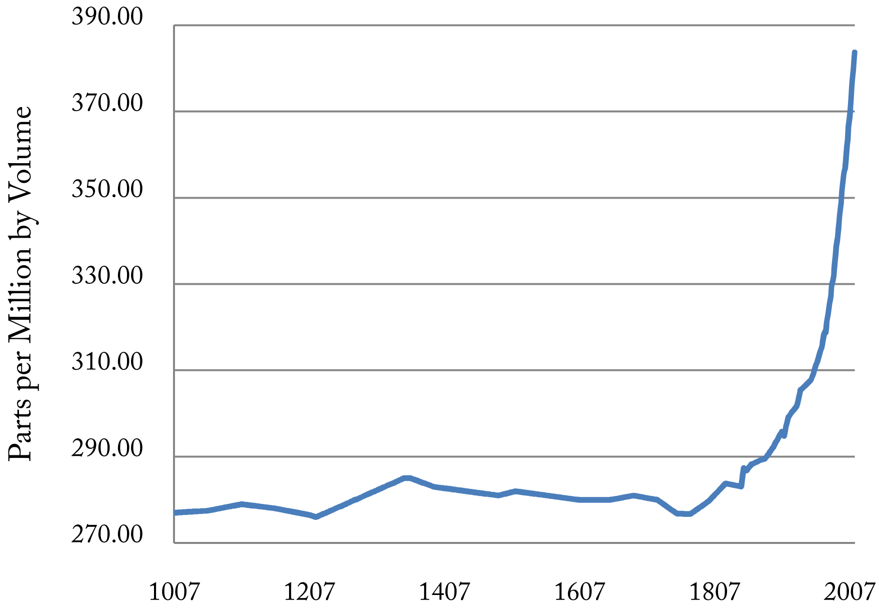

Figure 1-1. Global Atmospheric Concentration of Carbon Dioxide, 1000-2007. (Source: NOAA, Scripps, CDIAC and World-watch)

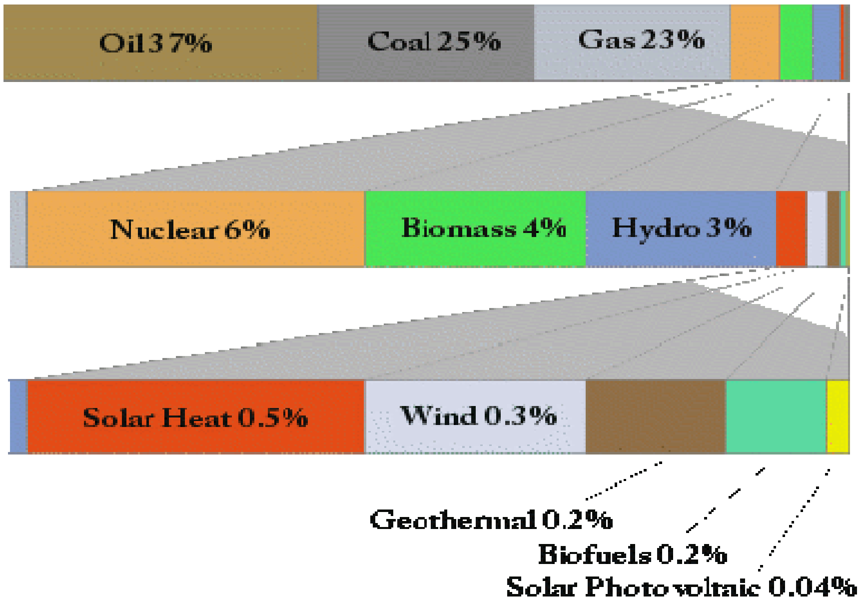

Figure 1-2. Global energy usage in successively increasing detail. (Source: REN21 2006 global status report on renewable).

1.2 Energy consumption in buildings

The heating and cooling of buildings today accounts for a high proportion of energy consumption. Higher living standards lead to active climatization of buildings, often without any adaptation to the buildings themselves, which leads to excessive energy consumption and high costs. As Figure 1-3 indicates, in many countries, especially in the industrialized world, buildings account directly for almost half (48%) of total energy consumption, and even more, when one includes the cost of manufacturing the materials required for construction. Energy consumption in office buildings is one of the highest compared to the consumption of other building types. In fact, office building energy bills are the highest of any commercial building type.

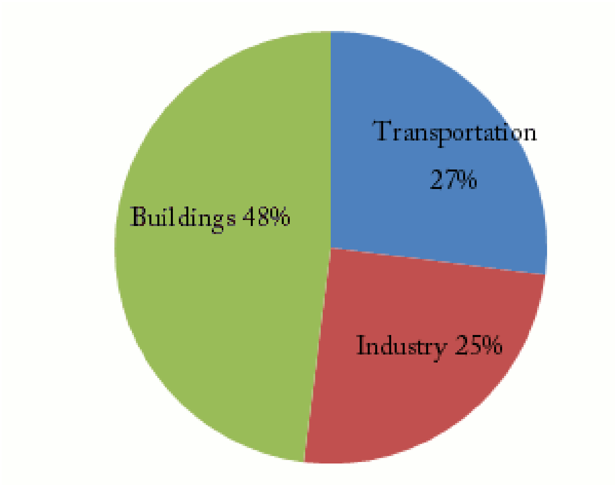

Figure 1-3. Global Energy Consumption. (Source: US Energy Research and Development Administration).

As Figure 1-4 indicates, the largest use of energy in office buildings is for heating (25%), followed by cooling (23%), office equipment (20%), lighting (17%), and miscellaneous other uses (10%), such as ventilation fans, elevators, and other equipment and appliances. The annual energy consumption in office buildings varies depending on geographic location, use and the type of equipment, operational schedules, type of construction (envelope), use of HVAC systems, type of lighting, etc.

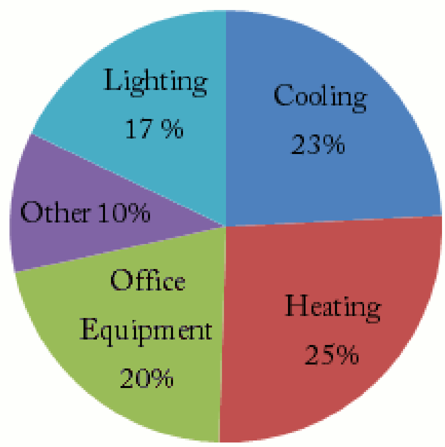

Figure 1-4. Energy use in office buildings. (Source: Energy Information Administration, Commercial Buildings Energy Consumption Survey).

1.3 Energy efficient techniques in buildings

1.3.1 Introduction

The purpose of energy saving measures is to reduce energy consumption by using energy effectively without giving up comfort conditions. Energy efficient office buildings, apart from reducing operational costs, can enhance the comfort of workers and improve their performance, thereby boosting productivity [3].

For a building to be energy efficient it is necessary to control the input of energy and energy loss through regulatory systems and/or through 'passive' techniques. Traditional buildings often neglected the exterior climate, even if 'comfort' was not always achieved at all times of the day or in all seasons. However, modern buildings without active climatization, both low-cost and luxury, often provide a poor indoor climate, leading to fatigue and health risks. Modern construction techniques offer technical possibilities to achieve high comfort levels though heating, cooling and inside fresh air. We therefore tend to forget the old knowledge about how to adapt buildings to the climate passively. The application of energy efficiency techniques, as well as use of solar or ambient alternative energy sources in buildings, require knowledge of the specific energy characteristics of the building — see [1]. Using energy-efficient design and technologies in constructing new office buildings can cut energy operating costs by as much as 50% [2].

For example, day-lighting through windows helps create a visually stimulating and productive environment for building occupants, while reducing as much as one-third of lighting energy costs [4]. Direct day-lighting through windows can cause glare and discomfort conditions because of the heat gain [5]. There are several techniques to introduce diffuse light into the office space to avoid creation of uncomfortable conditions. One of the most common techniques is shading devices [6]. As Figure 1-5 illustrates, during summer, external window shading is an excellent way to prevent unwanted solar heat gain from entering a conditioned space; during winter, it may be desirable to allow solar radiation to pass directly into the room, to provide a useful heating effect. Furthermore, energy-efficient windows can be utilized with special coating that reflect up to 90% of heat energy but are transparent to visible light [7]. In hot climates, they reflect external heat while admitting visible light, thereby keeping the house cooler in the summer months. In cold climates, they reflect heat back into the house providing an insulating effect while admitting visible light — see [8, 9] for more details. Additionally, when artificial lighting is required, the selection of energy efficient light sources and installation of lighting controls can help maintain visual comfort — see [10].

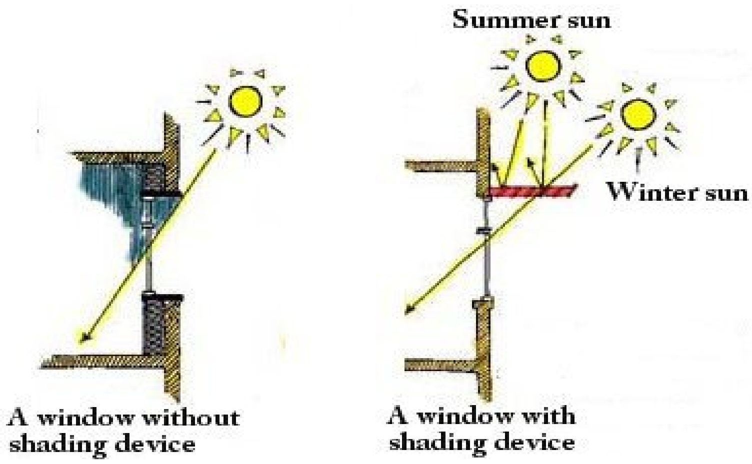

Figure 1-5. *The operation of an exterior shading device in winter and summer. (Source: Sustainable Energy Development Office of Australia)*

Additional considerations to improve comfort conditions is to maintain a non-toxic chemicals environment, better temperature control, and indoor air quality — see [11] for details. Fresh air is required in buildings to alleviate odors, to provide oxygen for respiration, and to increase thermal comfort. Natural ventilation can be used as an alternative to air-conditioning plants, saving 10%-30% of total energy consumption [12]. Ventilation serves to provide fresh air all year and to remove excess heat in summer. This may help to relieve symptoms associated with "sick building syndrome". As Figure 1-6 illustrates, natural ventilation systems rely on natural driving forces, such as wind and the temperature difference between a building and its environment, to drive the flow of fresh air through a building. If a system is carefully designed, wind may push air in at the facade and draw it out again at the roof [13]. There are many natural ventilation techniques, which use the natural forces of wind and buoyancy to deliver fresh air into buildings — see [14] for an overview.

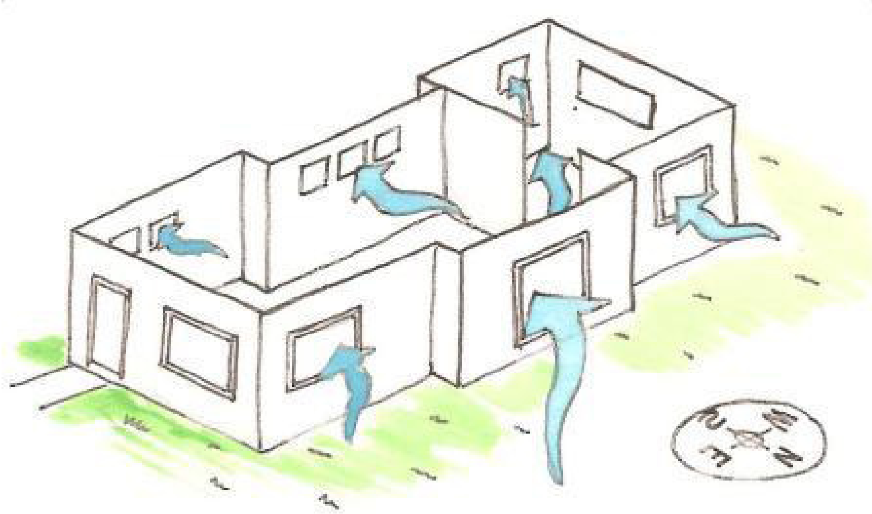

Figure 1-6. Natural ventilation concept where cold breezes air comes in from the north large openings and absorbs heat from the indoor environment

But if the building is in an urban environment (highly polluted environment) or/and if the outside temperature is higher than the inside temperature, then natural ventilation might not be the solution of choice, but mechanical ventilation might be more appropriate. Mechanical or forced ventilation is used to control indoor air quality. Excess humidity and odors can often be controlled via dilution or replacement with outside air. However, in humid climates much energy is required to remove excess moisture from ventilation air [13].

The selection of building's construction materials can have significant effect in its energy requirement and thermal behavior. The thermal properties of the materials and their properties when combined together to form building's elements have a direct effect on the building envelope. Too much attention is often given solely to the choice of building materials used for the construction. A greater role for the overall thermal performance is the interaction of the materials with the building design of the local climate. A standard recommendation is that 'local' materials should be used as much as possible. However, in the choice of materials not only the production, transportation and construction costs should take into account, but also the life-cycle cost of the building, including the operation and the demolition and possible recycling of the material.

A proper selection and combination of the above mentioned passive design strategies can have significant impact regarding thermal comfort and energy efficiency. This strongly depends on the climatic conditions of the region where the building was constructed.

These techniques and effect in building's envelope are further analyzed in Chapter 2. In Chapter 4, these techniques are applied on the case-study building to evaluate their potential in reducing energy consumption and improving internal conditions.

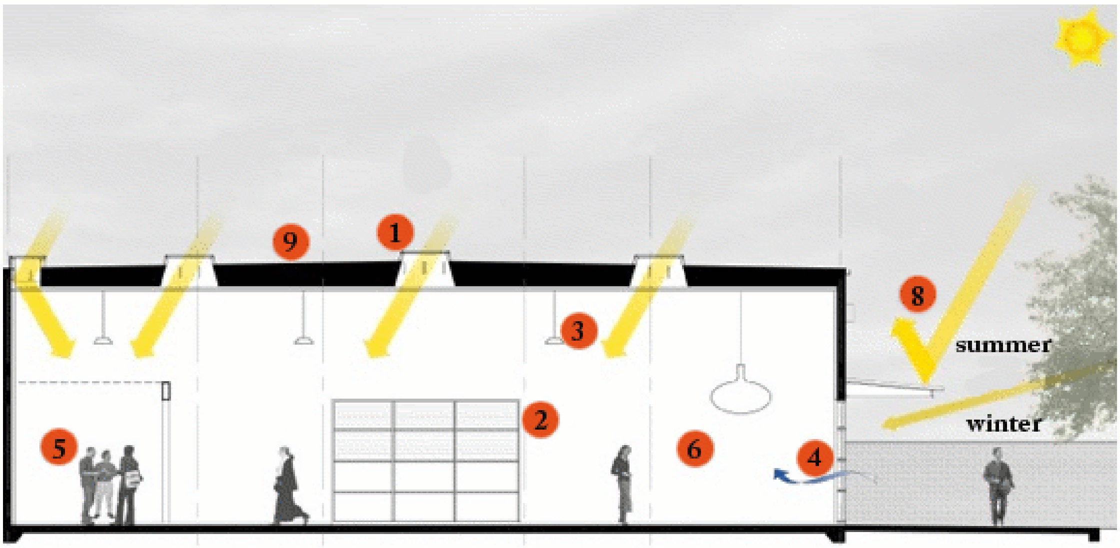

Figure 1-7. Key elements of energy efficient heating and cooling. 1. Day-lighting, 2. Energy efficient windows, 3. Energy efficient artificial lighting, 4. Natural ventilation, 5. Energy Efficient Office Equipment, 6. Construction materials, 8. Shading and 9. Insulated roof construction

1.3.2 Example of an energy efficient office building

To illustrate the potential and efficiency which is achieved by smart buildings we investigate an existing application: the design and construction of a bioclimatic and low-energy consuming building which utilize various soft–energy forms and energy–saving techniques. The bioclimatic office-laboratory building was designed in 1998 by associates of CRES as a demonstration building for the application of energy technologies. The building was completed in July 2001.

The building includes a large number of systems based on renewable energy sources (RES) and energy technologies for demonstration purposes as well as for monitoring and evaluation of their efficiency. Finally, to assess the performance of energy technologies the users interact with these systems to export conclusions regarding the effect of user behavior.

The building was constructed according to its design specifications and Greek building regulations. The building envelope was constructed using concrete with steel. The walls are double brick and, as Figure 1-8 indicates, the insulation was placed on the outside to avoid creating thermal bridges. The internal walls are made of drywall (gypsum board), internally insulated with fiberglass.

Figure 1-8. External insulation on the north face of the building

The building design use solar energy for heating by incorporation of passive solar systems: direct gain systems (openings on the south face for collecting solar radiation for passive heating during the winter. A greenhouse was added to the south face of the building, where solar radiation is collected as heat and is distributed through openings in the building. Solar air collectors' air panels were incorporated into the south face of the building which collect solar radiation and give off heat either through openings (directly) or as preheated air to a heat pump on the roof (indirectly). As Figure 1-9 indicates, a solar atrium (glazed part of the roof of the building) was used to collect solar radiation and produce thermal energy to heat the central internal part of the building. Transparent insulation was also used to reinforce solar gains on the south facing parts of the building.

Parallel to and in conjunction with the passive solar systems, day-lighting systems were studied in order to provide the building with natural light for the greatest possible part of the day resulting in a reduction of electricity required for lighting. For this purpose, the following were designed: Roof lighting system using a partially glazed roof to let in natural light for the central part of the building; an atrium into which internal doors open to allow day-lighting to enter the innermost parts of the building.

Figure 1-9. Office building's solar atrium. The solar atrium is used as a passive cooling system, for direct natural lighting and solar radiation

Passive cooling systems installed to avoid overheating and reduce air conditioning requirements:

- Shading systems (vertical awnings) on the south facade, vertical window blinds on the east west facades) combined with internal venetian blinds, see Figure 1-10.
- Natural cross ventilation techniques with window openings, fans or skylights.
- Natural ventilation systems through mechanically operated openings in the roof and backed up with fans.

Figure 1-10. Sun protection systems on the south and east facades

Artificial light is supplied through the general lighting installation of the building which is automatically controlled by a Building Energy Management System (BEMS). The reason for installing a BEMS was the monitoring and/or automatic control of the building's electrical and mechanical installations so that it will be possible to have immediate access, uninterrupted operation, settings adjustment and data analysis for all the building and system functions from a single control station.

The energy technologies and systems installed in the building cost, in 1999 prices, 11% (39,780 €) of the total cost of the building. Based on the results of the first 126 days of energy measurements in the building and on the calculated energy saving (100 KWh/year/m^2) compared with similar conventional buildings, there is a payback period of 14.5 years. The building was a demonstration project and installed systems have increased the cost of energy technologies (three air conditioning systems, double number of sensors and actuators for the BEMS, etc.), otherwise, the payback period would have been much smaller.

1.3.3 Retrofitting: The solution for existing buildings

While it might be easier to apply these methods described above to new buildings, existing buildings can also benefit. The real-estate industry has recently begun to turn its attention to "greening" existing buildings. Within many European countries there is a considerably higher activity in retrofitting and reusing buildings, than in constructing new ones. All office buildings have to be retrofitted, more or less thoroughly, at least a couple of times during their lifetime. Renovations that replace older systems with more efficient technology can yield savings of up to 30%, with the same positive impact on building comfort. The aim of the retrofitting is to improve indoor environment together with a reduction of the energy consumption and environmental impact. Application of passive solar techniques coupled with energy efficiency retrofitting techniques present important energy and environmental benefits.

1.4 Significance of the study

1.4.1 Methodology

Efficient application of energy retrofitting measures in office buildings is mainly related to the application of systems and techniques dealing with the use of passive retrofitting options and the use of measures related to the rational use of energy.
The proposed interventions can be classified into

- Actions aiming to improve the envelope of the building,
- Use of passive solar heating techniques and components.

Specifically, actions aiming to improve the envelope of the buildings were classified to the reduction of the heat transmission through the building envelope, by applying insulated frames instead of non–insulated and by replacing energy efficient glazing instead of conventional glazing. Additionally, by integration of passive solar heating and day-light components and improvement of natural ventilation and solar control.

Retrofitting actions aim to improve thermal comfort conditions during the summer-period and decrease the cooling load of the buildings. These interventions aim to decrease solar and internal heat gains and to control the solar and internal heat gains in the building. These include mainly use of more appropriate solar control devices the use of natural ventilation, setback cooling or heating as well as techniques taking advantage of the thermal mass of the building. Finally, actions aiming to improve lighting conditions decrease the energy consumption for artificial lighting by introducing daylight.

In order to investigate the effectiveness of various retrofitting interventions on the improvement of the energy performance of the investigated building, different types of actions were studied, ranging from simple to global approaches. Regarding the retrofitting interventions considered for the building, three types can be considered:

- Measures, involving passive design actions.
- Scenarios, involving combined passive design actions

1.4.2 Scope and limitations

This research is focused on the proposed passive designs techniques applied in office buildings. This study does not investigate the effects of major changes to the configuration of the building in terms of building shape and form, orientation, size, or different window sizes and proportions. Additionally, this thesis does not investigate the effects of using hybrid designs, which involve a combination of passive designs and supplemental HVAC systems.

The proposed designs are focused on how to enhance the overall thermal performance and comfort conditions of this office building using only passive heating and cooling designs. In terms of comfort analysis, this research uses the comfort indices recommended by ASHRAE and Fanger, the Predicted Mean Votes (PMV), as indicators of how comfortable an indoor condition is. In addition, this research does not investigate the comfort preferences of Greece in particular. The assumption is that universal human comfort preferences are based on worldwide research that can be appropriately applied to any group of occupants. An estimation of building energy performance with simulations is performed by the chosen building design parameters. The influence of climatic conditions has a significant impact on building energy consumption, in relation to the HVAC service systems of the office building— see Chapter 2 for more details. Based on these two sources of input, suitable indoor environmental conditions that conform to minimum codes, performance standards, and the maximum total energy consumption, can be determined by the simulation program. An illustration of the elements and boundaries of the building energy simulation are seen on Figure 1-11.

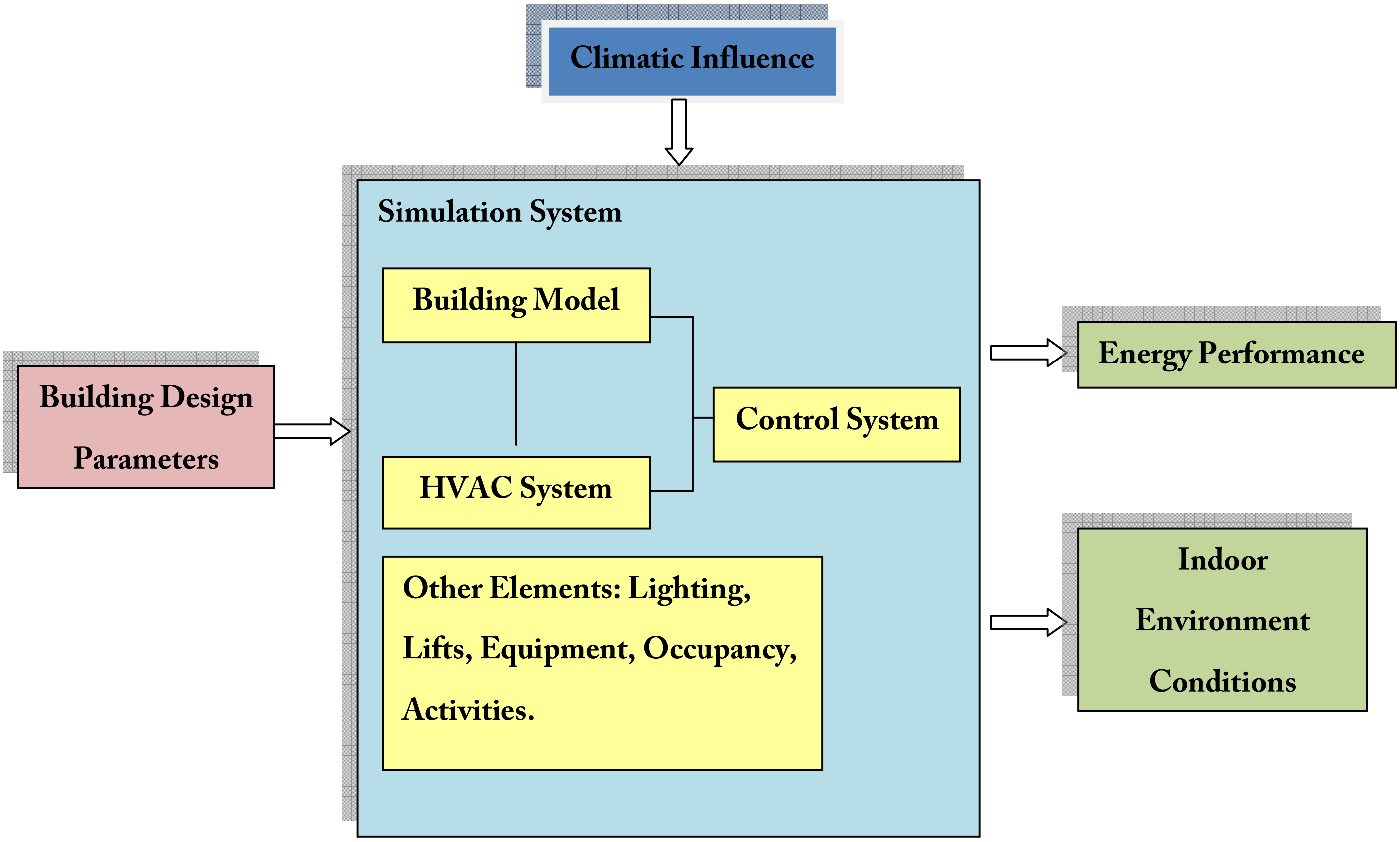

Figure 1-11. Major elements and boundaries of the building energy simulation

1.4.3 Organization

This chapter has discussed the general energy problem and the significance of building energy-efficient buildings. In this chapter there is also the methodology it is followed in this thesis. Chapter 2 reviews and discusses the previous studies related to this research, in order to provide a basis for conducting this research. This literature review includes information on passive cooling techniques for buildings, human thermal comfort and how the external and internal conditions effect building's energy consumption and thermal comfort. In this chapter there is also a review of energy and comfort codes and regulations about buildings. Additionally, there is an overview of the simulation tool applied to this thesis. Specifically it describes the simulation manager of the simulation tool and the heat balance equations which are used in order to simulate the office building's input data. Chapter 3 describes the office building and input data for the simulation tool, which include the location and climate, the construction, occupants' activity schedule and the HVAC system and its operation. Chapter 4 propose improved passive design strategies suggested in Chapter 2, which include shading devices, low-e glazing, natural ventilation, thermal mass techniques and temperature control by the HVAC system. These actions take place according to the methodology of retrofitting a building which is suggested in Chapter 1.

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Chapter 2

Literature Review

2.1 The building as an integrated dynamic system

2.1.1 Introduction

The building's envelope must respond to a wide and varying range of external and internal conditions. It can be argued that the main functional objective of a building design is to foster an acceptable environment for the building users. A number of sources acting via various heat and mass transfer paths help determine the building's indoor climate. As Figure 2-1 illustrates, these sources are:

- Outdoor climate of which — in the present context — the main variables are: air temperature, radiant temperature, humidity, solar radiation, wind speed, and wind direction.
- Heat generation by metabolic activity of the occupants.
- Usage of household or office appliances, lighting.
- HVAC system operation performing heating, cooling, and / or ventilation.

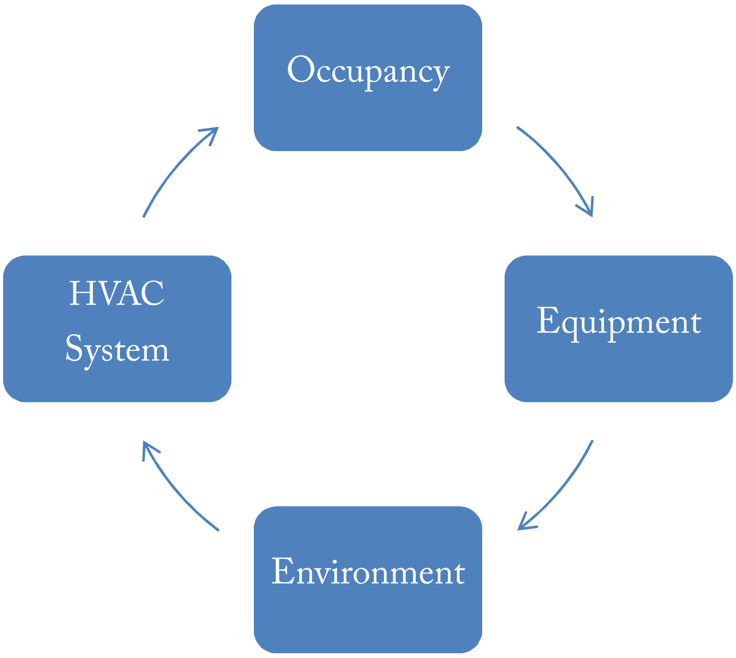


Figure 2-1. Parameters and their interaction to be taken into account when designing.

These sources alter the indoor climate via various heat and mass transfer path ways:

- Conduction through the building envelope and partition walls radiation in the form of solar transmission through transparent parts of the building envelope (e.g. glazing), and in the form of long-wave radiation exchange between surfaces.
- Convective heat exchange between building surfaces and the air, and for instance heat exchange inside plant components.
- Air flow through the building envelope, inside the building, and within the heating, cooling, and ventilation system.

2.1.2 Climate

Climate is defined as certain conditions of temperature, dryness, wind, light, etc. of a region. Different regions of the world have diverse characteristic climates. A place or region's climate is determined by both natural and human factors [15]. The natural elements include the atmosphere, geosphere, hydrosphere and biosphere; while the human factors can include land use and consumption of other natural resources. Changes in any of these factors can cause local, regional, or even global changes in the climate.

The relationship between people, climate and buildings is non-linear and interdependent [16]. Built up areas and cities would tend to have their own microclimate which would differ significantly from the climate of the region. Ground reflecting surfaces and artificial topographical features can affect wind flow, solar radiation and hence temperature patterns. It is now established that the consumption of energy in cities for buildings can make very significant changes to ambient temperature.

The most important strategy for low energy design of buildings is to design and build according to the climate where the building is located [17]. Buildings in developing countries are often designed with-out taking sufficient account of the climate. Factors such as the urban surroundings or climate characteristics (temperature, humidity, wind, solar radiation) are not given enough importance. Consequently buildings often have a poor indoor climate, which affects comfort, health and productivity [11]. As living standards rise people want to install heating and/or cooling equipment to improve thermal comfort. For buildings not adapted to the climatic conditions of their region they are located, the amount of energy to run the equipment, and its cost, can be excessively high with a negative impact on the environment [17].

2.1.3 Occupants thermal comfort

Buildings provide protection from external meteorological phenomena and aim at the development of comfort conditions for their occupants. Oftentimes, in the interior of buildings, climate control is not successful with direct impact in comfort conditions in the health of their users [3].

A precise definition of thermal comfort is hard to define. A range of environmental and personal factors need to be taken into account in the selection of the temperatures and ventilation that will make employees feel comfortable. Thermal comfort is the sensation of well-being of an individual in a specific environment.

According to [18], as thermal comfort is fixed situation of brain at which an individual does not wish any thermal change of internal environment and expresses satisfaction with prevailed thermal conditions.

Before mechanical heating, cooling and ventilation the design of the thermal environment was decided by experience. With the advent of modern air-handling and central heating systems the question of what conditions the system should be providing became critical. One of the major advances such systems afforded was control over the humidity, concentrated on finding combinations of temperature and humidity which best describe the feeling of warmth given by the environment.

One approach to finding what conditions are comfortable is to conduct field surveys. The experimenter then measures the physical characteristics of the environment and relates these to the subjects' feeling of warmth to find a relationship. Experimental work can also be carried out in a climate chamber. Climate chambers are laboratories which enable the experimenter to adjust the air and radiant temperature, humidity and air velocity. Such chambers have been widely used in controlled experiments investigating the effect of physical parameters on comfort.

Empirical approach

In the field survey (conducting a survey) the method is to ask subjects (group of people) taking part in the survey to assess their thermal sensation on a subjective scale. This assessment is generally known as the 'Comfort Vote'. The environmental variables are measured at the same time as the subjective reactions are taken. The aim is to find a temperature or a range of temperatures and other environmental variables which people will find comfortable. The full complexity of the situation is included in the responses of the subjects.

The first aim is to discover what combination of environmental variables best describe the subjective responses of the subjects. A number of such 'comfort indices' have been put forward over the years. Another approach is to use probit analysis which enables the proportion of people comfortable at any particular or combination of variables to be calculated.

The underlying assumption of the field survey is that people are able to act as meters of their environment. This assumption is rooted in the findings of psychophysics. In effect the subject is used as a comfort meter, not of temperature alone but of all the environmental and social variables simultaneously. Only the effect of time is generally ignored in the analysis.

Analytical Approaches

There is an obvious advantage to having a complete picture of the various thermal factors involved in man's interactions with the environment. A number of scientists have set out to build models of the physical and physiological conditions governing thermal comfort, the best known are those of Fanger's (1970) Predicted Mean Vote (PMV) and Gagge's (1972) Standard Effective Temperature (SET). Fanger's model forms the basis for ISO Standard 7730 which includes a computer programme for calculating the PMV.

In order to feel comfortable, humans must maintain an internal body temperature within a narrow range of 36.5-37 °C. As Figure 2-2 illustrates, the human body exchanges heat with its environment through conduction (by direct contact), convection (transported by air), radiation (mainly short-wave visual light and long-wave heat) and evaporation/condensation (heat released through change of state of water, also called latent heat). Fanger's basic premise is that a balance between the heat produced by the body and the heat lost from it is a necessary, but not a sufficient condition for thermal comfort. It is not sufficient because there are situations in which a theoretical balance would occur, but which would not be considered. So the determination of comfort conditions is in two stages: first find the conditions for thermal balance and then determine which of the conditions so defined are consistent with comfort.

The basic equation for thermal balance is:

$$H - E_{is} - E_{sw} - E_{res} - C_{res} = K = R + C \qquad (1)$$

Where:

H: is the net metabolic heat production (metabolic rate less work done),

K: is the heat transfer from the skin to the outer surface of the clothed body by conduction, through the clothing.

E_{is} : is the evaporative heat loss from the skin,

E_{sw}: is the heat loss from the evaporation of sweat,

E_{res} and C_{res} : are the evaporative and convective heat losses from respiration,

R and C : are the radiant and convective heat losses from the surface of the clothing

Equations can be derived for E_{is}, E_{sw}, E_{res}, C_{res}, R and C if the metabolic rate, the clothing resistance and the environmental parameters are known. It remains to define the conditions consistent with comfort within the conditions for heat balance.

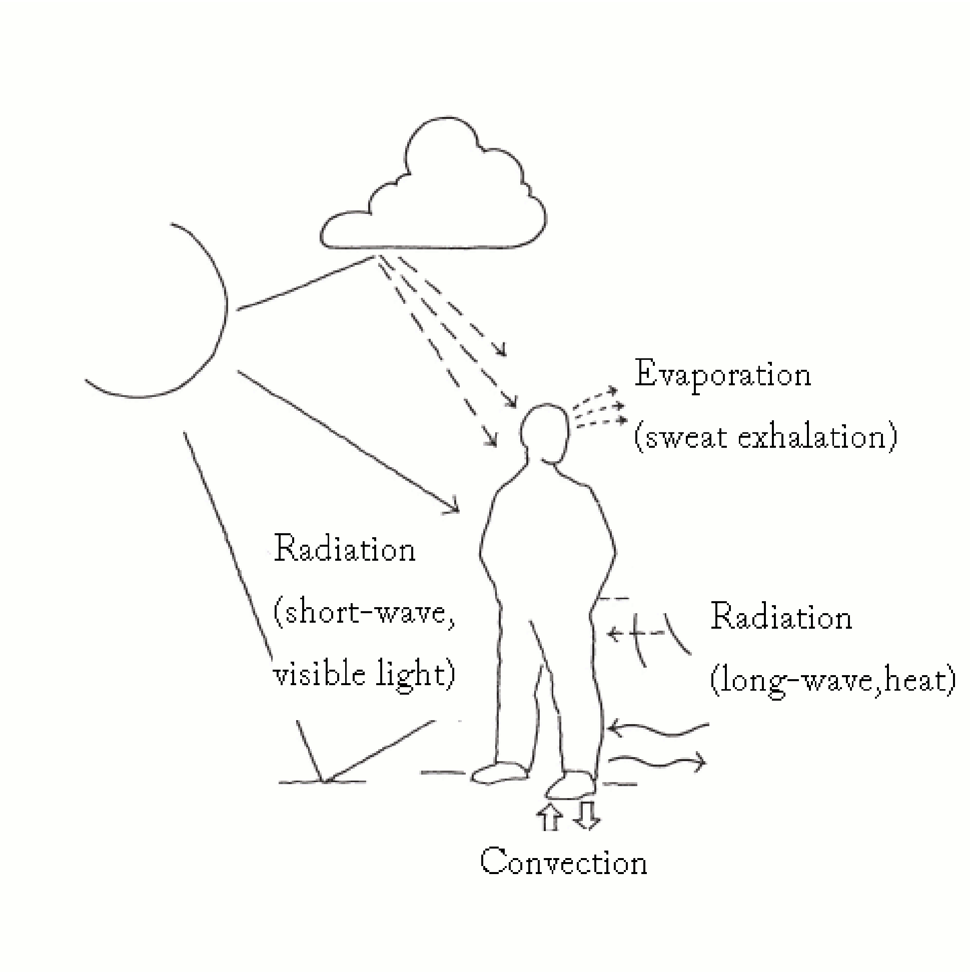


Figure 2-2. The four modes of heat exchange: conduction, convection, radiation and evaporation. (Source: ASHRAE Handbook, Thermal Comfort)

Fanger proposed that the condition for thermal comfort is that the skin temperature and sweat secretion lies within narrow limits. Fanger obtained data from climate chamber experiments, in which sweat rate and skin temperature were measured on people who considered themselves comfortable at various metabolic rates. Fanger proposed that optimal conditions for thermal comfort were expressed by the regression line of skin temperature and sweat rate on metabolic rate in data from these experiments. In this way an expression for optimal thermal comfort can be deduced from the metabolic rate, clothing insulation and environmental conditions. Fanger extended the usefulness of his work by proposing a method by which the actual thermal sensation could be predicted. His assumption for this was that the sensation experienced by a person was a function of the physiological strain imposed on him by the environment. This he defined as "the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level". He calculated this extra load for people involved in climate chamber experiments and plotted their comfort vote against it. Thus, he was able to predict what comfort vote would arise from a given set of environmental conditions for a given clothing insulation and metabolic rate. The final equation for optimal thermal comfort is fairly complex and need not concern us here. Fanger has solved the equations by computer and presented the results in the form of diagrams — see Figures 2-3, 2-4 — from which optimal comfort conditions can be read given knowledge of metabolic rate and clothing insulation.

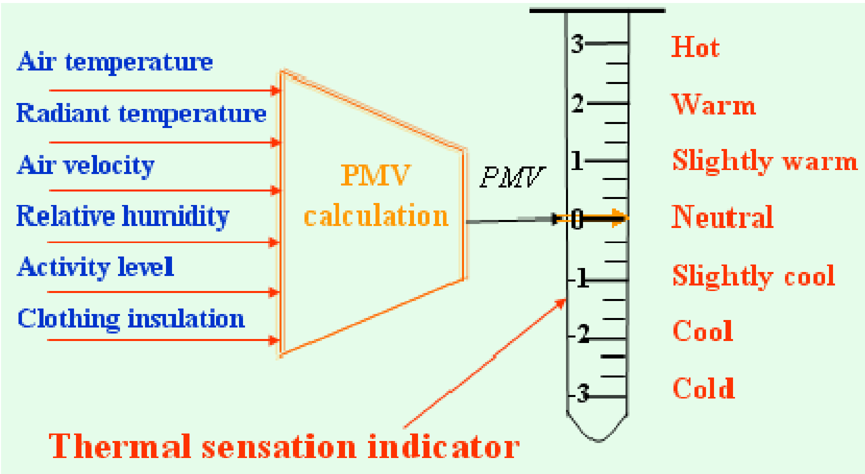


Figure 2-3. A measure for the thermal comfort, one can use the seven point psycho-physical ASHRAE scale

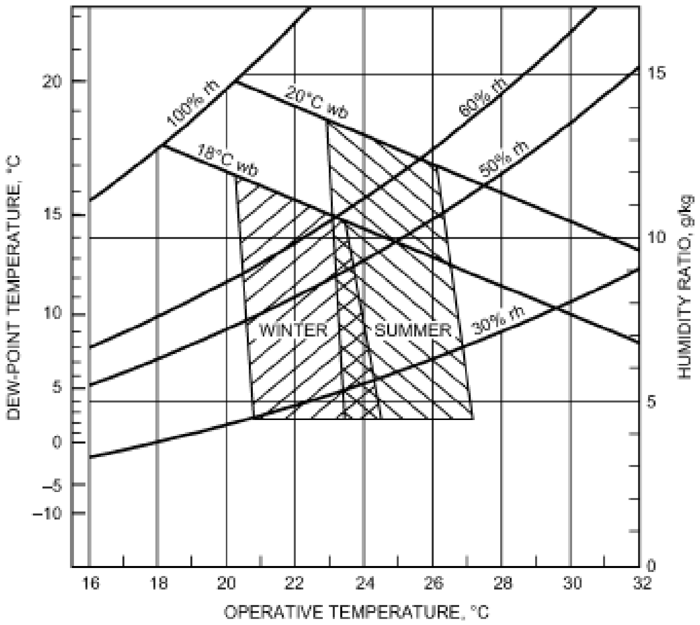


Figure 2-4. ASHRAE summer and winter Comfort Zones (Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.)

Fanger realized that the vote predicted was only the mean value to be expected from a group of people, and he extended the PMV to predict the proportion of any population who will be dissatisfied with the environment. A person's dissatisfaction was defined in terms of their comfort vote. Those who vote outside the central three scaling points on the ASHRAE scale were counted as dissatisfied. PPD is defined in terms of the PMV, and adds no information to that already available in PMV.

Thermal comfort studies based on laboratory research indicate that all humans react similarly to an artificial indoor climate or air-conditioning. This is only partially true. A number of factors concerning the occupants' behavior indicate that the results regarding thermal comfort are overestimated [13]. International standards can act as guidelines, but they cannot, however, be applied globally [19]. Especially in the case of Mediterranean climate, the tolerance in higher temperatures is given. While, for example the standard indicates that 28 °C is outside the comfort zone, a resident in Greece would find the conditions acceptable. For buildings regulated by passive design measures and in real-life situations where adaptation influences the comfort zone, a locally perceived acceptable comfort must be used as the reference for thermal design. This will in turn-reduce the possible needs for active measures, i.e. air-conditioning.

2.1.4 Active Systems (HVAC)

In the past, buildings were constructed using passive design measures because of the lack of any energy supply or resources. In industrialized countries, active measures gained predominant use after the World War II, as an easy and quick means of satisfying comfort concerns in buildings. Active systems involve mechanical equipment, which requires constant mechanical regulation. The advantage of such a system is the possibility of fully controlling the internal conditions, regardless of daily or seasonal variations in the external climate. The disadvantage of such a system is that it has high and ongoing running costs [7]. This may consequently have resulted in the lack of attention paid to the real costs associated with this form of progress.

It is not always necessary to install a complex active system to realize an acceptable thermal condition indoors. In this the building design is an important factor. Good thermal insulation, low proportion of glazing, outdoor solar shading, the use of thermal mass and night ventilation can sometimes jointly make a cooling system redundant [20]. These forms of passive climate controls need less energy, for cooling as well as heating, and make the indoor environment more stable. Even in combination with an active climate control system, good passive design can make the environmental conditions more comfortable.

2.1.5 Internal Gains

The energy released by people, equipment, lighting and other sources which are not part of the heating system can have a profound effect on the indoor climate [15]. In buildings such as office buildings, commercial stores, shopping centers, entertainment halls etc much of the overheating problem during the summer can be caused by heat produced by equipment or by a high level of artificial lighting. When there are a large number of occupants or clients their metabolic heat can also add to the problem. The main reasons are the lack of large equipment and the relative ease of applying natural cooling strategies such as ventilation and shading. The increase in the number and installed power of electrical appliances in buildings, both residential and offices, has led to important changes in the energy balance of buildings because internal gains become higher [15]. This leads to a decrease of the heating load in winter, but the new load is electrical and the heating load it replaces will generally be in a more efficient fuel such as oil or gas. On the other there will be an increased (normally electrical) cooling load in summer, the latter being more significant than the former in terms of primary energy.

2.2 Passive design techniques

2.2.1 Introduction

Passive design is a design that does not require mechanical heating or cooling. Buildings that are passively designed take advantage of natural energy flows to maintain thermal comfort. There are many sources of energy available locally within a building site. These include direct and diffuse radiation from the sun, air movement from winds and temperature differences, biomass from vegetation, as well as geothermal and hydro-kinetic sources.

The basic idea of passive design is to allow in daylight, heat and airflow only when they are most beneficial, and to exclude them when they are not [13]. This includes the storage of ambient energies where possible, for distribution later when there may be greater need. The full range of passive techniques are considered, such as the correct orientation of the building, appropriate amounts of fenestration and shading, an efficient envelope, maximum use of daylighting and the appropriate level of thermal mass, as well as the use of renewable resources in preference to non-renewable.

The effective use of these low-grade energy sources in a building requires only some careful thought and a little innovative design. According to [7], many projects have shown that such buildings do not have to cost any more than less carefully designed buildings, and can be significantly cheaper to run.

In the past, buildings were constructed using passive measures, quite obviously due to the lack of any energy supply or resources. Passive measures rely on utilizing the elements of a region's climate and its natural sources. This involves 'listening' to nature and reacting to the changes that occur with the seasons of the year and the time of day, e.g. closing and opening windows according to changes in temperature, prevailing wind conditions and natural cooling systems.

2.2.2 Background history

The techniques of energy efficiency buildings were practiced for thousands of years, by necessity, before the advent of mechanical heating and cooling. It has remained a traditional part of vernacular architecture in many countries [21] .There is evidence that ancient cultures considered factors such as solar orientation, thermal mass and ventilation in the construction of residential dwellings.

Pre-20th Century – structures were designed and built by builder-architects who had an ability to understand the entire building from design through construction and lifetime operations; see [13] for earlier applications of energy efficient constructions. Orientation of buildings so that they could utilize solar input more efficiently, first took place in Greece 2500 years ago. A few centuries later, Rome bathhouses were built so that their windows faced the south to let in the warmth of the sun. As Figure 2-5 illustrates, the buildings in the Iranian desert regions were constructed according to the specific climatic conditions and differ with those built in other climates. In 1940, the Sloan Solar House in Chicago, designed by Keck, became the first contemporary building making use of passive solar heating. In 1953, Dan Trivich of Wayne State University made the first theoretical calculations of the efficiencies of various materials based on the spectrum of the sun. Finally, in 1994, the National Renewable Energy Laboratory (formerly known as the Solar Energy Research Institute) completed a construction of its Solar Energy Research Facility, which was recognized as the most energy-efficient of all U.S. Government buildings worldwide.

Figure 2-5. A traditional Iranian building. The desert buildings are equipped with air traps, arched roofed, water reservoirs with arched domes and ice stores for the preservation office.

Now days, because of the worldwide energy problem, as mentioned in Chapter 1, research for energy efficient building's is at the forefront. Plenty of energy efficiency institutes have been created in order to develope global energy efficient strategies, tools and design guidelines of new or existing buildings. For example, The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is the world's foremost technical society in the fields of heating, ventilation, air conditioning, and refrigeration. Its members worldwide are individuals who share ideas, identify needs, support research, and write the industry's standards for testing and practice. The result is that engineers are better able to keep indoor environments safe and productive while protecting and preserving the outdoors for generations to come.

Investigations in that direction have resulted with some new standards and regulations in various countries depending on their own conditions on energy.

2.2.3 Major principles of passive design

Good passive design for energy efficiency and thermal comfort is based on the following six major principles:

Orientation

The orientation of a building must be based on its interaction with the sun and the prevailing winds maximizing opportunities for passive solar heating, solar heat gain avoidance during cooling time, natural ventilation, and day-lighting throughout the year — see [13] for an overview. It is the solar orientation of a building that determines the intensity of solar radiation that falls on the individual surfaces. Southern exposure is the key physical orientation feature for passive solar energy in the northern hemisphere [6]. As Figure 2-6 illustrates, in winter the sun comes up in the southeast and sets in the southwest. In the middle of the day in the winter, the sun is low in the southern sky, providing solar collection in the building. In summer, in the middle of the day, the sun is high in the sky overhead, avoiding solar heat gain.

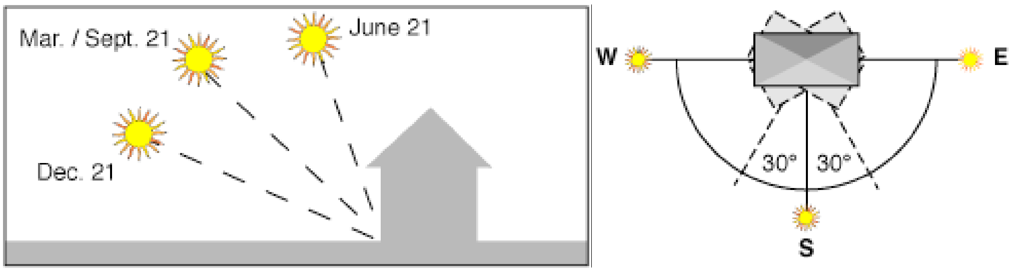


Figure 2-6. Orientation in relation with the position of the sun

Wind orientation will also need to be considered in order to maximize natural ventilation around and through the building [13]. The greatest pressure on the windward side of a building is gained when it is perpendicular to the direction of the wind. Conflicts between solar and wind orientation should be carefully analyzed on each individual site. The optimum directional orientation depends on site specific factors and on local landscape features such as trees, hills, or other buildings that may shade the sunspace during certain times of the day. An analysis of building's orientation is presented in [22].

Windows

Windows and skylights play a crucial role in admitting heat and light, and can have a significant impact on energy consumption. They are also the most difficult parts of the building envelope to adequately insulate. Care needs to be taken to ensure that windows are positioned, sized and protected so as to get the most benefit from winter sun while avoiding overheating in summer and heat loss in winter. Employing energy conservation techniques can decrease heat loss or gain. As Figure 2-7 illustrates, windows lose and gain heat by conduction, convection and radiation. The energy efficiency of windows is represented by U-value, Solar Heat Gain Coefficient (SHGC), Visible Light Transmission and Air leakage rating. The U-factor is a value that measures window's rate of heat loss. The Solar Heat Gain Coefficient (SHGC) is a measurement of the amount of direct solar radiation that enters the home through the glass as heat. Air leakage or air infiltration is the amount of air passing in and out of a building through cracks in walls, windows, and doors.

In recent years, advances have been made in coatings that are deposited onto a window surface to reduce these factors of a window in the winter, but also reduce heat gain in the summer. For example, low-e coatings which are microscopically thin, invisible metal or metallic oxide layers applied to a window surface allowing light through, but reduce ultraviolet light. The coatings are transparent to visible light and, depending on the coating, will allow for high, moderate or low solar gain; see [23] for more details. As Figure 2-8 illustrates, when the long-wave heat energy outside of the window hits the glass, the coating on the glass acts as a mirror to keep the heat outside the building keeping the house colder in summer. Equivalently, in winter low-e glazing keeps the heat inside the building keeping the house hotter.

According to [24], low-e glass blocks about two times more ultraviolet light than clear, single-pane glass windows.

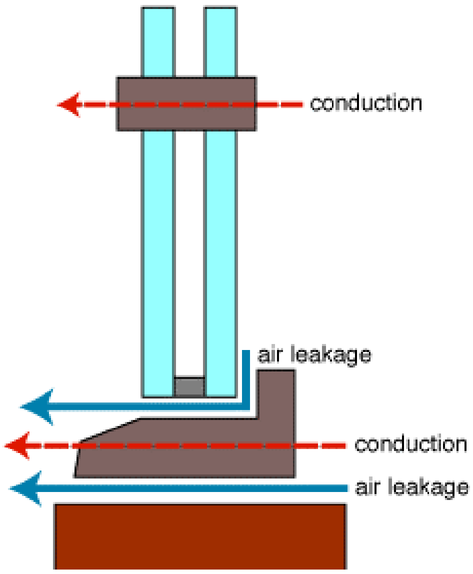


Figure 2-7. Windows lose heat in four ways.

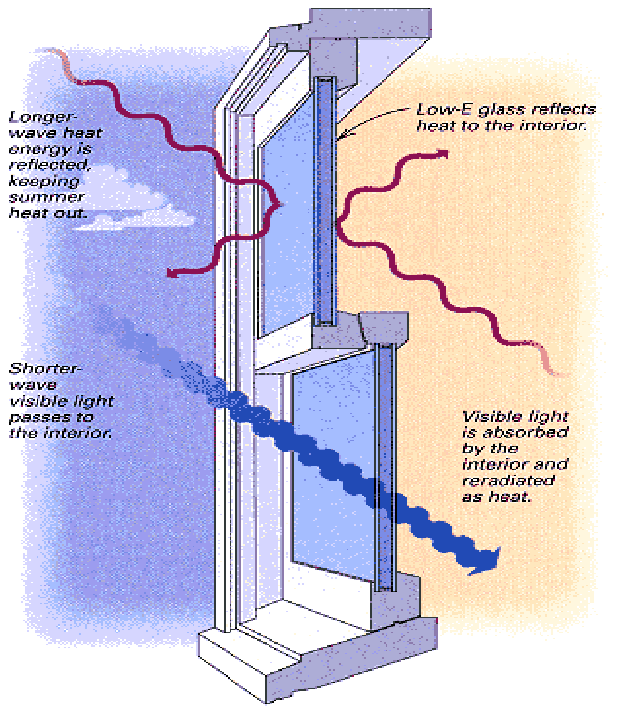


Figure 2-8. Low-e glass reflects heat energy while admitting visible light. This keeps heat out during the summer and during the winter. In the winter, low-angle visible light passes into the house and is absorbed by the home's interior.

Thermal Mass

The amount of heat that is transferred through a material or building elements is determined as the amount which is stored and the time it takes for the heat to be transferred to its inner surface. The capacity that a material or element has to retain heat is referred as its thermal storage capacity. Generally, the greater the capacity, the slower will be the transfer of heat gains made internally [25]. The delay in the transfer of heat is referred to as the time lag property of a material or a building element. The time lag property is expressed in terms of hours. It is the time it takes the external heat to impact internally on a material or element. The values will be different in a real and dynamic situation, i.e. changes in outside temperature during the day and dynamic influence of other building elements.

As Figure 2-9 illustrates, these properties provide the opportunity to store heat in a structure when the temperatures are very high inside the building and release the heat in periods of low temperature. In summer, thermal mass absorbs heat that enters the building. In hot weather, thermal mass has a lower initial temperature than the surrounding air and acts as a heat sink. By absorbing heat from the atmosphere the internal air temperature is lowered during the day, with the result that comfort is improved without the need for supplementary cooling. During the night, the heat is slowly released to passing cool breezes (natural ventilation), or extracted by exhaust fans, or is released back into the room itself. In winter, thermal mass in the floor or walls absorbs radiant heat from the sun through windows. During the night, the heat is gradually released back into the room as the air temperature drops. This maintains a comfortable temperature for some time, reducing the need for supplementary heating during the early evening. For good winter performance, thermal mass should be exposed to direct sunlight and is best located in areas with unobstructed north-facing windows — see [26] for more details. Thus, thermal mass within an insulated building's structure helps reduce the extreme temperatures inside the building, making it more comfortable and energy efficient.

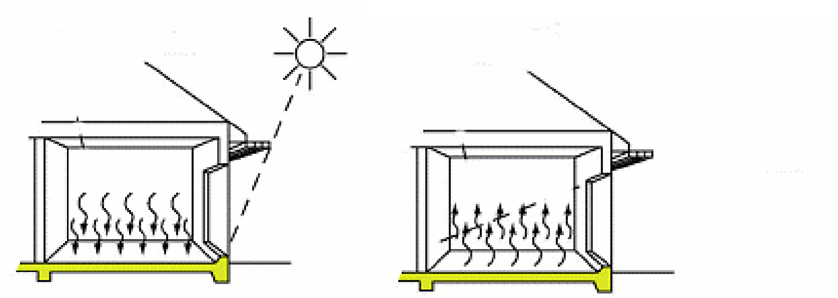


Figure 2-9. Thermal mass

According to [27, 2] thermal mass is particularly important for comfort in climates where summer temperatures are high and there is a large difference between daily average maximum and minimum temperatures. Thermal mass is less important, but still beneficial, in climates with lower summer temperatures. However, in situations where solar access is poor, thermal mass could increase winter heating requirements.

Insulation

Insulation specifications are another important design feature. The building envelope provides a barrier against the extremes of the outdoor environment, allowing the thermal comfort levels indoors to be adjusted to suit the occupants. This might require heating or cooling depending on the season and location of the building. The energy required for heating or cooling will be greatly reduced if the building envelope is well insulated to reduce incidental losses; the analysis presented in [9]. As Figure 2-10 indicates, this means insulating the ceiling, walls and floor of the building, an easy task during construction, but often more difficult for existing buildings. Insulation reduces the rate at which heat flows through the building fabric, either outwards in winter or inwards in summer [15]. In temperature controlled buildings, this will result in significant energy savings and increased thermal comfort.

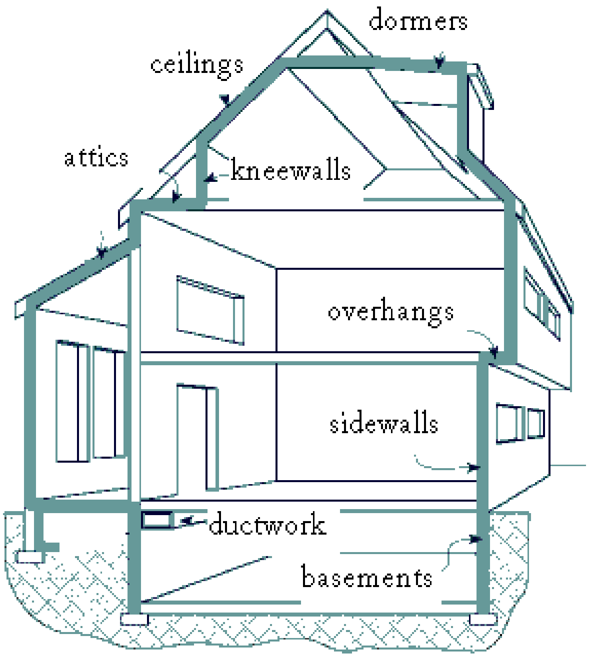


Figure 2-10. Places in a building to install insulation

Insulation has an additional benefit it that it also reduces noise transfer through the fabric, however its resistance to both fire and insects should also be major considerations. Proper installation is also essential to maximize performance, and there often local and international standards to cover the fire safety and health aspects of installation [28].

Natural Ventilation

Natural ventilation supply fresh air and aid to the removal of odors and the removal of internal heat cool the structure and reduce structural radiation. The fresh air intakes in codes and standards are normally expressed in terms of the required number air changes per hour and/or as a number of cubic meters of fresh air per hour per person for different spaces and activities. Air change per hour (ACH) works out how much a time per day it is essential is renewed completely the air of space.

Ventilation based on passive measures should not be confused with standard requirements for odour removal and fresh air intake [13]. These regulations serve performance requirements for mechanical ventilation or air-conditioning systems where rigid rules can be applied. Passive natural ventilation, especially for hot dry and warm humid climates, depends to several different functions which vary in accordance to the time of day and night and the time of the year. For example, air changes may need to be reduced less than the minimum requirements for odour removal if there are extremely hot days. This is because the internal hot air will be replaced by even hotter external air. Thus, night time ventilation is useful as a mean of structural cooling in periods with high day time temperatures and considerably lower night time temperatures. Besides, air change per hour depends to the occupancy per m^2, the occupants' activities the size of zone per m^3 and the type and the size of openings of space and from the way that the user of space handles them — see [12] for an overview.

It should be noted that wind speed and air change rates are not related [13]. For example, high air speeds can be found in a room close to a ceiling fan but the air change rate can be very low, and an open building exposed to winds might experience low wind speeds at the level of the occupants but a relatively high air change rate.

According to [11], uncontrolled ventilation/infiltration of air through openings and gaps in badly constructed building may in many cases amount to more than the minimum ventilation rate, occurring a discomfort environment for the occupants and insufficient energy performance for a building — see [3] for more details.

Natural ventilation can occur due to:

- Wind-generated air pressure differences
- Temperature-generated air pressure differences.

Wind-generated air pressure differences

Ventilation in buildings based on wind-generated air pressure differences is the result of the air pressure differences created between two sides or two openings of a building. When air strikes to an obstacle, such as a building, it will cause pressure on the obstructing surface occurring vortices. On the windward side of a building, vortices pressure increased, while on the leeward side their pressure reduced. Thus, if a building has an opening facing a high-pressure zone and another facing a low-pressure zone, the air movement will be generated through the building. As illustrated in Figures 2-11 and 2-12, cross and sided ventilation are based on this concept. Ventilation based on wind-generated air pressure difference can potentially create higher wind speeds or air changes rates than required. Because of that, building must carefully designed. The siting, orientation, internal layout, surrounding features and building's form can be used to manage the wind before entering a building — see [12] for an overview.

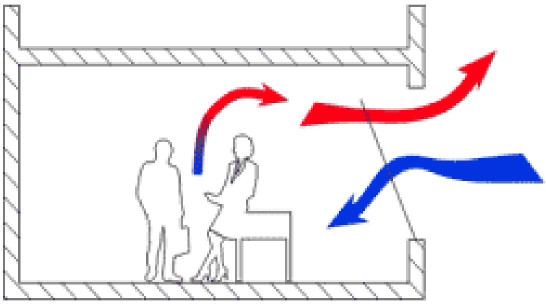


Figure 2-11. Single Sided Ventilation

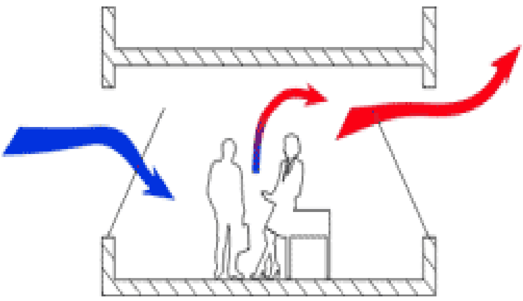


Figure 2-12. Cross Ventilation

Temperature-generated air pressure differences

If a building has two openings at different levels in two zones, e.g. two openings inside or one outside and one inside, and if there is a temperature difference between them, the stack effect operates. It is the natural tendency of warm air to rise and escape through the top opening. As Figure 2-13 illustrates, the rising hot air will be replaced by cool air entering through low openings. The simple effect of cold dense air moving down and hot less dense air rising is called the buoyancy effect, which assist the stack effect. The air velocity achieved by the stack effect alone is usually not enough to provide a cooling effect to occupants bodies directly, but it is useful as a way of expelling the build-up of warm the inside a building and for night-time structural cooling, so having a cooling effect by letting in cooler air [3]. In areas or at times where the wind speed is low or non-existent, the stack effect can be used to generate internal ventilation [13]. The size and shape of the openings, and the distance between them, can be used to control the ventilation [13]. In addition, elements such as wind towers or extract fans can be used when outside wind pressure differences are available in order to increase air movements and direct air flows.

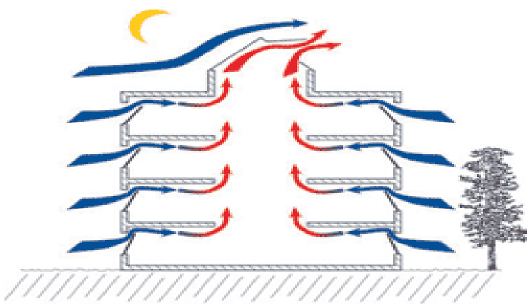


Figure 2-13. Stack Ventilation

Natural ventilation solutions can be used even at difficult, noisy regions — see [14] for more details. New design tools, such as CFD, are suitable in the early design phases to evaluate different ventilation concepts and in the following phases optimizing natural ventilation solutions. Natural ventilation can be designed to fit a specific building if architect and ventilation consultant cooperate closely [13].

Zoning

When the location, general orientation and shape of the building have decided, the organization of interior zones is the next consideration. Substantial savings can be made through proper zoning [22]. For example, in temperate climates living spaces should be placed along the south face of the building. Rooms that may benefit from morning sunlight should be on the east wall. Least occupied spaces - such as storage areas, circulation areas and garages- should be placed along the north where they act as a buffer between living space and the cooler southern wall. All these considerations about zoning organization can cause considerable comfort and energy improvements.

2.3 Review of energy and comfort codes and regulations about buildings

2.3.1 International standards

On the international level ISO (International Organization for Standardization, ISO EN 7730), CEN (European Committee for Standardization, prEN15251, EN13779) and ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) are writing standards related to the indoor environment and energy efficiency. In the future, recommendations will be specified as classes allowing differences in the requirements at a national level and also for designing buildings for different quality levels. This will require enhanced communication between the client (builder, owner) and the designer. For example, it is being discussed how people can adapt to accept higher indoor temperatures during summer in naturally ventilated buildings. Several of these standards have been developed mainly by experts from Europe, North America and Japan, thus guaranteeing a worldwide basis. Critical issues of thermal comfort conditions such as adaptation, effect of increased air velocity, humidity, type of indoor pollutant sources etc. are still being discussed, but in general these standards can be used worldwide.

The Kyoto protocol binds the developed countries to reduce the collective emissions of six key greenhouse gases — among which CO_2 — at least by 5% by 2008–

2012. This protocol encourages the governments amongst others to improve energy efficiency and to promote renewable energy. Therefore, counterbalancing the energy and environmental effects of air conditioning is a strong requirement for the future.

2.3.2 The European energy performance of buildings directive (EPBD)

From the beginning of 2006 all new European buildings (residential, commercial, industrial etc.) must have an energy declaration based on the calculated energy performance of the building, including heating, ventilating, cooling and lighting systems. This energy declaration must refer to the primary energy or CO_2 emissions. The directive also states that the energy performance calculation must take into account the indoor climate, but gives no guidelines. The European Organization for Standardization (CEN) is now preparing a series of standards to cover the requirements for the indoor environment, energy performance calculations for buildings and systems, ways of expressing energy performance, inspection of heating-cooling-ventilation systems and conversion to primary energy.

The directive requires of member countries to:

- develop a comprehensive methodology for calculation of integrated energy performance of buildings and HVAC systems including heating, cooling, ventilation and lighting;
- set minimum requirement of energy performance for new buildings;
- apply energy requirements in existing buildings;
- develop energy certification systems for both new and existing buildings, and:
- inspect heating, air-conditioning and ventilation regularly.

Energy consumption of buildings depends significantly on the demands for the indoor environment, which also affects health, productivity and comfort of the occupants. The indoor environment therefore is mentioned several times in the EU directive. It is stated for example that energy saving measures should not lead to sacrifices in comfort and health of building occupants. Secondly it is recommended besides the energy certificate and actual values for the energy consumption also to display in the building the design values for the indoor environment and indicators for the actual environmental comfort. Hence, at the beginning of the development process of the 'EPBD package', a need to specify criteria for the indoor environment was identified. This involves IEQ criteria for design, energy calculations, performance evaluation and display of operation conditions (IEQ= Indoor Environmental Quality). The 'EPBD IEQ criteria' are presented in draft standard CEN prEN 15251: 2005 'Criteria for the Indoor Environment including thermal, indoor air quality, light and noise.' The draft standard contains (energy use related) criteria for thermal comfort (e.g. winter en summer temperature ranges), indoor air quality (e.g. minimum requirements for fresh air supply), lighting (e.g. lighting levels) and acoustics (e.g. maximum allowable sound pressure levels from HVAC systems). The objective of this Directive is to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. As Table 2-1 indicates, CEN prEN 15251 message was that indoor climate and productivity must be taken into account as well as energy performance.

CEN prEN 15251 addressed the following topics
✓ Adaptation in natural ventilated buildings. ✓ Natural ventilated buildings- without mechanical cooling ✓ Recommended design ventilation rates in residential buildings ✓ Recommended criteria for ventilation ✓ Recommended values of CO_2 for demand controlled ventilation ✓ Recommended criteria for the humidity if humidification or dehumidification is required ✓ Indicators for the indoor environment ✓ Recommended over all evaluation of the indoor environment and certification

Table 2-1. CEN prEN 15251 topics

2.3.3 Implementation of the EPBD in Greece

The implementation of the EPBD in Greece is the responsibility of the Ministry of Development and the Ministry of Environment. By early 2007, the Parliament was planning to adopt the Decree; see [29], regarding the transposition of the EPBD in national law. The execution orders are the responsibility of the Ministries of Development and Environment; a review can be found in [30].

Status of the implementation

Greek government announced in 17 of June 2008 the regulations for the EPBD (general design/inspection principles and minimum requirements for the building cell, lighting, boiler/heating system, air conditioning etc). The Government of Greece completed a study on minimum requirements for all new and existing buildings. The task is being undertaken by the Ministry of Development with the help of the Regulatory Authority for Energy. The type and level of requirements are function of the type of building (dwellings, office buildings, schools …) and may cover:

- Maximum U-value;
- Requirement on average insulation level;
- Maximum primary energy consumption per m^2 of floor area;
- Boiler and air conditioner efficiencies.

New buildings should produce an energy study for the building permit to be issued. The proof of compliance must be made after completion of the building. The procedure followed for new buildings covers also existing buildings. The ongoing studies examine minimum requirements for new building components when building renovation is done and for extensions to existing buildings.

2.4 The Simulation tool

2.4.1 Introduction

As identified in this Chapter previously, the objective of the present work is development / enhancement of building performance evaluation tools which treat the building and plant as an integrated dynamic system. One of the techniques which may be employed to achieve this is modeling and simulation. Modeling and simulation have become indispensable engineering techniques in the fields of design (e.g. of buildings, plant configurations, and on the component level) and operation (system control, understanding, and interaction). In the current context, modeling and simulation is thus used for predictions to help solve real world problems regarding buildings and the HVAC systems which service them. The building may be an existing structure, a proposed modification of an existing structure, or a new design.

The simulation tool employed in this research was the EnergyPlus simulation engine with a purpose built interface called DesignBuilder. EnergyPlus was developed by the U.S. Department of Energy, Lawerence Berkeley Laboratories, U.S. Army Construction Engineering Research Laboratories and the University of Illinois. EnergyPlus is a modular structured software tool based on the best attributes of the BLAST and DOE-2.1 software.

DesignBuilder was developed as an interface for EnergyPlus and as a possible energy performance certification tool. DesignBuilder facilitates the attribution of a building's construction, internal environment conditions, standard activity schedules and system characteristics to the simulation model. The greater the availability of information on a building's construction and system parameters the more accurate DesignBuilder and EnergyPlus can be in representing and simulating its energy performance.

2.4.2 The EnergyPlus simulation environment

EnergyPlus is a building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows. EnergyPlus is an evaluation of the models developed in the two software packages: the Building Loads and System Thermodynamics (BLAST) program and the DOE-2 program. EnergyPlus includes many innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, and photovoltaic systems.

EnergyPlus has three basic components — a simulation manager, a heat and mass balance simulation module, and a building systems simulation manager. The simulation manager controls the entire simulation process. The heat balance calculations are based on IBLAST — a research version of BLAST with integrated HVAC systems and building loads simulation. The building systems simulation manager handles communication between the heat balance engine and various HVAC modules and loops, such as coils, boilers, chillers, pumps, fans, and other equipment/components. The building systems simulation module also manages data communication between the HVAC modules, input data, and output data structures. The simulation manager, heat balance simulation manager, and building systems simulation manager are described in more detail below.

Simulation Manager

The Simulation Manager controls the interactions between all simulation loops from a sub-hour time step through the user selected time step and simulation period — whether day, month, season, year or several years. The integrated solution manager manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager.

Heat and Mass Balance Simulation Module

The surface heat balance module simulates inside and outside surface heat balance; interconnections between heat balances and boundary conditions; and conduction, convection, radiation, and mass transfer effects.

The air mass balance module deals with ventilation, exhaust air, and infiltration. It accounts for thermal mass of zone air and evaluates direct convective heat gains.

The daylighting module calculates interior daylight illuminance, glare from windows, glare control, and electric lighting controls (on/off, stepped, continuous dimming), and calculates electric lighting reduction for the heat balance module.

The fenestration module computer accurate angular dependence of transmission and absorption for both solar and visible radiation, and temperature-dependent U-value. Users can enter a layer-by-layer window description or choose windows from the library (such as conventional, reflective, gas fill, low-e, and electrochromic windows).

For sun control, movable interior and exterior window shades and blinds and electrochromic glazing can be simulated. The sky model includes non-isotropic radiance and luminance distribution throughout the sky based on an empirical model of [31] as a function of sun position and cloud cover. More information on the window calculations within EnergyPlus are provided by [32].

Building Systems Simulation Manager

After the heat balance manager completes simulation for a time step, the Building Systems Simulation Manager takes part, which controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions. EnergyPlus does not use a sequential simulation method (first building loads, then air distribution system, and then central plant) Instead, the building systems simulation manager designed as follows:

Integrated simulation models capacity limits more realistically and tightly couples the air and water side of the system and plant. Modularity is maintained at both the component and system level. To implement these concepts, it uses loops throughout the building systems simulation manager — primarily HVAC air and water loops.

The air loop simulates: air transport, conditioning and mixing, and includes supply and return fans, central heating and cooling coils, heat recovery, and controls for supply air temperature and outside air economizer. The air loop connects to the zone through the zone equipment. Zone equipment includes diffusers, reheat/recool coils, supply air control (mixing dampers, fan-powered VAV box, induction unit, VAV dampers), local convection units (window air-conditioner, fan coil, water-to-air heat pump, air-to-air heat pump), high-temperature radiant/convective units (baseboard, radiators) and low-temperature radiant panels. More than one equipment type can be specified for a zone. However, users must specify equipment in the order it will be used to meet zone heating and cooling demand.

For the air loop, the solution method is iterative. In order to specify equipment connections to a loop, nodes are defined at key locations around the loop with each node assigned a unique numeric identifier. Node identifiers store loop state variables and set-point information for that location in the loop

Is an hourly-based thermal simulation program used to calculate multizone envelope, system, and plant loads. This simulation program allows users to perform hourly building energy simulations for a one-year period using ASHRAE's algorithms. The heat transfer by conduction and radiation through walls, roofs, floors, windows, and doors are calculated separately using response factors, in which the effects of thermal mass are carefully considered. In addition, interior surface convection is computed based on user-specified convection coefficients, while the exterior convection is calculated by the program itself, based on the surface roughness and outdoor wind speeds taken from the weather data.

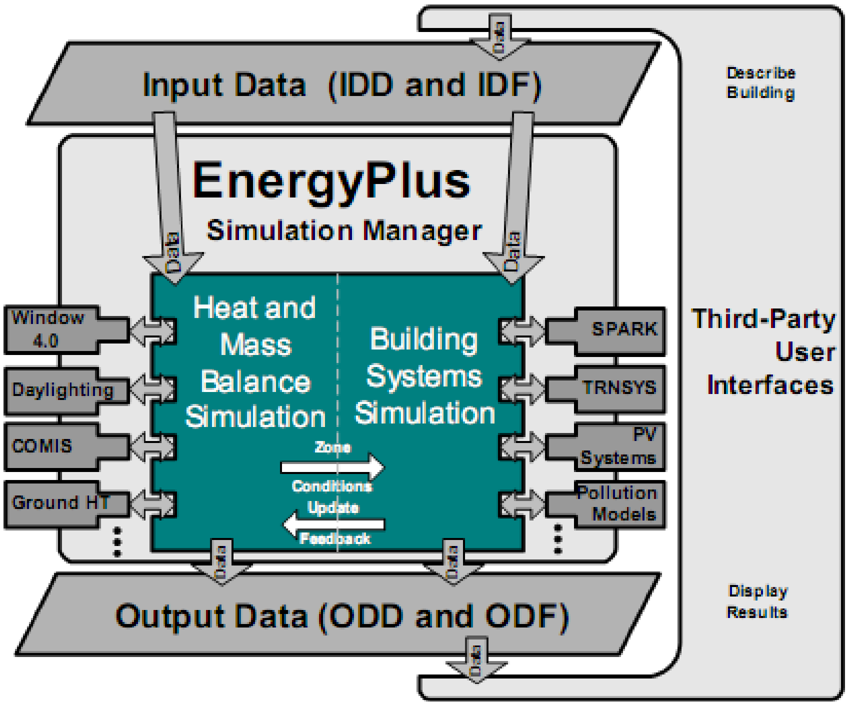


Figure 2-14. Overall EnergyPlus Structure

2.4.4 Other thermal simulation programs

Numerous thermal simulation computer programs for the purposes of new building design and existing building analysis have been developed worldwide. Generally, most simulation codes calculate dynamic heat transfer through building materials and evaluate overall building energy performance. In addition to the EnergyPlus simulation program, there are at least two other programs worth mentioning: 1) ESP-r, 2) HTB-2 and 3) Ecotect .

1) ESP-r was developed in 1974 by the Energy Simulation Research Unit (ESRU) at the University of Strathclyde. In addition to performing thermal analyses of buildings, ESP-r is also integrated with modeling tools for simulating the visual, airflow, and acoustic performances of buildings. Currently, ESP-r has been

developed to link with AutoCAD, Radiance, and CFD. This linkage makes the program the most versatile software available for overall building environmental analyses. ESP-r algorithms are based on a finite volume, conservation approach where a problem is transformed into a set of conservation equations representing energy, mass, momentum, etc., and then solved in successive time-steps. Even though ESP-r is a very powerful program for building environmental analyses, it is mostly used only by government and university research groups because it requires special knowledge of particular subjects, including the UNIX operating platform. This has placed the program out of reach for most building designers.

2) HTB2 developed by the Welsh School of Architecture at the University of Wales at Cardiff, is a dynamic finite difference thermal model that is capable of assessing the effects of a building's envelope, ventilation, solar gain and shading on internal thermal conditions. This program can be used to predict indoor temperatures in naturally ventilated buildings if passive designs are applied. It is suitable for use within research, consultancy, and teaching environments. Because the program was developed primarily for passive cooling designs, researchers do not widely use it for whole-building energy analyses.

3) Ecotect developed by the Welsh School of Architecture at the University of Wales at Cardiff, is a complete environmental design tool which couples an intuitive 3D modeling interface with extensive solar, thermal, lighting, acoustic and cost analysis functions. Ecotect is driven by the concept that environmental design principles are most effectively addressed during the conceptual stages of design. The software responds to this by providing essential visual and analytical feedback from even the simplest sketch model, progressively guiding the design process as more detailed information becomes available.

Chapter 3

Case study: An office building

3.1 Basic description of the office building

To evaluate the potential of passive design technique in a realistic context, we selected an existing office building constructed in 2007 and located in Chania, an island in the southern part of Greece. The building is a part of an office block at the Technical University of Crete. The occupants of the building are architects and civil engineers who provide the technical services to the university community. The office building has two floors; each with an area of 157 m^2. As Figure 3-1 illustrates, the shape of the building is triangular. The office building constitutes of 10 office rooms, an open meeting space, two corridors (one in each floor), the main entrance, an equipment room and a toilet. As Figures 3-2 and 3-3 illustrate, in both floors there is a central corridor running the length of the building on both levels with offices on either side. In the middle of the corridor there is an open meeting space of semicircular shape. The plan of the second floor is similar with the only difference an opening semicircular space which is on top been of the first floor meeting area. This forms an atrium lit by 9 m^2 area of glazing at the roof. For each zone of the office building the area in square meters and heights is shown in Table 3-1.

Figure 3-1. Façade of the office building in DesignBuilder (virtualization module).

Description	Area(m^2)	Reference height (m)
Office building	314	6.5
First floor	157	3.5
Second floor	157	3.0
Corridor	59.7	3.5
Meeting space (atrium)	10.6	6.5
Entrance	1.4	3.5

Office 1	2.4	3.5
Office 2	15.9	3.5
Office 3	6.9	3.5
Office 4	9.3	3.5
Office 5	13.7	3.5
Office 6	9.5	3.0
Office 7	5.3	3.0
Office 8	6.7	3.0
Office 9	8.7	3.0
Office 10	13	3.0
Toilet	6.9	3.5
Equipment office	7.2	3.0

Table 3-1. Area and height for each zone of the building.

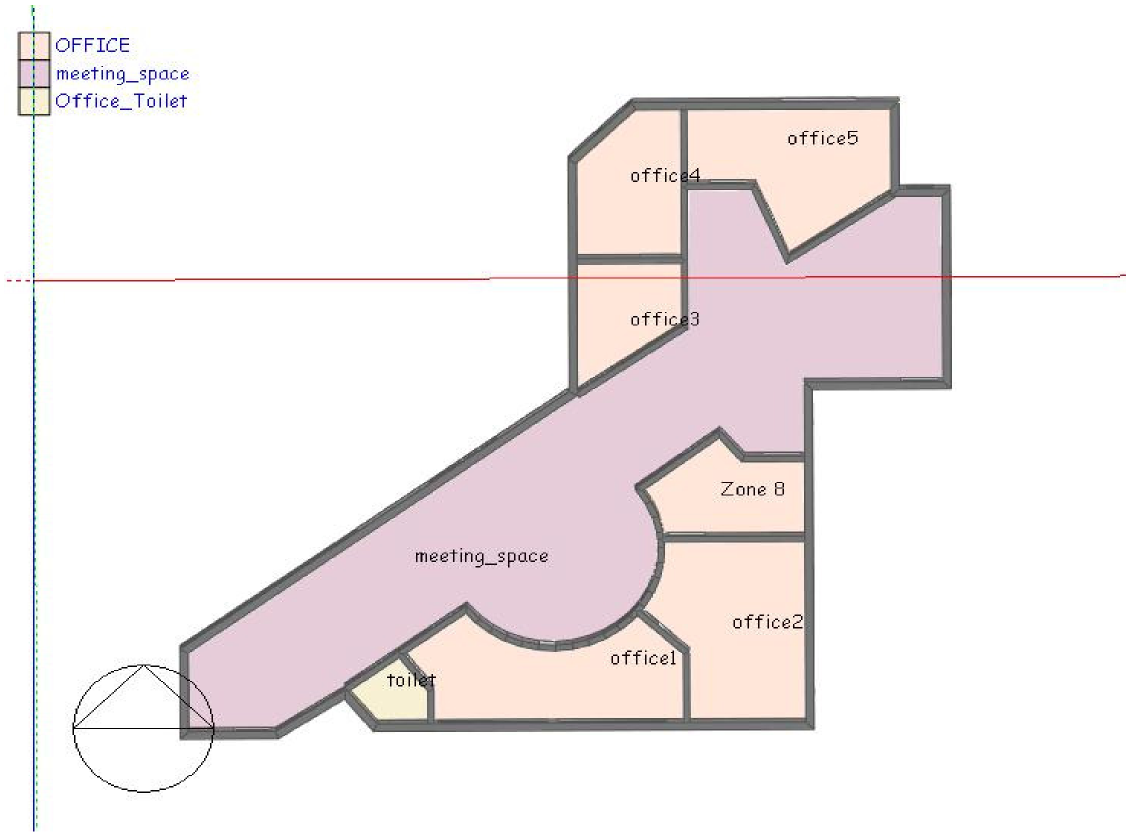


Figure 3-2. Plan of the first floor as designed in DesignBuilder.

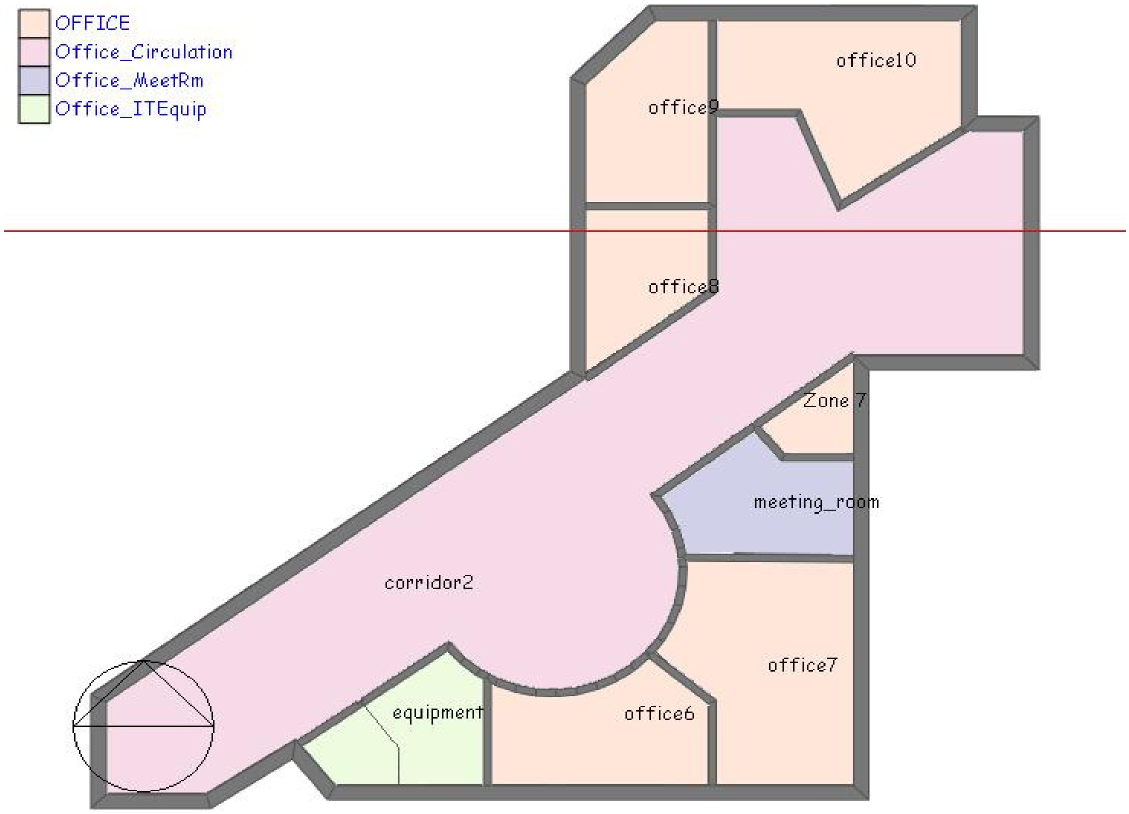


Figure 3-3. Plan of the second floor as designed in DesignBuilder.

Figure 3-4. First floor of the office building.

Figure 3-5. Second floor of the office building

3.2 Site level and input data

3.2.1 Location

The building is located in the area of Akrotiri, 7 km northwest of Chania. The area is thinly built-up, with an open view towards the north. The elevation above the sea level of the area is 157 m. The main characteristic of the building's location is exposure to north winds during most days of the year.

3.2.2 Climate

The region is characterized by long hot summers, cool wet winters and with long periods of sunlight at the bigger duration of year — typical of a Mediterranean climate.

The winter starts in November and ends in April and summer starts in May and ends in September. The mean maximum temperature in January is 23.3 ˚C and the mean minimum in July is 19.9 ˚C. The absolute maximum temperature of the year is 43.7 ˚C, and the absolute minimum temperature of the year is - 0.2 ˚C. There is a large diurnal variation between maximum and minimum temperatures. On average in January, the diurnal swing is 16.6 ˚C, while in July it is 9.1 ˚C. In January, the mean daily average temperature is 13.2 ˚C. In June, the mean daily average temperature is 27.1 ˚C. During the summer months, there are 19 days when the maximum temperature is expected to be over 35 ˚C, while during the winter there are 3 days with a minimum temperature below 2 ˚C. Furthermore for two months during the year the daily maximum temperature is below 20 ˚C. In the area the relative humidity in the winter is 72% and 56% in the summer on average.

Input Data

A reference year for Chania was used for the outdoor climate from the [33]. The location and climatic parameters of the building are detailed in Tables 3-2 and 3-3.

Location Parameters	
Latitude (φ)	35.5
Longitude (φ)	24.2
Elevation (m)	157

Table 3-2. Location Parameters.

	Design Weather	
	Winter Design Day	***Summer Design Day***
Maximum Dry-Bulb Temperature (˚C)	22.0	43.7

Minimum Dry-Bulb Temperature (˚C)	-2.0	18
Wind Speed (m/sec)	17.7	9.8
Wind Direction (φ)	0.0	0.0

Table 3-3. Design weather data

3.3 Building level modeling and input data

The discussion that follows details the selection of materials, equipment, activities and schedules used to create the office building thermal model in the EnergyPlus environment.

3.3.1 Building construction

The office building was constructed using three blocks:

- Block 1 – First floor
- Block 2 – Second Floor
- Block 3 – Main Entrance

The construction template in DesignBuilder was used to assign the construction characteristics of the office building:

- External walls,
- Flat roof,
- External and internal doors,
- Ceiling/internal floor slab,
- Ground floor slabs,
- Floor covering and roof space insulation, and
- Infiltration air change rate.

The office building was constructed with 290 mm wall thickness exterior walls, asphalt roof and a slab concrete floor with marble. Windows are with double-pane clear glass with aluminum frames. As Figure 3-6 illustrates, the building's main structural system is cast concrete. No adequate ceiling insulation was installed. No attic ventilation was used. During the site visit, it became clear that the windows were not adequately shaded. Office building's construction specifications are as shown in Table 3-4, 3-5, 3-6, 3-7.

Figure 3-6. Façade of the office building

		U-Value (W/m^2 K)
External Walls	150 mm Cast concrete(dense), 30 mm insulation (DOW), 90 mm brickwork, 20 mm gypsum plastering	0.749
Internal Partitions	Lightweight 2 x 25 mm gypsum plasterboard with 10 mm air gap	1.923
Internal Floor	300 mm marble(white), 300 mm concrete(medium density)	2.220

External Floor	30 mm wooden flooring, 70 mm screed, 100 mm cast concrete, 60 mm UF foam	0.460
Flat Roof	190 mm asphalt, 130 mm fibreboard, 650 mm extruded polystyrene(XPS), 100 mm cast concrete (medium density)	0.390

Table 3-4. Office Building's construction specification

Glazing	U-Value (W/m² K)	Total Solar Transmission (SHGC)	Direct Solar Transmission	Light Transmission
6mm/13mm double glazing, clear, air filled	2.708	0.607	0.604	0.781

Table 3-5. Office Building's windows specification

Frames	U-Value (W/m² K)
5 mm aluminum window frame	5.881

Table 3-6. Office Building's frames specification

Internal Shading	Solar transmittance	Solar reflectance
Blind with medium reflectivity slats, inside	0.500	0.200

position, horizontal orientation		

Table 3-7. Office Building's internal shading specification

3.3.2 Activity input data and lighting

The office activity schedule for the office building was defined using the activity input template in DesignBuilder. This template allowed for the specification of:

• The occupancy schedule and density,
• the activity taking place and the associated metabolic factor,
• the holiday schedule,
• the set point temperatures for heating and cooling and
• the heat gains associated with the use of office equipment and lighting.

The office building is occupied from 9:00 am to 15:00 pm every day, excluding weekends and holidays. The highest occupancy hours of the day are usually from 10:00 am to 12:00 am. During a typical summer day, all doors and windows are normally left open during the occupied hours, and they are completely closed after these hours for security reasons. During a typical winter day, all windows are closed because of the low outside temperatures.

Internal loads from computers and equipment was set on average to 17 W/m^2 and 5 W/m^2 respectively, for each office room. Thermal comfort is evaluated by Fanger's comfort theory — see [18, 34]. The critical indoor operative temperature meeting this requirement depends on the metabolism and clothing resistance, as described in Chapter 2. Assuming seated light office work (metabolism of 120 W/person) and light working clothes (0.75 Clo), a threshold temperature of 25 °C for cooling season and 22 °C for heating season is found — see [18]. All this information is summarized in the following table:

Occupancy schedule	09.00-15.00 Monday to Friday

Occupancy density (person/m^2)	0.17
Zone Activity	Seated light office work
Metabolic Rate per person (W/person)	120
Metabolic Factor (Men=1.00,Women=0.85,Children=0.75)	0.90
Winter Clothing (Clo)	1.00
Summer Clothing (Clo)	0.50
Setpoint Temperature for Cooling (°C)	25
Setpoint Temperature for Heating (°C)	22
Computer Gains (W/m^2)	17 W/m^2 (average for each office room)
Other Equipment Gains (W/m^2)	5
Fluorescent lighting Gains(W/m^2)	9.20

Table 3-8. Activity input data of the building

3.3.3 HVAC system and operation

The HVAC system is modeled using a compact HVAC description. In DesignBuilder the unitary single-zone option makes it possible to model a constant-volume air conditioning configuration. In this system, wall-mounted air-condition chillers (electricity consumption) and central heat radiator (oil consumption) are used to condition air which is delivered in each of the zones through an air delivery system. It should be mentioned here that air deliveries are not set up to achieve minimum supply requirements of fresh air.

According to occupants' reports, the temperature throughout the building is preset to maintain the building to 24 °C during the summer cooling period and to 22 °C during the winter heating period.

It was not possible to experimentally determine the distribution losses of the boiler and the chiller and as no better information was available it was assigned an 80% seasonal efficiency. This number was chosen based on the "good modern boiler design matched closely to demand" [18]. System efficiencies for both heating and cooling were set to 2.5.

Three different periods for heating and cooling were set in DesignBuilder based on information obtained as part of a data gathering phase. These were a heating period, a cooling period and a heating and cooling period. The duration, days and hours of heating and cooling are detailed in Table 3-9.

Month	Heating	Cooling	Days	Hours
January	✓		Monday – Friday	09.00 – 15.00
February	✓		Monday – Friday	09.00 – 15.00
March	✓		Monday – Friday	09.00 – 15.00
April	✓	✓	Monday – Friday	09.00 – 15.00
May	✓	✓	Monday – Friday	09.00 – 15.00
June		✓	Monday – Friday	09.00 – 15.00
July		✓	Monday – Friday	09.00 – 15.00
August		✓	Monday – Friday	09.00 – 15.00
September		✓	Monday – Friday	09.00 – 15.00
October	✓	✓	Monday – Friday	09.00 – 15.00
November	✓		Monday – Friday	09.00 – 15.00
December	✓		Monday – Friday	09.00 – 15.00

Table 3-9. Heating and Cooling schedule of the building

3.3.4 Description of occupants thermal comfort

The employees of the office building were interviewed regarding the quality of the indoor environment and its effect on their comfort and productivity. The majority of the employees' complaints were about strong overheating during summer months. They mentioned that the cooling system was unable to reach the set point temperature. Thus, the indoor operative temperature of the building was usually very high during working hours. Also, most of the employees mentioned that their productivity was effected because of glare — too much light falls on the computer screen reducing contrast to the point that the image is no longer easy to see or to use. This causes sensations of discomfort, such as dizziness or headaches. A remarkable percentage of employees also complained about draft months. Because of this, some of the employees are forced to use auxiliary heating units, further increasing energy consumption of the office building. There were no complaints about indoor air pollution, which is the main cause of the "sick building syndrome". This is because the office building is not situated in an urban or a highly-polluted region.

Building occupants provide useful information regarding indoor environment quality and its effect on comfort and productivity. Their answers, combined with simulation results, were used to assess the performance of the office building, and helped identify areas in need of improvement.

3.4 Office building energy performance calculation

3.4.1 Simulation model

The basic mechanisms of energy flow within buildings are shown in Figure 3-7. Heat is gained by solar radiation, lighting, heating, metabolic activity and equipment. Heat is lost via air leaks, ventilation, radiation through windows and conduction (transmission) through walls, windows and floors. Heat is stored and released by the thermal mass of the building.

In EnergyPlus the heat gains by beam and solar radiation are calculated using an empirical model based on radiance measurements of real skies, as described in [31]. In this model, the sky radiance is simulated as direct solar radiation (short-wave) and as reflected (long-wave) from exterior surfaces and ground which then enters the building through its external fenestration. EnergyPlus estimates the distribution of short-long-wave radiation in the interior of each thermal zone. Interior zones, which do not have external fenestration, can receive solar radiation in two ways: they may receive direct beam solar transmitted through the external fenestration and then through transparent surfaces (windows and glass doors) in the internal partition walls; they may also receive multi-reflected beam and diffuse radiation from the adjacent zones. Figure 3-8 illustrates these two possibilities of short wave radiation transfer between zones.

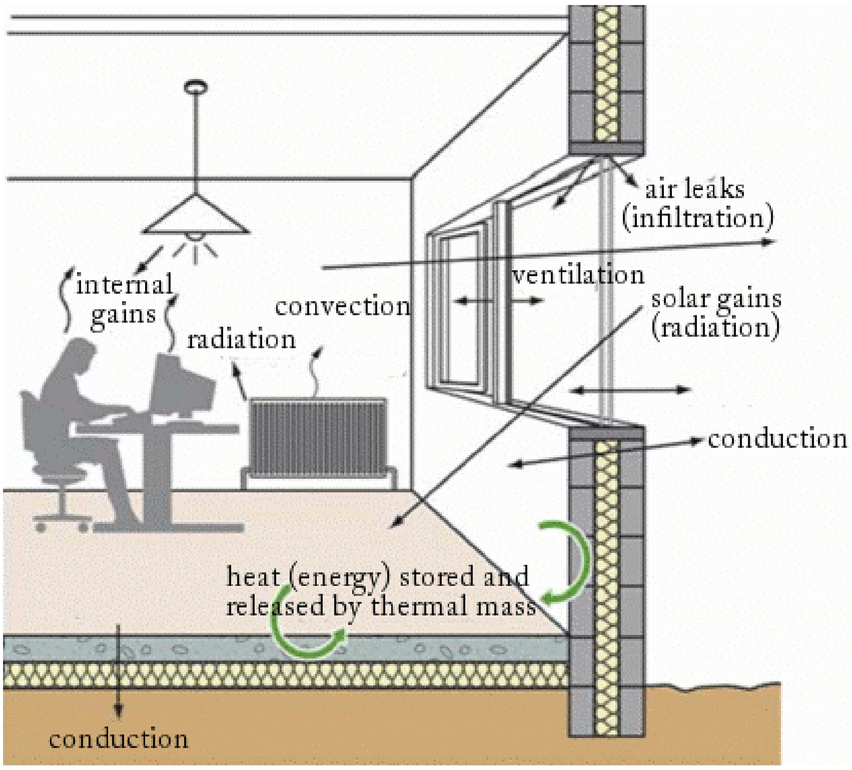


Figure 3-7. Heat (energy) flows within a building.

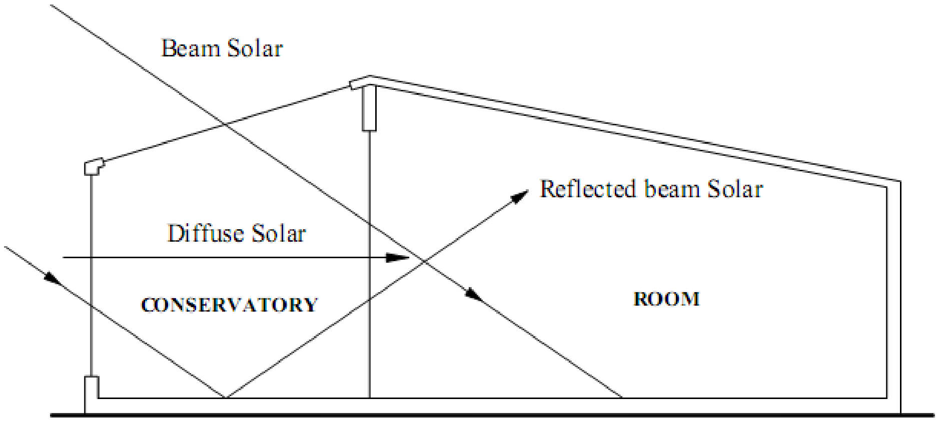


Figure 3-8. Solar transfer to interior zones

The amount of beam radiation absorbed by each surface is determined by the solar absorptance ratio and the sunlit area on the surface. The reflected portion, and the entering diffuse solar, are assumed to be uniformly distributed among the surfaces as long-wave radiation. Thus, interior radiation consists of beam solar radiation, diffuse solar radiation, and short-wave radiation from electric lights, occupancy and office equipment.

In addition to heat gains because of radiative heat transfer, convection from internal sources also contributes to the overall heat gain of a zone. Infiltration and ventilation mechanisms contribute to air exchange between the outside and the zone air. The amount of air that infiltrated is quite complicated to determine. In the most common procedure, the infiltration and ventilation quantity is measured as the number of Air Changes per Hour (ACH) and included in the zone air heat balance model. The temperature of the infiltrating air is equal to the outside temperature at the current hour. Last but not least, in the heat balance the transfer of energy analysis conduction through building elements such as walls, floors, and roofs is modeled.

The total heat gains are obtained by algebraically adding contributions due to each of the mechanisms outlined above:

$$\dot{Q}_{load} = \dot{Q}_t + \dot{Q}_{tb} + \dot{Q}_v + \dot{Q}_s + \dot{Q}_i + \dot{Q}_h + \dot{Q}_c \quad (1)$$

where,

$\dot{Q}_t$: Conduction heat transfer through walls, windows and floors,
$\dot{Q}_{tb}$: Heat exchange due to infiltration of outside air,
$\dot{Q}_v$: Heat exchange due to natural ventilation,
$\dot{Q}_s$: Radiative heat transfer,
$\dot{Q}_i$: Convective heat exchange due to internal loads,
$\dot{Q}_h$: HVAC system (heating operation), and
$\dot{Q}_c$: HVAC system (cooling operation).

Proper estimation of each of these contributions is performed in Energy Plus using appropriately selected models and implemented as modules in the software. The heating or cooling loads to be delivered by the HVAC system depends on the climatic conditions and the internal set point temperature.

For stability reasons it was necessary to derive an equation for the zone temperature that included the unsteady zone capacitance term and to identify methods for determining the zone conditions and system response at successive time steps. The formulation of the solution scheme starts with a heat balance on the zone.

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{\inf} \; C_p (T_\infty - T_z) + \dot{Q}_{sys} \quad (2)$$

$C_z \frac{dT_z}{dt}$: Energy stored in zone air.

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$: Sum of the convective internal loads.

$\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$: Convective heat transfer from the zone surfaces.

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$: Heat transfer due to interzone air mixing.

$\dot{m}_{\inf} \; C_p (T_\infty - T_z)$: Heat transfer due to infiltration of outside air.
$\dot{Q}_{sys}$: System output.

Using the parameters outlined in Section 3.3, a thermal simulation of the office building performed to estimate the energy performance and thermal comfort conditions. Simulation performed using an annual weather data file to cover a period of one year starting from 1st of January to 31st of December. The simulation results present office building's monthly mean air temperature, radiant temperature, occupants' discomfort hours, outdoor temperature, and heat gain and losses. The fabric and ventilation data shows the annual heat losses due to glazing, walls, roofs, ceiling, and external infiltration related to the number of air changes to the building and heat gain due to internal floor and natural ventilation. Additionally, simulation results present the electricity and space cooling and heating energy consumption of the office building. The results can be seen in the following Figures 3-9, 3-10, 3-11, 3-12, 3-13.

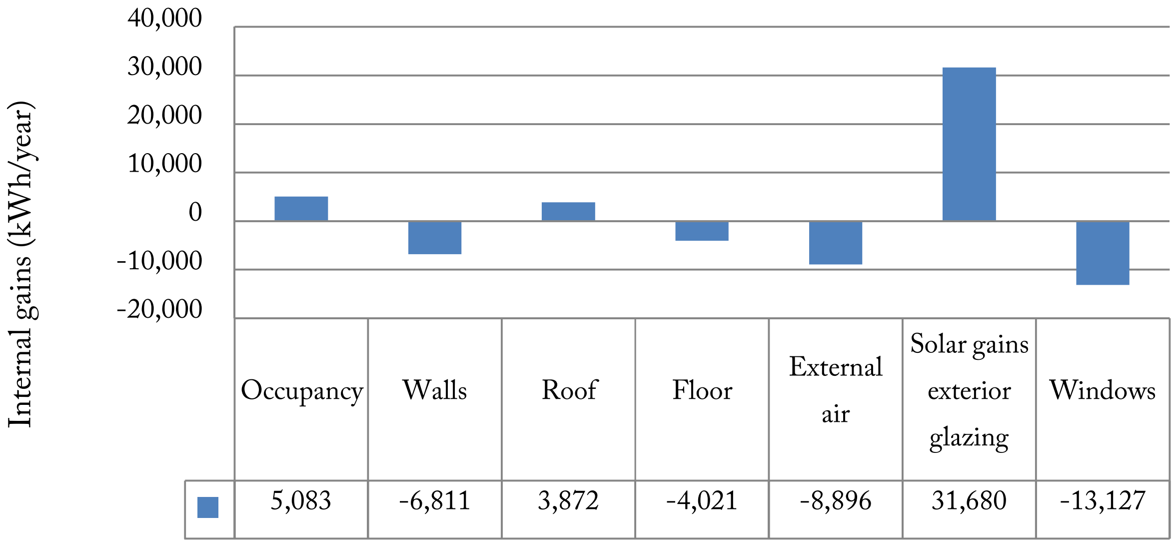
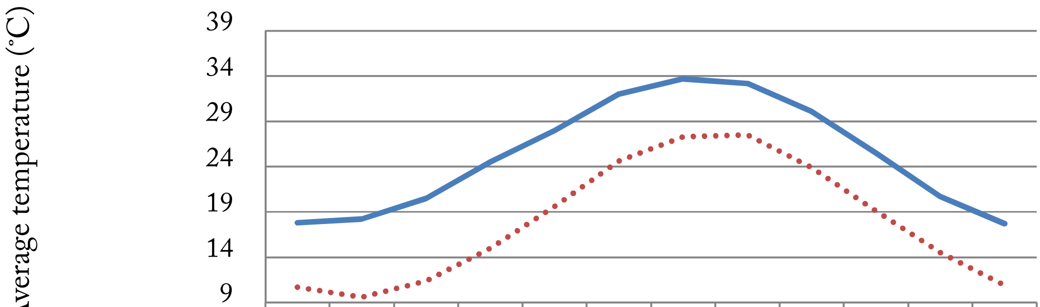
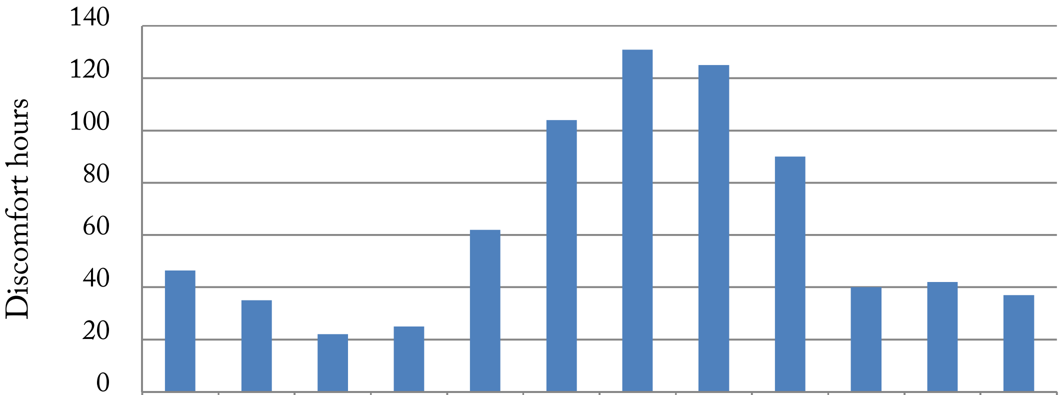


Figure 3-9. Energyplus simulated indoor internal for a one-year period



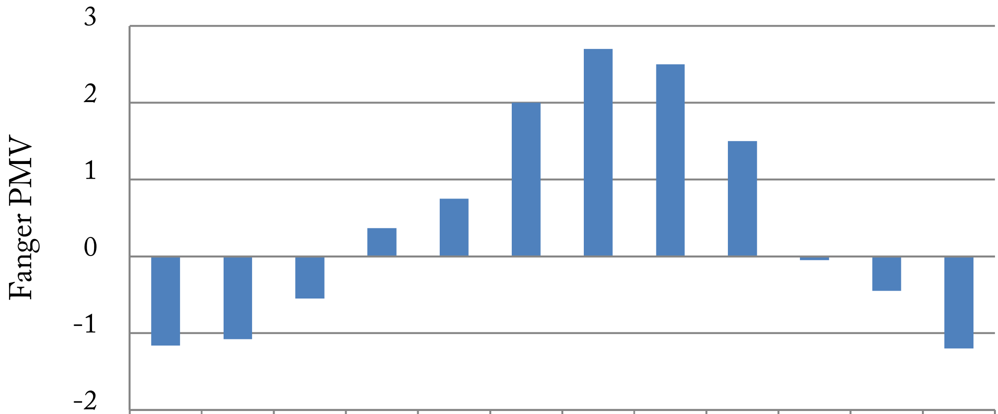
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Operative temperature (°C)	17.8	18.2	20.5	24.5	28	32	33.7	33.2	30.1	25.5	20.7	17.7
Outside dry-bulb temperature (°C)	10.7	9.6	11.4	15	19.6	24.6	27.3	27.5	23.9	19.1	14.5	10.9

Figure 3-10. EnergyPlus simulated indoor average temperatures for a one-year period



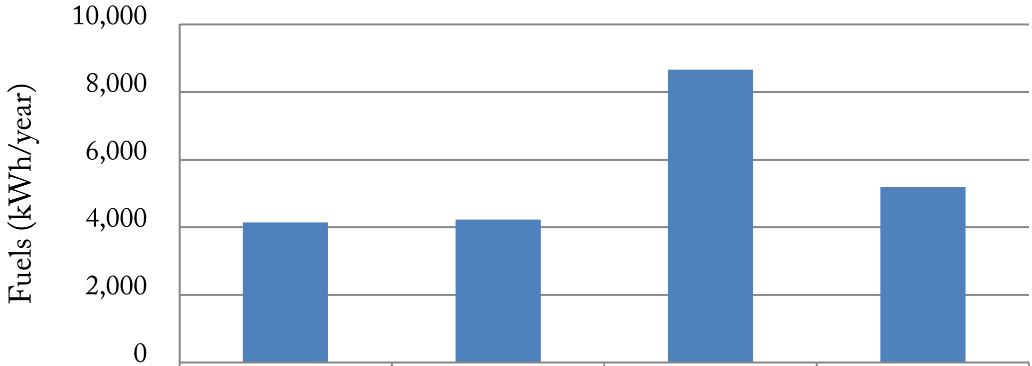
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
■	46.5	35	22	25	62	104	131	125	90	40	42	37

Figure 3-11. EnergyPlus simulated discomfort hours of the occupants for a one-year period



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
■	-1.16	-1.08	-0.55	0.37	0.75	2	2.7	2.5	1.5	-0.05	-0.45	-1.2

Figure 3-12. EnergyPlus simulated Fanger PMV for a one-year period



	Artificial lighting	Office equipment	Heat generator (oil)	Chiller (electricity)
■	4,143	4,230	8,660	5,181

Figure 3-13. EnergyPlus simulated fuels energy consumption for a one-year period

3.4.2 Analysis and discussion of simulation results

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The internal heat gain due to lighting, occupancy, transmitted solar heat, computer and other office equipment is shown on an annual basis in Figure 3-9. According to the simulation results the highest heat gains are solar gains due to exterior glazing. Gains due to occupancy and office equipment are next and finally gains due to lighting. The reason that lighting has a small contribution, compared with other heat gains, is due to the working schedule of the office building which is only during the daytime.

It was found that, throughout the year, the indoor temperatures are above the comfort zone recommended by ASHRAE (2001). As Figure 3-10 shows, the indoor temperatures are higher than the outdoor since the average temperature difference is + 7 °C all year around. High internal temperatures are found to be especially in the summer when it is usually hot and humid. Because the heat trapped inside the building and stored in building's materials this condition is became worse since the building is completely closed to the outside in the summer evening. These high temperatures lead to a significant increase in the discomfort hours as Figures 3-11, 3-12 indicate. It is observed that discomfort hours are almost double in the summer months compared to the winter. The monthly average indoor temperatures are between 31 °C and 33 °C during the summer months, with the hottest period recorded in July, which are higher than those of the outdoors. The indoor relative humidity was normally above 50% in summer with the means value ranging from 50% to 80% on an annual basis. This can be attributed to the effect of excessive heat gains through windows and uncontrolled daytime ventilation as shown in Figure 3-9.

The fuel consumption simulation results, illustrated in Figure 3-13, indicate that chiller consumption is responsible for 23.3% of the building's total energy consumption, while energy consumption for heating is 38.9% of total building's energy consumptions. This was expected because of the heat loss through walls, floor and ceiling as Figure 3-9 indicates. Given the set-point temperatures for cooling and heating, the building's HVAC system seems to be unable to maintain these temperatures. This happens because of the undersizing HVAC systems and inefficient building construction not adapted to the local climatic conditions.

The results of case-study building indicate that the problem of thermal discomfort and energy consumption is concentrated on the summer months. During winter months the problem became less intense. Passive design methods can be used to improve both the thermal comfort and energy consumption. In the next Chapter we investigate passive design modifications (retrofitting scenarios) minimizing energy consumption and improve thermal comfort.

Chapter 4

Passive design measures to improve energy efficiency and thermal comfort

4.1 Introduction

The results presented in Chapter 3 suggest that indoor condition of the case study building is in need of improvement. In this section we study modifications to achieve this goal. As mentioned earlier, windows are the major source of heat gain for the indoor space. This heat gain is the result for solar radiation entering the building and poor window insulation — see [35] for an overview. In addition, heat is trapped inside the building because of the combined effect of limited ventilation and high thermal mass. According to the building schedule of doors and openings are closed in the evening causing entrapment of heat inside — see [9]. As a result, temperatures of the building are higher inside than outside during the summer evening and the building remains warm until the next morning [12, 27]. Therefore, our design techniques will focus on: reducing windows heat gain, and second indoor heat removal using only natural means. Each design option must also consider the following two important criteria: 1) only minor changes to the building's footprint are allowed, and 2) no major change in the style of architecture are permitted.

To reduce heat gain from windows, three design modifications are studied. First, application of low-e spectrally selective argon filled glazing — see [23] for details. Second, it was found that no thermal insulation was used in the frames of the building.

Therefore, the addition of insulated frames would be an effective option to block the heat gain from the windows — see [15] for details. Third, because of the significant amount of solar radiation in region, shading from the sun all year long is necessary — see [36] for more details.

Additionally, the simulation results presented in Chapter 3 suggest that the high-thermal mass of the building combined with uncontrolled natural ventilation has a significant impact on indoor temperatures. Therefore, it is important to investigate the effect of controlled natural ventilation.

Finally, we investigate the effects from the application of concrete slab floor with insulation to increase building's thermal mass.

As described in Chapter 2, the performance of these passive cooling and heating techniques depend on multiple building and environmental parameters. The performance of these techniques depend strongly on climatic parameters (indoor-outdoor temperature difference, average outdoor temperature range), building characteristics (thermal inertia of the building and convective heat transfer between ventilation air and thermal mass) and technical parameters (ventilation rate at night and control strategy). These three design options and combinations create different retrofitting scenarios and are shown in Table 4-1. The EnergyPlus simulation software was used for each scenario and indicators regarding thermal performance were computed for each design option. For the sake of comparison the following were computed for each design option: 1) the average annual and monthly indoor operative temperature, 2) the monthly discomfort hours of the occupants, 3) the annual fuels consumption of the building, and 4) the annual CO_2 emissions. Table 4-2 summarizes the results for all passive design scenarios, with a more detailed discussion in the following paragraphs.

	Measures, involving passive design actions.
1.	Controlled natural ventilation
2.	Glazing and shading
3.	Thermal mass (floor concrete slab)
	Retrofitting scenarios, involving combined designs actions
Scenario 1	Controlled natural ventilation to existing building

Scenario 2	Glazing and shading to existing building
Scenario 3	Glazing, shading and controlled natural ventilation to existing building
Scenario 4	Controlled natural ventilation and concrete slab to existing building
Scenario 5	Glazing, shading, controlled natural ventilation and concrete slab to existing building

Table 4-1. Measures and scenarios of passive design actions

	Fuels (kWh/year)	Chiller (kWh/year)	Heat Generator (kWh/year)	CO_2 (kg/year)	Discomfort hours/year
Existing Building	22,214	5,181	8,660	11,649	759
Scenario 1	19,539	4,063	7,103	10,460	666
Scenario 2	15,528	2,491	4,788	8,664	557
Scenario 3	14,979	2,230	4,500	7,902	504
Scenario 4	34,389	5,300	20,716	15,021	295
Scenario 5	14,549	2,120	4,180	7,466	298

Table 4-2. Simulation results of passive design scenarios

4.2 Scenario 1: Controlled natural ventilation

4.2.1 Introduction

In the case-study office building, both measurement, and the simulation results presented in Chapter 3. Suggest that, during the evening, the indoor temperatures were higher than the outdoor temperatures. This happens because the occupants open the doors and windows in an uncontrolled matter, only during working schedule, during the spring, summer and autumn seasons. Thus, outside hot air enters the building from the outside increasing discomfort during working hours. At the end of the working schedule windows are kept shut until the next morning, and at night heat stored in the building material, is trapped inside the building. Under these conditions it is necessary to use controlled natural ventilation that prohibits circulation of external air unless the incoming air is cooler than the inside. Therefore, the recommendation is to use 24-hour controlled natural ventilation as a cooling passive technique.

4.2.2 Simulation model

Office building's architectural design helps us to implement stack and cross ventilation concept — see natural ventilation subsection in Chapter 2. As Figure 4-1 indicates, north wind causes a positive pressure on the windward side and a negative pressure on the leeward side of the office building. To equalize pressure, fresh-cold air (high pressure air) will enter from any windward opening and be exhausted as hot air (low pressure air) from any leeward opening of the office building (windows on top of the circulation zone, opposite windows). The relationship describing the airflow through a large intentional opening is based on the Bernoulli equation for steady, incompressible flow. The flow caused by the stack effect can be expressed by

$$Q = C_D A \sqrt{2g\Delta H (T_{in} - T_{out})/T_i} \qquad (2)$$

where,

Q : airflow rate (m^3/s)

C_D : discharge coefficient of the opening

ΔH : height from midpoint of lower opening (m)

T_{in} : indoor temperature (K)

T_{out} : outdoor temperature (K)

The discharge coefficient C_D is a dimensionless number that depends on the geometry of the opening and the Reynolds number of the flow. Equation (28) applies when $T_i > T_o$.

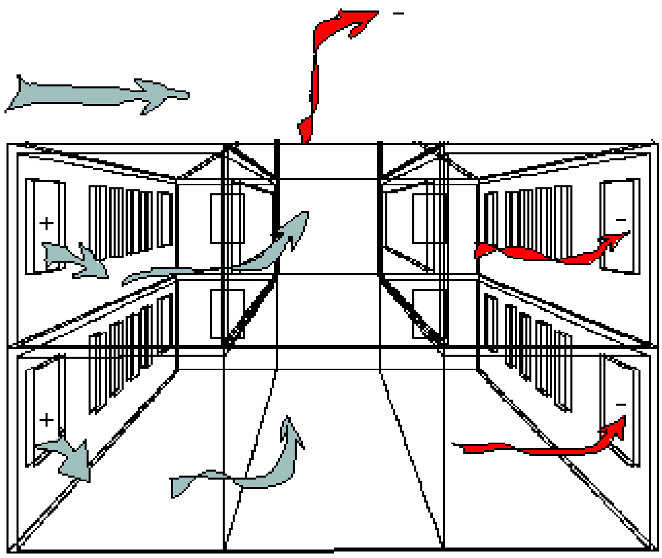
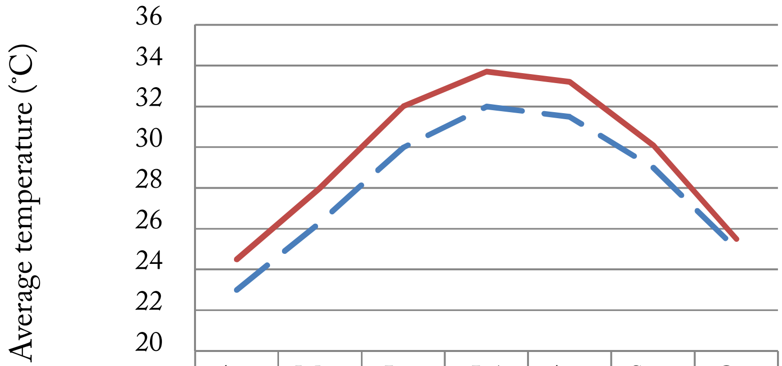


Figure 4-1. The Natural Ventilation concept of Scenario 1.

In the simulation, the timing and operation of the openings used for natural ventilation are determined by the following two rules: the air temperature in the zone is higher than the ventilation cooling set-point temperature which is 24 °C and; the difference between inside and outside air temperatures (Ti - To) is more than 2 °C.

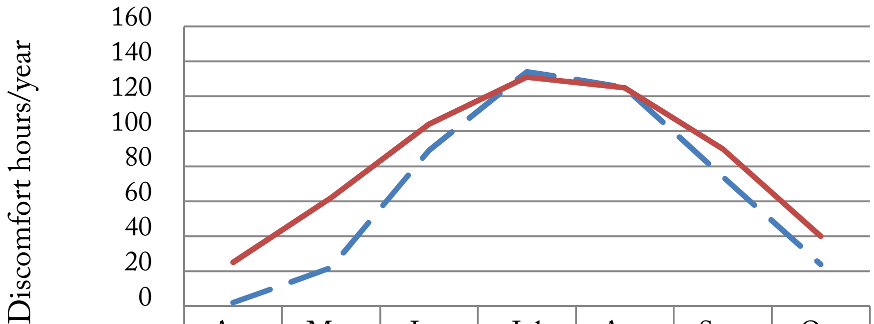
Controlled natural ventilation does not operate when only heat generator operates (November-March) as it is considered to be a cooling mechanism - windows should be closed during the coldest winter periods to prevent heat losses.

As mentioned in Chapter 2, natural ventilation of a passive design building, should not be identified with standard requirements for odour removal and fresh air recirculation. The minimum air change requirements might not be achieved by natural ventilation only, in which case mechanical ventilation or air-conditioning systems should also be utilized. In our simulation results the minimum air change requirement might not be achieved.



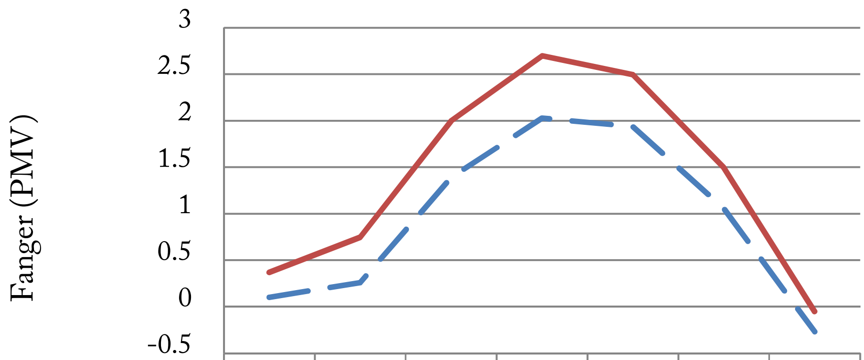
	Apr	May	Jun	Jul	Aug	Sept	Oct
Scenario 1	23	26.3	30	32	31.5	29	25
Existing building	24.5	28	32	33.7	33.2	30.1	25.5

Figure 4-2. EnergyPlus simulated indoor average temperatures for a one-year period: Existing building vs Scenario 1.



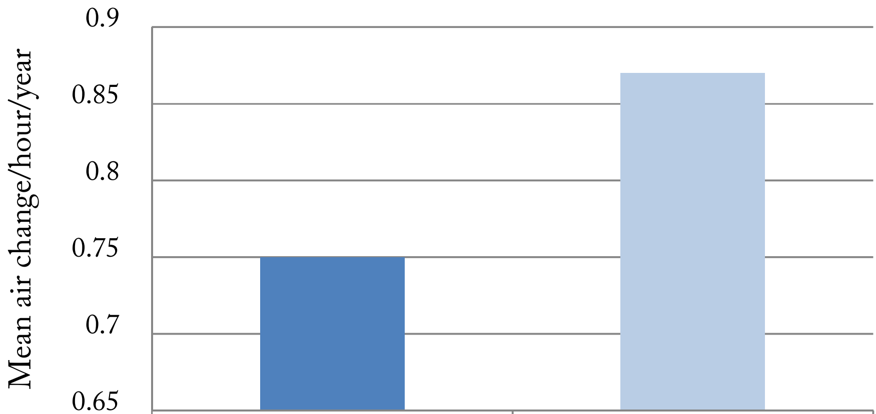
	Apr	May	Jun	Jul	Aug	Sept	Oct
Scenario No 1	2	22	89	134	125	74	24
Existing office building	25	62	104	131	125	90	40

Figure 4-3. EnergyPlus simulated discomfort hours of the occupants for a one-year period: Existing building vs Scenario 1.



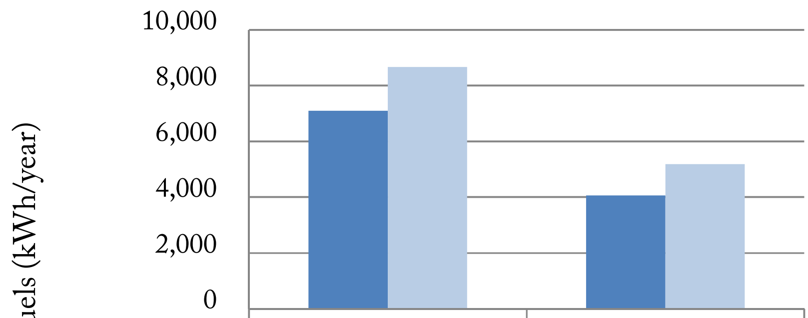
	Apr	May	Jun	Jul	Aug	Sept	Oct
Scenario No 1	0.1	0.26	1.39	2.03	1.94	1.06	-0.27
Existing office building	0.37	0.75	2	2.7	2.5	1.5	-0.05

Figure 4-4. EnergyPlus simulated Fanger PMV for a one-year period: Existing building vs Scenario 1.



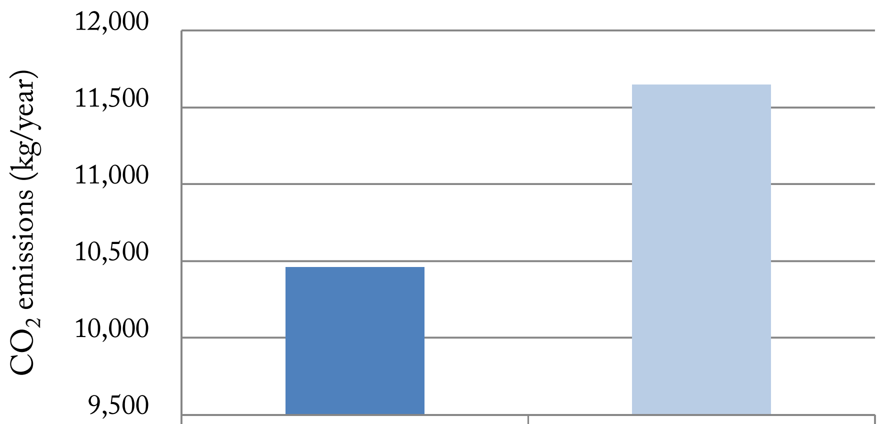
	Scenario 1	Existing office building
■	0.75	0.87

Figure 4-5. EnergyPlus simulated air changes per hour because of natural ventilation and infiltration for a one-year period: Existing building vs Scenario 1.



	Heat generator (oil)	Chiller (electricity)
Scenario 1	7,103	4,063
Existing office building	8,660	5,181

Figure 4-6. EnergyPlus simulated fuels for a one-year period: Existing building vs Scenario 1.



	Scenario 1	Existing office building
■	10,460	11,649

Figure 4-7. EnergyPlus simulated CO_2 emissions for a one-year period: Existing building vs Scenario 1.

4.2.3 Analysis and discussion of simulation results

Simulation results indicate that building performed better in terms of thermal comfort when a controlled natural ventilation strategy was applied. Controlled natural ventilation without any changes in the building configuration could reduce peak temperatures up to 2 ˚C, as Figure 4-2 indicates. This would result in a reduction of the average temperature deviation from the outdoors from + 7 ˚C to + 5 ˚C, which means that inside building temperatures would still be higher than outside, but cooler compared to the existing building. As Figure 4-3 shows, discomfort hours during the spring and autumn months decreased considerably since the outside temperature is often lower than the inside. The Figure 4-3 indicates that because of the high outdoor temperatures, natural ventilation does not have radical effect in July and August in occupants' discomfort hours' improvement. This has as a result to reduce air changes per hour less than the minimum requirements, in proposal to avoid the replacement of internal hot air by even hotter external air. Besides that, Figure 4-4 indicates, Fanger's thermal sensation indicator got closer to neutral point than before, and the occupants' feel less warm. Because of these results the reduction of discomfort hours was up to 12.2%. If the difference in the maximum day temperature and minimum night temperature was higher and mechanical ventilation (e.g., whole-building fan) was used to increase the airflow rate, there is a potential that controlled natural ventilation could be more effective.

As we can see in Figure 4-6 the use of controlled natural ventilation can bring significant advantages in fuel consumption of the office building, reducing chiller and heat generator energy consumption by 21.57% and 17.9 respectively. Finally, as Figure 4-7 indicates there is up to 10.2% reduction of CO_2 emissions.

Conclusively, simulation results of Scenario 1 indicate that elimination of uncontrolled building ventilation during the day and allowing for ventilation during the evening, when the outside temperatures are lower than the inside, the overall comfort conditions and chiller energy consumption were be improved.

4.3 Scenario 2: Glazing and shading devices

4.3.1 Introduction

The results of existing office building indicate that a significant part of heat gain can be attributed to solar radiation transmitted through the glazing and, to a lesser extent, conduction heat transfer through exterior walls. Direct sun in the workplace is almost always a comfort problem [3]. Occupants uncomfortable feeling will be less productive, close their window coverings, bring in energy-using portable fans and, if possible the lower thermostat. The EnergyPlus daylighting module, in conjunction with the thermal analysis module, can help investigate the impact of daylighting strategies in energy consumption using analysis of daylight availability, site conditions, window management in response to solar gain and glare.

We investigate the use of shading devices as the simplest passive method to protect against solar heat gain in the interior space [2]. Shading also helps reduce solar glare [22]. Additionally, shading devices modify the intensity and distribution of daylight entering the space [13]. Shading is expected to lead to reduced cooling demands and improvement of thermal comfort [2]. Additionally, transmission of solar radiation incident upon the glazing can be reduced by selecting improved glazing.

4.3.2 Simulation model

Shading devices

Since the case-study building has only small openings, additional shading devices can be selected to shade parts of the exterior windows. Table 4-3 present a conceptual design of the proposed new shading devices used for these simulations. As Figure 4-8 illustrates, the selection of shading devices can be different for each direction. Shading devices should be selected depending on the orientation of the window. According to

[13], there are two basic forms of shading devices: If the sun passes high in the sky across an opening, a horizontal shading device should be used to reduce solar radiation. This can be effective for south openings. If the sun passes low in the sky to shine into opening, a vertical shading device can be used to exclude solar radiation. This is effective for east- and west-facing windows.

The table below indicates the shading design strategy applied to the case-study building.

Orientation	Effective Shading
South (equator-facing)	Fixed horizontal device
East and West	Vertical device/louvres
North (pole-facing)	Not required

Table 4-3 . Shading devices selection strategy for the case-study building depending upon the orientation

Regarding selection of materials for shading devices with thermal performance is concerned; we have to consider two important parameters: the preferred absorption and the emissivity of materials, see [13] for details. Materials which reflect rather than absorb radiation are preferred. The material of shading devices which applied in the case-study office building was high reflectance steel.

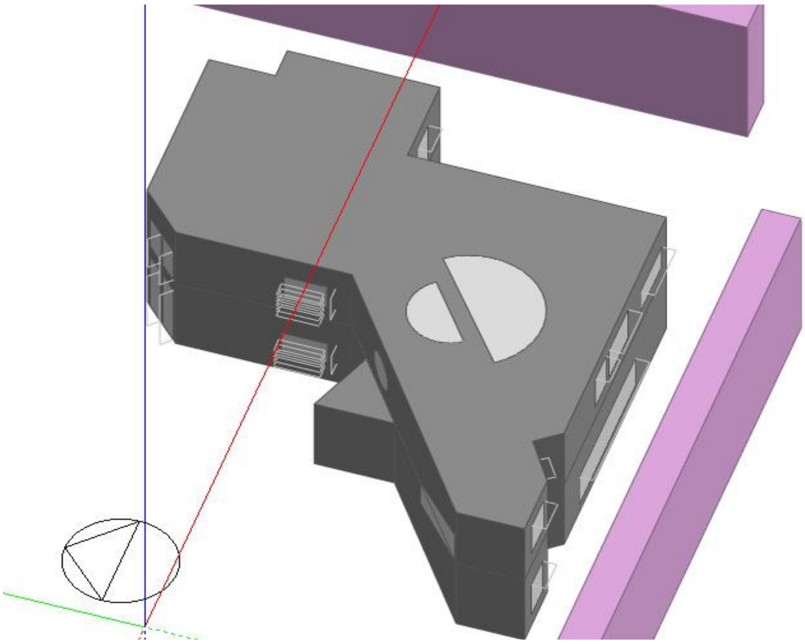


Figure 4-8. The office building with shading devices

Glazing improvement

In EnergyPlus, the window glass face temperatures are determined by solving heat balance equations on each face at every time step. For a window with N glass layers there are $2N$ faces and therefore $2N$ equations to solve. Figure 4-9 shows the variables used for double glazing (N=2).

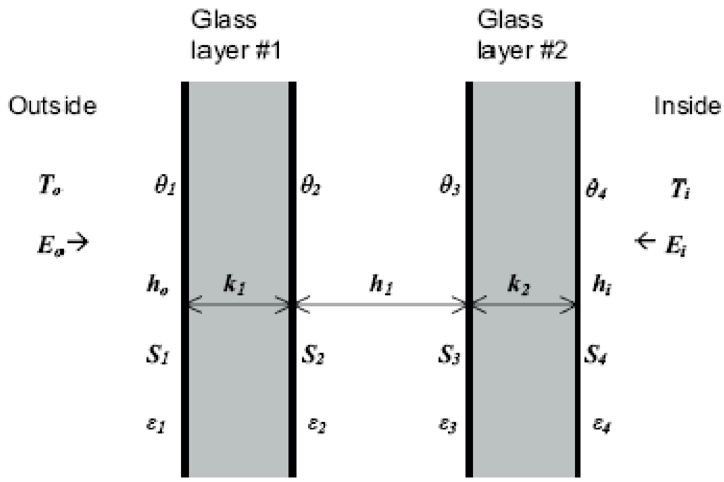


Figure 4-9. Glazing system with two glass layers showing variables used in heat balance equations.

$$E_o\varepsilon_1 - \varepsilon_1\sigma\theta_1^4 + \frac{k_1}{l}(\theta_2 - \theta_1) + h_o(T_o - \theta_1) + S_1 = 0$$

$$\frac{k_1}{l}(\theta_1 - \theta_2) + h_1(\theta_3 - \theta_2) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}(\theta_3^4 - \theta_2^4) + S_2 = 0$$

$$h_1(\theta_2 - \theta_3) + \frac{k_2}{l}(\theta_4 - \theta_3) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}(\theta_2^4 - \theta_3^4) + S_3 = 0$$

$$E_i\varepsilon_4 - \varepsilon_4\sigma\theta_4^4 + \frac{k_2}{l}(\theta_3 - \theta_4) + h_i(T_i - \theta_4) + S_4 = 0 \qquad (3)$$

Here

E_o, E_i : Incident exterior and interior long-wave radiation (W/m[2])

h_o, h_i : Outside and inside air film convective conductance (W/m[2] K)

S_i : Radiation (short-wave and long-wave) from zone lights absorbed on face i (W/m[2])

T_o, T_i : Outside and inside air temperatures (K)
ε_i : Long-wave emissivity of face i
h_j : Conductance of gas in gap *j* (W/m^2 K)
σ : Stefan-Boltzmann constant
l: width of glass (m)

Heat is lost and gained through windows by direct conduction through the glass and frame, by air leakage through and around the window assembly, and by the radiation of heat into the building (typically from the sun) and out of the building from room temperature objects such as people, furniture, and interior walls. Three measured criteria corresponding to each of these heat loss and gain methods: U-factor, air leakage coefficient, and solar heat gain coefficient (SHGC).

The U-value at a window defined as the amount of heat lost through a one square meter of the material for every degree difference in temperature on either side of the material. In EnergyPlus the overall U-factor is estimated using area-weighted U-factors for each part of the window:

$$U_O = \frac{U_{cg}A_{cg}+U_{eg}A_{eg}+U_fA_f}{A_{pf}} \qquad (4)$$

where the subscripts *cg*, *eg*, and *f* refer to the center-of-glass, edge-of- glass, and frame, respectively, A_{pf} is the area of the fenestration product's rough opening in the wall or roof less installation clearances.

The SHGC is the fraction of solar radiation admitted through a window, either transmitted directly and/or absorbed by a window assembly and subsequently released as heat inside the building. In the most general way, the solar heat gain *q* and the solar heat gain coefficient (SHGC) are defined as angle-dependent and spectrally-dependent properties:

$$q(\theta) = \int_\lambda E_D(\lambda)[T(\theta,\lambda) + NA(\theta,\lambda)]d\lambda = \int_\lambda E_D(\lambda)SHGC(\theta,\lambda)d\lambda \qquad (5)$$

and the SHGC coefficient is defined:

$$\mathrm{SHGC}(\theta,\lambda) = \frac{\int_{\lambda} E_D(\lambda)[T(\theta,\lambda)+N_1 A(\theta,\lambda)]d\lambda}{\int_{\lambda} E_D(\lambda)d\lambda} \quad (6)$$

where

$E_D(\lambda)$: incident solar spectral irradiance (W/m^2)
$T(\theta,\lambda)$: spectral transmittance of the glazing system (W/m^2)
A (θ,λ) : total spectral absorptance of the glazing system (W/m^2)

Air leakage is a measure of the rate of air infiltration around a window in the presence of a specific pressure difference across the window.

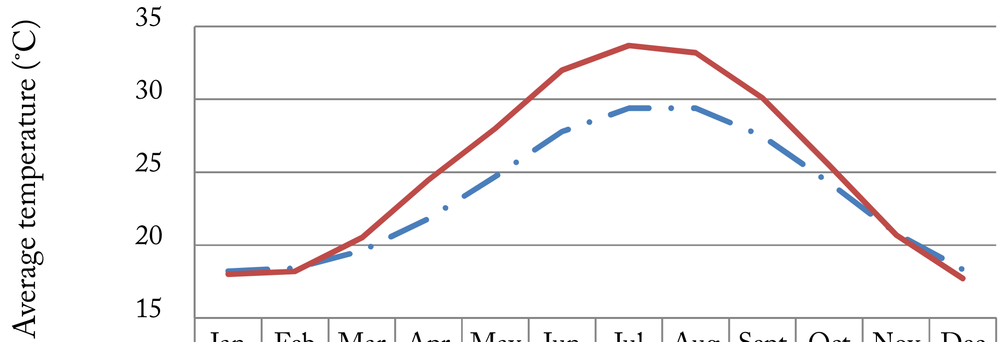
Heat lost and gained through the glass can be reduced by applying low emittance coatings on the glazing surface. A low-emittance (or low-e) coating is a microscopically thin, virtually invisible, metal or metallic oxide layer deposited directly on the surface of one or more of the panes of glass in a window with insulated glazing. The low-e coating reduces the infrared radiation (E_o, E_i) from a warm pane of glass to a cooler pane, thereby lowering the U-factor and SHGC of the glazing. Spectrally selective glazing was applied in this research. It is a special category of low-e coating. This coating is optically designed to reflect particular wavelengths and be transparent to others. According to [23] spectrally selective coatings filter out 40%–70% of the heat normally transmitted through glazing, while allowing the full amount of visual light to be transmitted. Thus, helps to create a window with a low U-factor and SHGC but a high visible transmittance 24. This type of glazing is the most appropriate for an office building, because the occupants appreciate the clear view and natural light, as well as the ability to stay in direct sunlight without becoming uncomfortably warm [3]. As Table indicates, the U_{cg}-factor of the existing double glazing of the office building is 2.7 W/m^2 K. With spectrally selective glazing the U_{cg}-factor is reduced to 1.8 W/m^2 K.

Additionally, filling the gap between the glass panes with a low-conductivity gas improves window performance by reducing conductive and convective heat transfers. This phenomenon results from the fact that the density of the gas is greater than the density of the air. In the case-study office building, argon gas was selected because of its excellent thermal performance and cost-efficiency in comparison to other gas fills. Thus, as Table 4-4 indicates the U_{cg}-factor of windows was reduced to 1.3 W/m^2 K.

Finally, in proposal to reduce air leakage through windows, the non-insulated window frames were replaced with insulated. As Table 4-4 indicates, that had as a result to reduce frames U_f-factor from 5.8 W/m^2 K to 4.7 W/m^2 K.

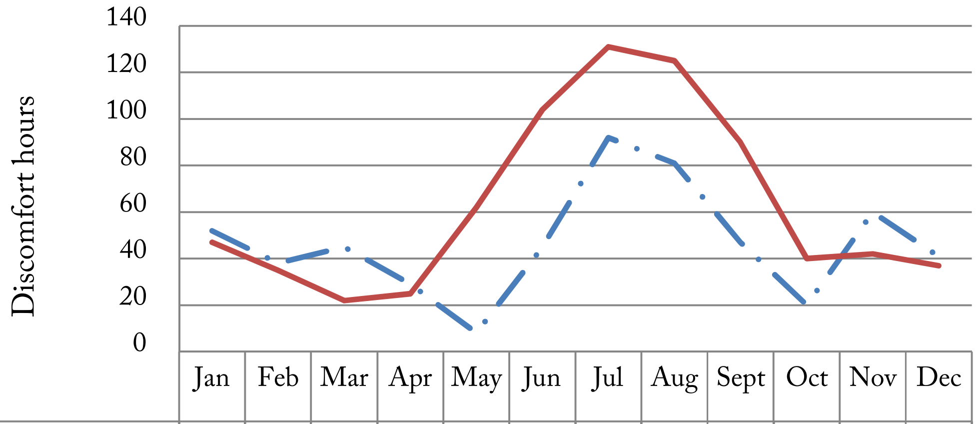
Orientation	Effective Shading
South (equator-facing)	Fixed horizontal device
East and West	Vertical device/louvres
North (pole-facing)	Not required

Table 4-4. Thermal characteristics of existing and improved windows



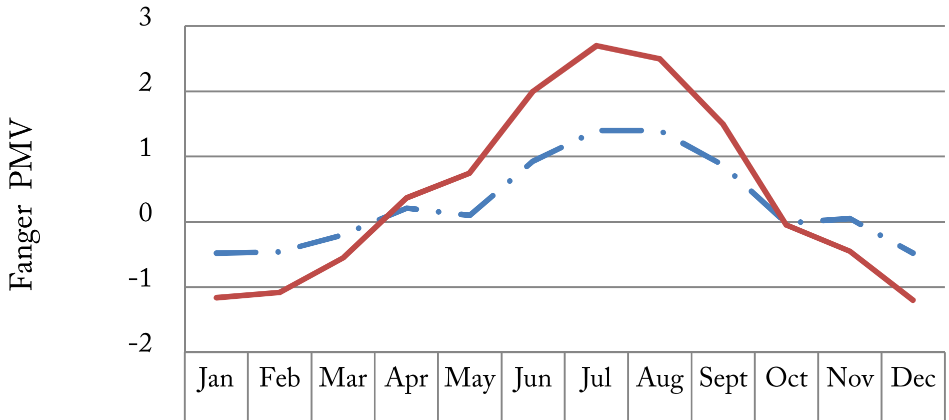
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 2	18.2	18.4	19.6	21.8	24.7	27.8	29.4	29.4	27.5	24.3	20.8	18.3
Existing building	18	18.2	20.5	24.5	28	32	33.7	33.2	30.1	25.5	20.7	17.7

Figure 4-10. EnergyPlus simulated indoor average temperatures for a one-year period: Existing building vs Scenario 2.



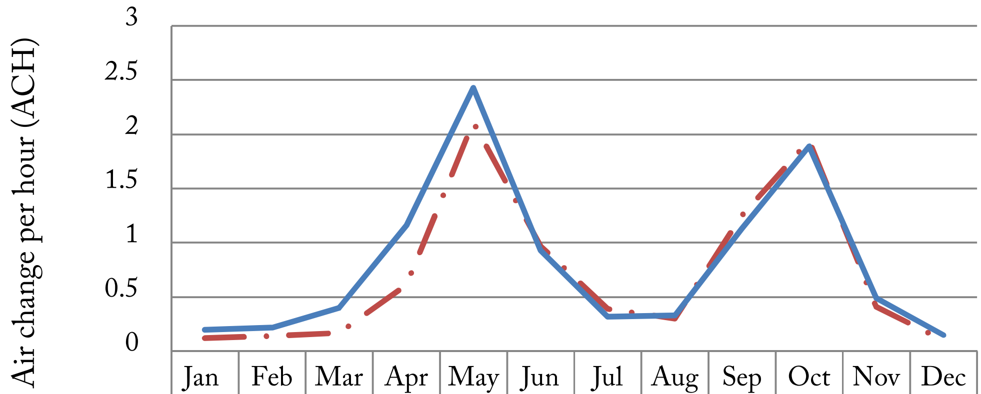
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 2	52	38	45	29	8	45	92	81	47	20	60	41
Existing building	47	35	22	25	62	104	131	125	90	40	42	37

Figure 4-11. EnergyPlus simulated discomfort hours of the for a one-year period: Existing building vs Scenario 2.



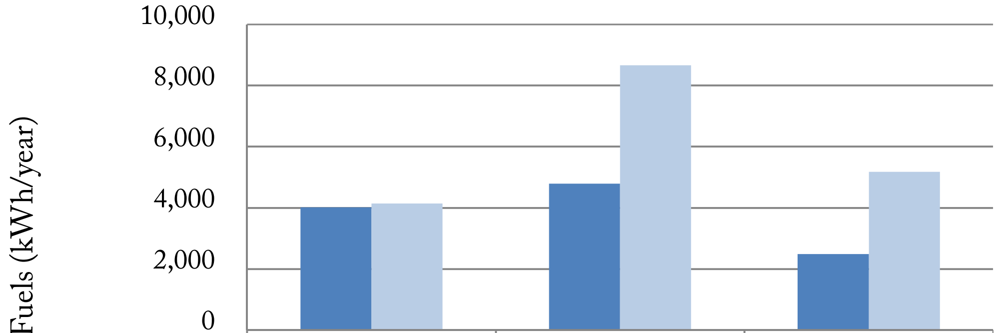
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 2	-0.48	-0.46	-0.2	0.21	0.1	0.93	1.4	1.4	0.87	-0.02	0.05	-0.48
Existing building	-1.16	-1.08	-0.55	0.37	0.75	2	2.7	2.5	1.5	-0.05	-0.45	-1.2

Figure 4-12. EnergyPlus simulated indoor Fanger PMV for a one-year period: Existing building vs Scenario 2.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Scenario No 2	0.12	0.14	0.17	0.61	2.11	0.97	0.39	0.3	1.25	1.94	0.41	0.1
Existing office building	0.2	0.22	0.4	1.16	2.43	0.93	0.32	0.33	1.13	1.89	0.49	0.15

Figure 4-13. EnergyPlus simulated air change per hour for a one-year period: Existing building vs Scenario 2.



	Artificial lighting	Heat generation (oil)	Chiller (electricity)
Scenario 2	4,019	4,788	2,491
Existing office building	4,143	8,660	5,181

Figure 4-14. EnergyPlus simulated fuels for a one year period: Existing building vs Scenario 2.

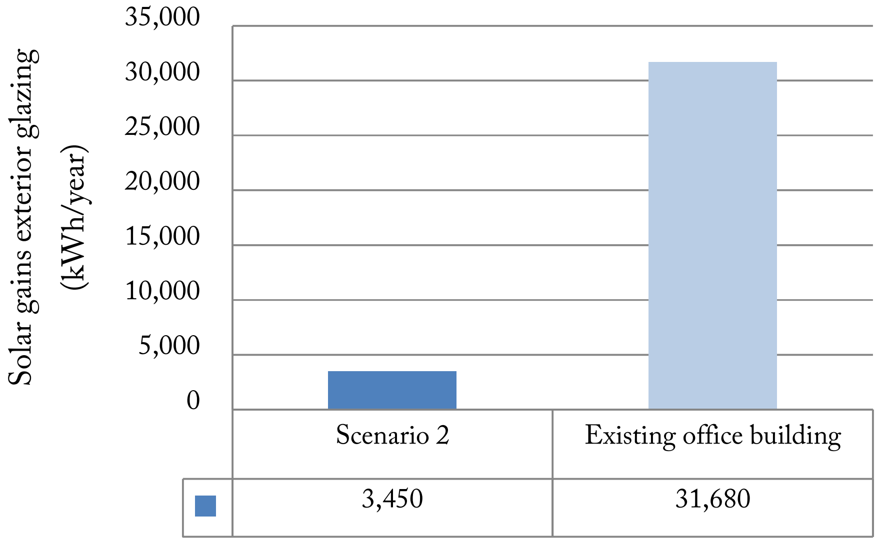


Figure 4-15. EnergyPlus simulated solar gains from the exterior glazing for a one-year period: Existing building vs Scenario 2.

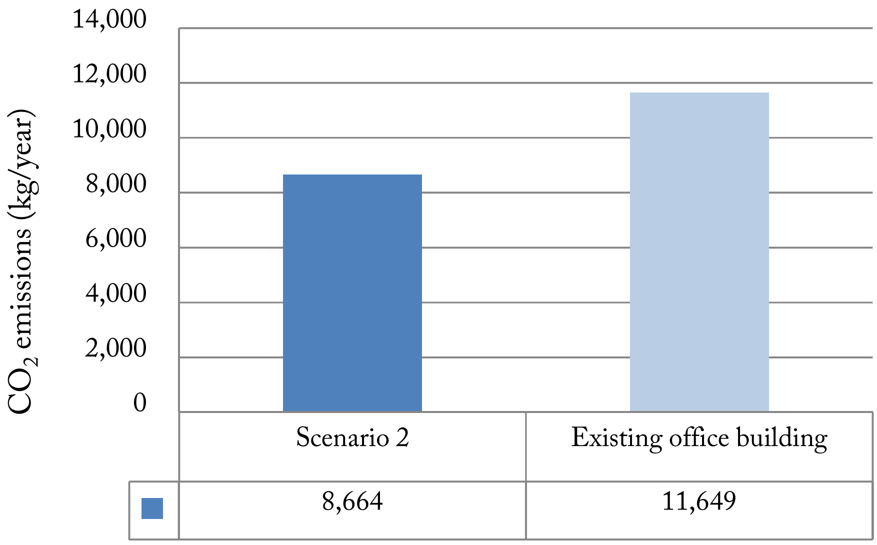


Figure 4-16. EnergyPlus simulated CO_2 emissions for a one-year period: Existing building vs Scenario 2.

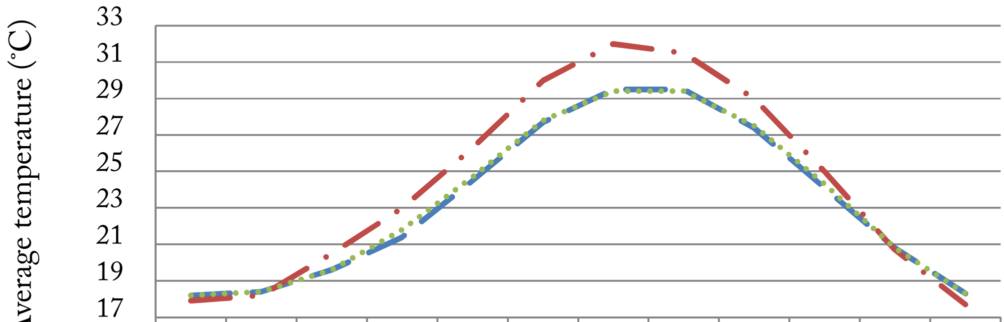
4.3.2 Analysis and discussion of simulation results

The simulation results presented in Figures 4-10, 4-11, 4-12 indicate that the case-study building would perform much better in terms of indoor thermal comfort if shading devices and improved glazing were installed. When compared to the existing building, Figure 4-10 shows that a combination of shading devices and spectrally selective argon- filled glazing could help reduce peak temperatures by as much as 4 ˚C, on summer days. In addition, these results indicate a reduction of the indoor-outdoor average temperature difference to 3 ˚C. The discomfort hours on annual bases were reduced from 759 to 557 — a reduction of 26.6%. As Figure 4-11 shows, this can be attributed to a decrease of up to 40 hours on average during the summer months. Unfortunately these passive techniques do not decrease thermal comfort in winter months. On the contrary, the monthly occupants discomfort hours in winter are slightly worst. As indicated in Figure 4-13, insufficient natural ventilation of building space in conjunction with shading devices does not allowed the building to reach the required minimum fresh air for odour removal. Thus the effects of shading devices to occupants' thermal comfort would be more noticeable if these were adjustable according to wind and sun position. In terms of external windows internal gains, Figure 4-15 shows that the decrement of solar heat gains through glazing is more than remarkable, heat gains decrease by as much as 82% from external window. As a consequence, energy requirements for cooling of the building are decreased by 51.9% compared with the existing building, as Figure 4-14 indicates. Improved windows can also reduce energy consumption for heating. As we can see in Figure 4-14, there is energy reduction for heating of 44.7%. This is due to low-e glazing (see glazing description in Chapter 2), which does not allow heat (long wave radiation) to escape through glazing, as it happened in existing building. It is also due to insulation frame that reduce heat conduction through the frame material. As a conclusion, these techniques aid in the entrapment of heat inside the building and this assists to reduce heating demands from building's HVAC system. The energy consumption has a result of reduced CO_2 emissions by up to 25.6% , as Figure 4-16 shows.

In conclusion, careful windows selection help to improvement of cooling and heating energy consumption, but only on summer months help to improvement of thermal comfort. It would be interesting to examine how shading devices effect the airflow distribution through the office building and that is what we are going to examine in Scenario 3.

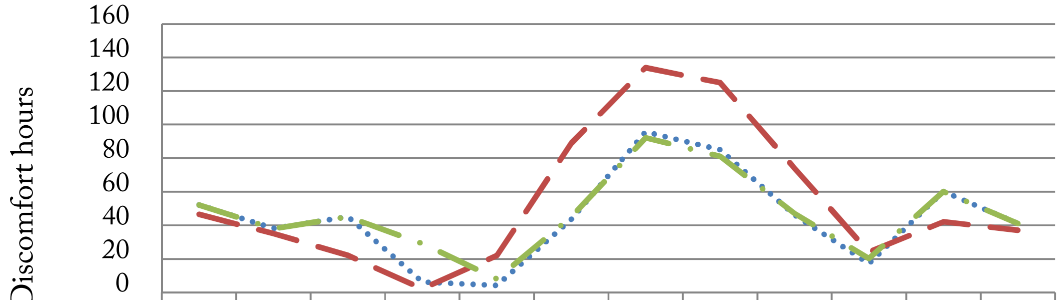
4.4 Scenario 3: Glazing, Shading and Controlled natural ventilation to existing office building

We combinated the modifications proposed in Scenarios 1 and 2 — see subsections 4.2.2 and 4.3.2 for an extensive discussion on modeling and the selection of simulation parameters. External shading devices have been utilized to reduce the amount of solar radiation entering into the buildings. However, this will affect natural ventilation for passive cooling and thermal comfort because natural ventilation can be used as a wind 'catcher'. In this Scenario, the effect of shading devices on controlled natural ventilation is examined. The combination of two effective passive techniques, as Scenarios 1, 2 indicated is examined.



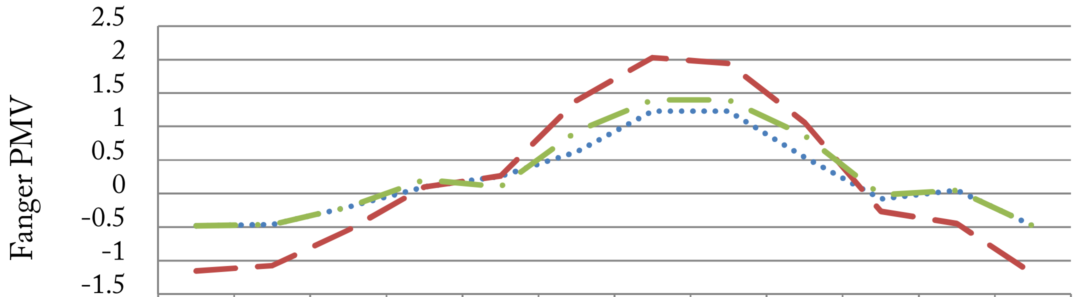
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 3	18.2	18.4	19.6	21.4	24.5	27.7	29.5	29.5	27.4	24.1	20.8	18.3
Scenario 1	17.9	18.2	20.5	23	26.3	30	32	31.5	29	25	20.7	17.7
Scenario 2	18.2	18.4	19.6	21.8	24.7	27.8	29.4	29.4	27.5	24.3	20.8	18.3

Figure 4-17. EnergyPlus simulated indoor average temperatures for a one-year period: Scenario 1 vs Scenario 2 vs Scenario 3.



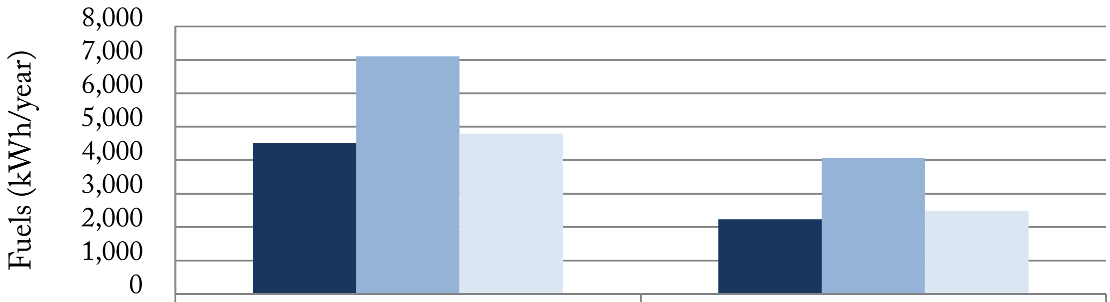
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 3	52	38	45	6	4	43.5	95.6	85	46	17	60	41
Scenario 1	46.5	35	22	2	22	89	134	125	74	24	42	37
Scenario 2	52	38	45	29	8	45	92	81	47	20	60	41

Figure 4-18. EnergyPlus simulated discomfort hours of the occupants for a one-year period: Scenario 1 vs Scenario 2 vs Scenario 3.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 3	-0.48	-0.46	-0.2	0.1	0.26	0.62	1.23	1.23	0.54	-0.08	0.05	-0.48
Scenario 1	-1.16	-1.08	-0.55	0.1	0.26	1.39	2.03	1.94	1.06	-0.27	-0.45	-1.2
Scenario 2	-0.48	-0.46	-0.2	0.21	0.1	0.93	1.4	1.4	0.87	-0.02	0.05	-0.48

Figure 4-19. EnergyPlus simulated Fanger PMV for a one-year period: Scenario 1 vs Scenario 2 vs Scenario 3.



	Heat generation (oil)	Chiller (electricity)
Scenario 3	4,500	2,230
Scenario 1	7,103	4,063
Scenario 2	4,788	2,491

Figure 4-20. EnergyPlus simulated energy consumption for heating and cooling for a one-year period: Scenario 1 vs Scenario 2 vs Scenario 3.

4.4.1 Analysis and discussion of simulation results

Figure 4-17 shows that the combination of improved windows and controlled natural ventilation when compared to Scenario 1 improve indoor temperature for all months of the year except for December and January. But a comparison between Scenario 1 and 3 shows that temperature differences are small. If we investigate closely we notice that temperatures are reduced for all months except for the summer months (June, July and August). Thus, as Figure 4-18 indicates, discomfort hours were reduced for all months except the months of excessive cold (January, February and March). This can be explained because in months natural ventilation does not provide fresh air most of the time because of excessively low and high outside temperatures. On the contrary, the other months of the year, especially in the spring and autumn, natural ventilation act as an effective cooling mechanism and discomfort hours are reduced perceptibly. For Scenario

3, when compared to the existing building, discomfort hours were reduced by 504 on annual basis. This translates to 9.51% reduction when compared to Scenario 2, 24.3% reduction when compared to Scenario 1 and 33.5% reduction when compared to the existing office building.

As we can see in Figure 4-20, cooling energy requirements are reduced by 10.9% in comparison to Scenario 2 and up to 56.9% in comparison with the existing building. The reduction of heating energy consumption is 6% in comparison to Scenario 2 and to 48% in comparison to the existing building. This decrease in energy requirement leads to CO_2 emissions reduction by 32.1% if Scenario 3 is applied to the existing building.

To summarize, the combination of natural ventilation and improved windows selection helps improve thermal comfort during the spring and autumn months. The effects regarding savings are especially important regarding cooling and heating operations.

4.5 Scenario 4: Controlled natural ventilation and concrete slab to existing building

4.5.1 Introduction

Besides window improvement and controlled natural ventilation we investigate third passive-design technique which is the effect of the thermal mass. Building materials have the ability to store an amount of heat which is directly proportional to their heat capacity. The basic characteristic of materials with high thermal heat capacity (mass) is their ability to absorb heat, store it, and at a later time release it [26]. In our work the effect of increased thermal mass applied to floor was investigated. The thermal mass and time lag of the floor must be selected depending on the function and time schedule of the building [13]. Proper selection of thermal mass can be beneficial with regards to heating and cooling losses.

4.5.2 Simulation model

In the case-study building offices are used during the morning hours, according to the schedule presented in Table 3-9, thus a 6-8 hours time lag is required. The benefit of using the concrete slab as thermal storage unit is beneficial both in summer and winter months. In summer, during the morning heat will be stored when the building is occupied, keeping interior cooler and released at evening by natural ventilation when the building is unoccupied — [37] for details. In winter, if building is well-insulated, heat is released back into the room reducing inside temperatures differences until the next morning. This leads to a downsizing of the cooling and heating systems and improved thermal comfort especially during the early hours of the occupancy schedule — see [2, 27] for details. The concept of Scenario 4 is illustrated in Figures 4-21, 4-22.

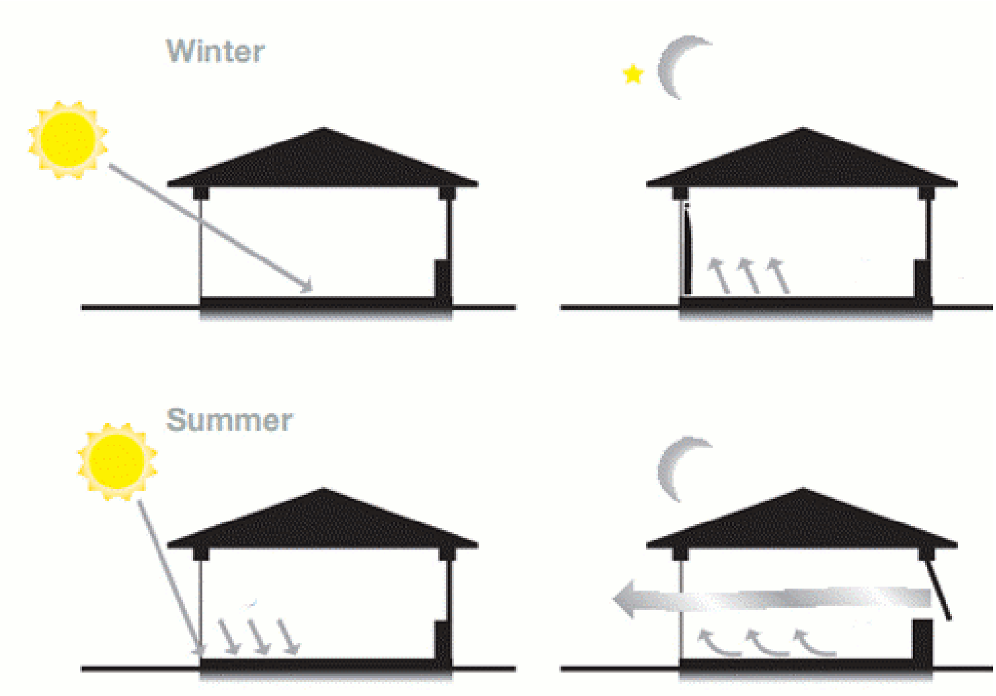


Figure 4-21.Thermal mass effects

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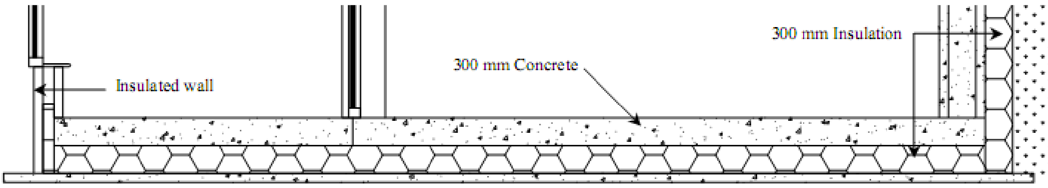
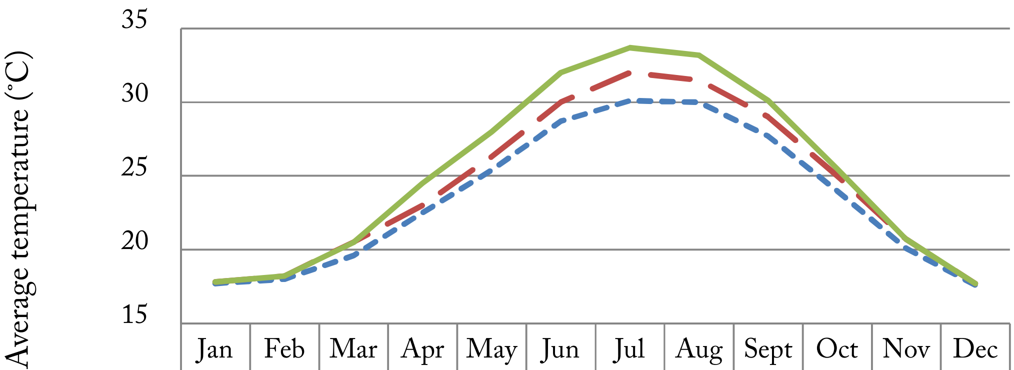
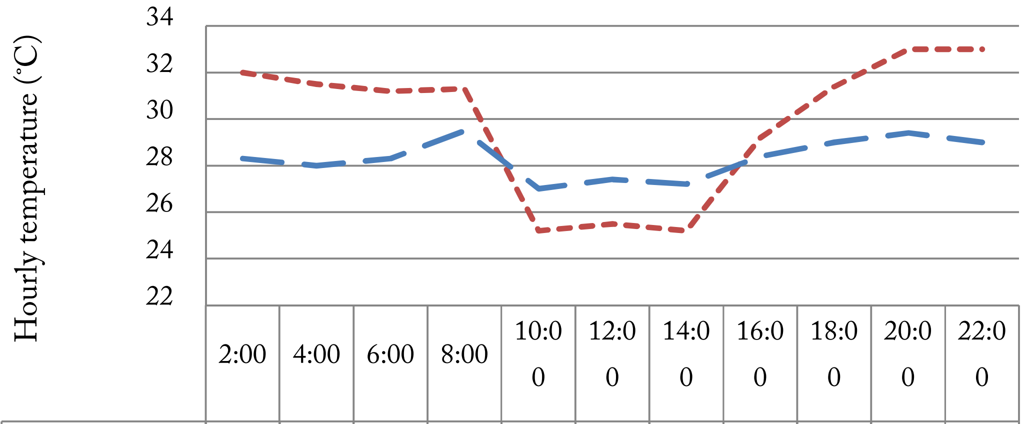


Figure 4-22. Typical section of high thermal mass floor



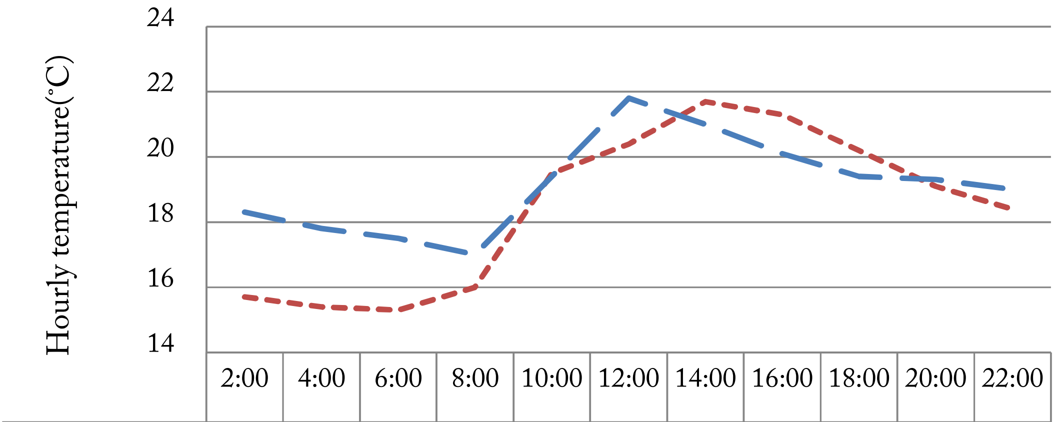
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 4	17.7	18	19.6	22.5	25.4	28.7	30.1	30	27.7	24	20.1	17.6
Scenario 1	17.8	18.2	20.5	23	26.3	30	32	31.5	29	25	20.7	17.7
Existing office building	17.8	18.2	20.5	24.5	28	32	33.7	33.2	30.1	25.5	20.7	17.7

Figure 4-23. EnergyPlus simulated indoor average temperature for a one-year Period: Existing office building vs Scenario 1 vs Scenario 4.



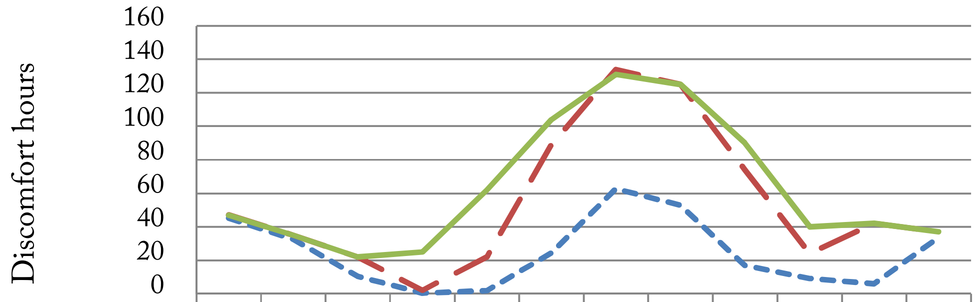
	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Scenario 4	32	31.5	31.2	31.3	25.2	25.5	25.2	29.2	31.4	33	33
Scenario 1	28.3	28	28.3	29.5	27	27.4	27.2	28.4	29	29.4	29

Figure 4-24. EnergyPlus simulated indoor hourly average temperature for the summer design day: Scenario 1 vs Scenario 4.



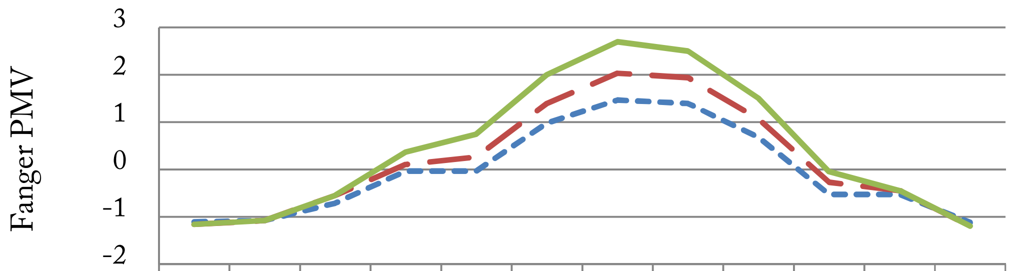
	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Scenario 4	15.7	15.4	15.3	16	19.5	20.4	21.7	21.3	20.2	19.1	18.4
Scenario 1	18.3	17.8	17.5	17	19.4	21.8	21	20.1	19.4	19.3	19

Figure 4-25. EnergyPlus simulated indoor hourly average temperature for the winter design day: Scenario 1 vs Scenario 4.



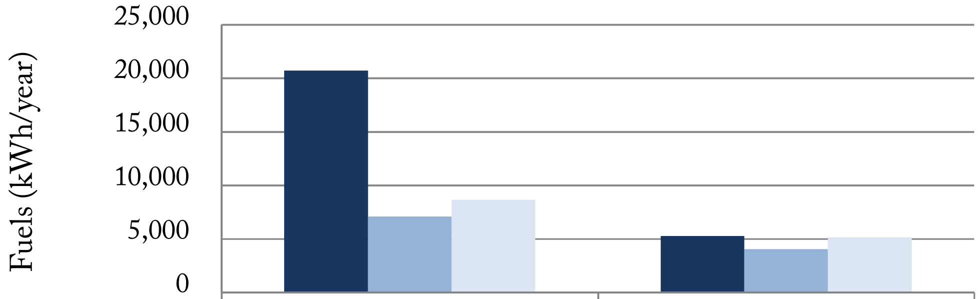
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 4	45.2	32.5	10.5	0.4	1.9	24.4	62.6	52.7	16.9	9.2	5.9	33.6
Scenario 1	47	35	22	2	22	89	134	125	74	24	42	37
Existing office building	47	35	22	25	62	104	131	125	90	40	42	37

Figure 4-26. EnergyPlus simulated discomfort hours of the occupants for a one-year period: Existing office building vs Scenario 1 vs Scenario 4.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Sceanrio No 4	-1.11	-1.08	-0.71	-0.03	-0.03	0.98	1.47	1.4	0.68	-0.53	-0.53	-1.12
Scenario No 1	-1.16	-1.08	-0.55	0.1	0.26	1.39	2.03	1.94	1.06	-0.27	-0.45	-1.2
Existing office building	-1.16	-1.08	-0.55	0.37	0.75	2	2.7	2.5	1.5	-0.05	-0.45	-1.2

Figure 4-27. EnergyPlus simulated Fanger PMV for a one-year period: existing office building vs Scenario 1 vs Scenario 4.



	Heat generator (oil)	Chiller (electricity)
Scenario 4	20,716	5,300
Scenario 1	7,103	4,063
Existing office building	8,660	5,181

Figure 4-28. EnergyPlus simulated energy consumption for heating and cooling g for a one-year period: Existing office building vs Scenario 1 vs Scenario 4.

4.5.2 Analysis and discussion of simulation results

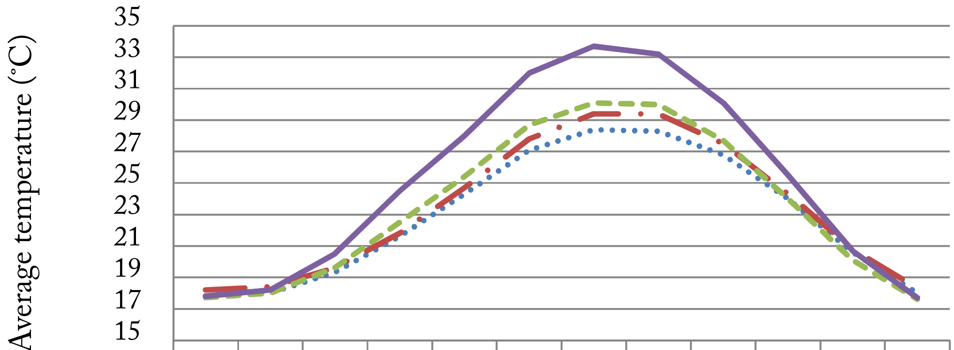
The results for this scenario indicate remarkable improvement on occupants' thermal comfort but the same cannot be claimed regarding energy consumption of the office building. As Figures 4-23, 4-24, 4-25 indicate, the operative temperatures fluctuate both during the summer and winter months, with high amplitudes on a diurnal basis. Specifically, in the summer months, during the working hours, the indoor space of the building is maintained within the thermal comfort zone because a large amount of the solar heat is stored in the concrete floor (and the other building's elements) and of the HVAC system operation. But after these hours, when the HVAC system does not operate, a small amount of this heat is transferred out of the building by controlled natural ventilation causing the indoor temperatures space to remain very high — 32 °C during the afternoon and night. The next morning, when the building is occupied, the HVAC system is activated to meet occupants' demands for thermal comfort. As a result increased cooling must be supplied from building's HVAC system and energy demands are 2.3% higher compared with the existing office building, Figure 4-28. An analogous situation occurs during winter days. In the winter, during the night hours, the heat from the concrete floor is gradually released back to the room as the outside air temperature drops but the inadequate thermal insulation is unable to seal the heat inside until the next morning. When the building is re-heated the next morning, it is not only necessary to raise the temperature of the air but the cold high thermal mass floor as well. This results in an increase on energy requirements for heating by 58.1% compared with the existing office building — Figure 4-28.

The conclusion is that when controlled natural ventilation and slab concrete floor are used, is considerably improved. Although it appears that the increase in the amount of thermal mass may lead to a building design system which is not efficient.

4.6 Scenario 5: Glazing, Shading, Controlled Natural ventilation and Concrete slab to existing building

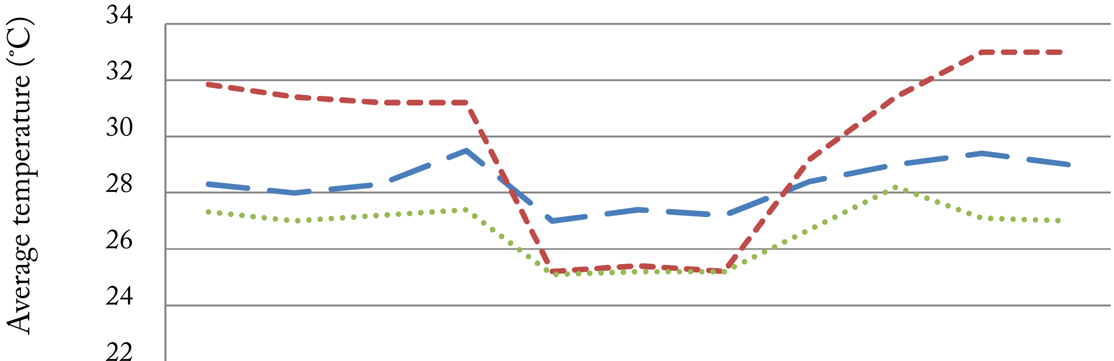
4.6.1 Introduction

The simulation results for the previous scenario indicate that the addition of thermal mass might be more effective if measures for heat-gain control are be taken. As Scenario 3 indicates, heat gains in the summer months can be reduced by application of shading devices. Loses during winter months can be reduced through the use of energy-efficient glazing. Therefore, combining the measures of Scenario 3 with Scenario 4 we expect an improvement of both the thermal comfort and energy consumption of the building.



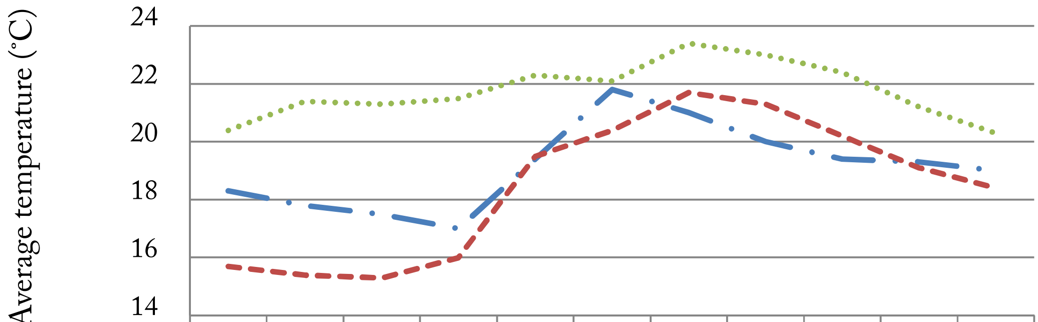
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 5	17.8	18	19.3	21.6	24.3	27.1	28.4	28.3	26.8	24	20.6	18
Scenario 2	18.2	18.4	19.6	21.8	24.7	27.8	29.4	29.4	27.5	24.3	20.8	18.3
Scenario 4	17.7	18	19.6	22.5	25.4	28.7	30.1	30	27.7	24	20.1	17.6
Existing office building	17.8	18.2	20.5	24.5	28	32	33.7	33.2	30.1	25.5	20.7	17.7

Figure 4-29. EnergyPlus simulated indoor average temperature for a one-year period: Existing office building vs Scenario 1 vs Scenario 4 vs Scenario 5.



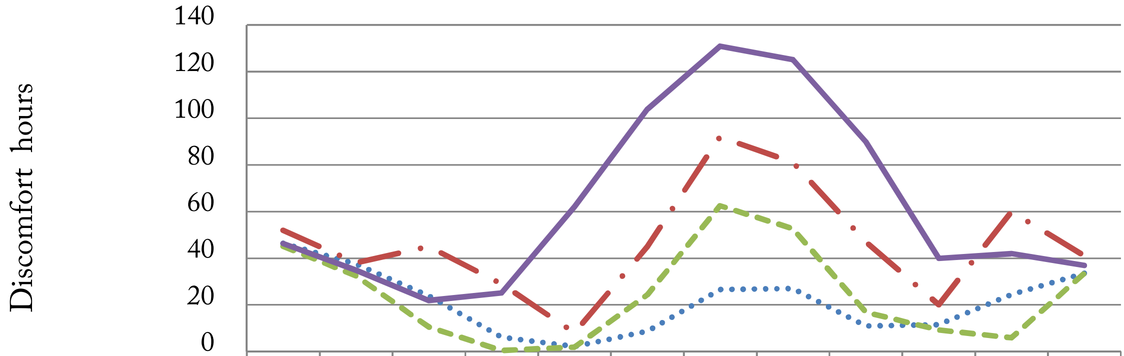
	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Scenario 1	28.3	28	28.3	29.5	27	27.4	27.2	28.4	29	29.4	29
Scenario 4	31.85	31.4	31.2	31.2	25.2	25.4	25.2	29.2	31.4	33	33
Scenario 5	27.32	27	27.2	27.4	25.1	25.2	25.2	26.7	28.2	27.1	27

Figure 4-30. EnergyPlus simulated indoor average temperature for the summer design day: Scenario 5 vs Scenario 2 vs Scenario 4.



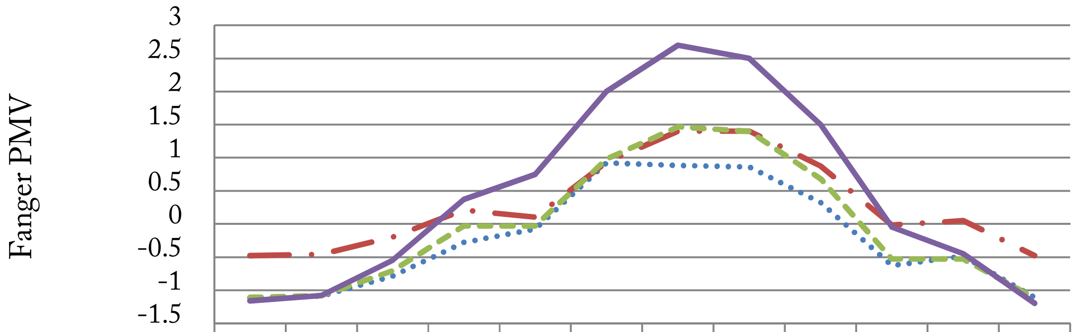
	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Scenario 2	18.3	17.8	17.5	17	19.4	21.8	21	20	19.4	19.3	19
Scenario 4	15.7	15.4	15.3	16	19.5	20.4	21.7	21.3	20.2	19.1	18.4
Scenario 5	20.4	21.4	21.3	21.5	22.3	22.1	23.4	23	22.4	21.2	20.3

Figure 4-31. EnergyPlus simulated indoor average temperature for the winter design day: Scenario 5 vs Scenario 2 vs Scenario 4.



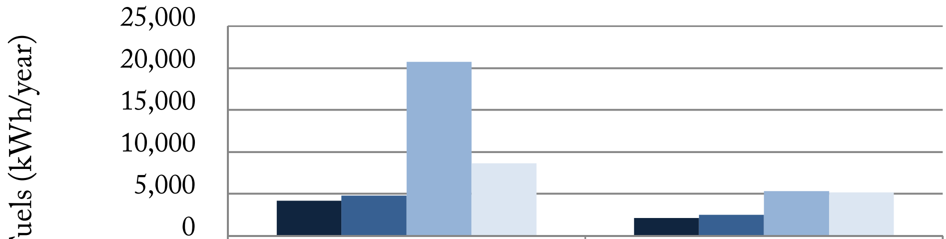
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario 5	46.4	37.6	24	6.2	2.2	8.7	26.7	27	11	11.5	24.5	33.6
Scenario 2	52	38	45	29	8	45	92	81	47	20	60	41
Scenario 4	45.2	32.5	10.5	0.4	1.9	24.4	62.6	52.7	16.9	9.2	5.9	33.6
Existing office building	46.5	35	22	25.2	62.24	104	131	125.3	90	40	42	37

Figure 4-32. EnergyPlus simulated discomfort hours of the for a one-year period: Existing office building vs Scenario 1 vs Scenario 4 vs Scenario 5.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Scenario No 5	-1.12	-1.09	-0.79	-0.28	-0.08	0.92	0.88	0.86	0.32	-0.63	-0.49	-1.11
Scenario No 2	-0.48	-0.46	-0.2	0.21	0.1	0.93	1.4	1.4	0.87	-0.02	0.05	-0.48
Scenario No 4	-1.11	-1.08	-0.71	-0.03	-0.03	0.98	1.47	1.4	0.68	-0.53	-0.53	-1.12
Existing office building	-1.16	-1.08	-0.55	0.37	0.75	2	2.7	2.5	1.5	-0.05	-0.45	-1.2

Figure 4-33. EnergyPlus simulated Fanfer PMV for a one-year period: Existing office building vs Scenario 1 vs Scenario 4 vs Scenario 5.



	Heat generation (oil)	Chiller (electricity)
Scenario 5	4,180	2,120
Scenario 2	4,788	2,491
Scenario 4	20,716	5,300
Existing office building	8,660	5,181

Figure 4-34. EnergyPlus simulated energy consumption for heating and cooling for a one-year period: Existing office building vs Scenario 1 vs Scenario 4 vs Scenario 5.

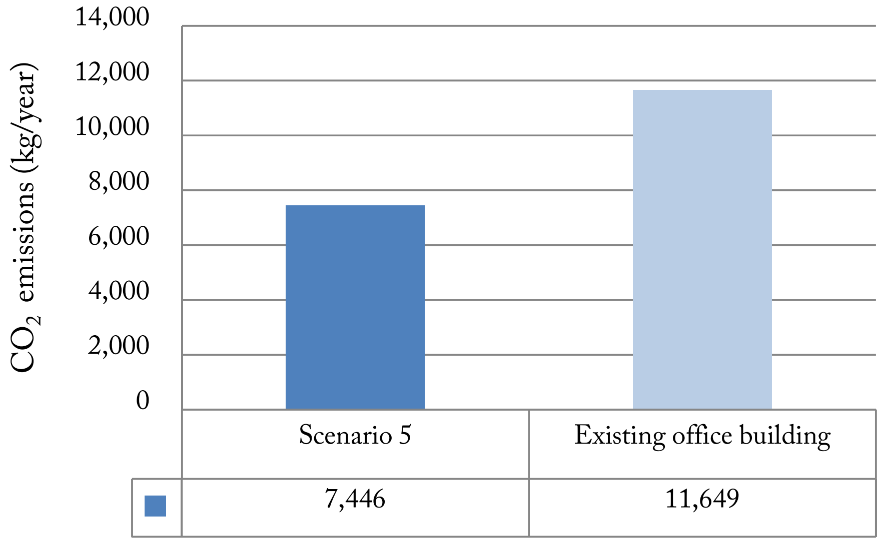


Figure 4-35. EnergyPlus simulated CO_2 emissions for a one-year period: existing office building vs Scenario 1 vs Scenario 4 vs Scenario 5.

4.6.1 Analysis and discussion of simulation results

In Scenario 5, sources of external heat gain were reduced by combining Scenario 4 with Scenario 2 to enhance the positive effect of thermal mass.

The simulation results indicate that the building of Scenario 4 would perform much better in terms of both indoor thermal comfort and energy consumption if shading devices and improved windows were installed. Figure 4-30 shows that the average indoor operative temperature on the cooling design day, when the building is unoccupied, is reduced to 27 ˚C from 32 ˚C and 28. 5 ˚C compared with Scenario 4 and 2 respectively. This situation has a result of reduced cooling requirements and a reduction in energy use of 59% compared with the existing office building, Figure 4-34.

Since controlled ventilation is only operational during the summer months, we understand that during the winter heat remains inside the better insulated building (due to efficient windows) reducing the need for supplementary heating the next morning. As Figure 4-31 indicates, increment of the indoor operative temperature in unoccupied hours up to 2 ˚C comparing with Scenario 2 and up to 4 ˚C compared to Scenario 4. As a result of reduced cooling requirements and a reduction in energy use of 51% compared with the existing office building, Figure 4-34. As a result, the energy consumption decreased: CO_2 emissions reduced by 27.3%, Figure 4-35.

Additionally, as expected, Figure 32 suggests a significant reduction in occupants' discomfort hours by 63.8% when compared to the existing building.

In conclusion, the combination of improved windows, thermal mass and natural ventilation helps improve energy requirements and thermal comfort of the occupants: both during the summer and winter months.

4.7 Summary of passive design measures and scenarios

In the thesis, simulations using the EnergyPlus whole-building simulation software for three design strategies with four different Scenarios were performed. Both the peak and annual average indoor temperatures, monthly discomfort hours and Fanger PMV were computed as indication on how comfortable conditions for the building under various passive cooling and heating design options. In addition, the annual energy consumption was calculated and used as indicator of how effective each proposed design would be with regard to the building's energy efficiency.

The simulation results demonstrated that the indoor conditions of the case study building could be remarkably improved by application of the passive design strategies. The use of high-thermal mass, controlled natural ventilation and improved windows can be greatly reducing the indoor temperatures. As a result, three design options are recommended from the investigation: 1) use controlled natural ventilation; 2) use of shading devices, spectrally selective, low-e, argon filled glazing with insulated frames; 3) and increase of thermal mass by usage of concrete slab floor.

Among all of the design options, it was found that a building constructed with either high thermal mass such as concrete slab floor, or improved windows would have a high level of indoor thermal comfort during the summer months. Controlled natural ventilation is an effective cooling strategy but not sufficient by it the excessive hot summer days. This is due to small temperature differences between day and night and, as a result, at most times the ventilation system is not operational.

During the winter months, efficient windows and high-thermal mass do not have a significant impact in thermal comfort of the occupants.

In terms of energy consumption, efficient windows have remarkable effect regarding energy efficiency of the building during both winter and summer months. Controlled natural ventilation also has considerable effect in the building's energy consumption during the spring, summer and autumn months. On the contrary, when thermal mass is not used in combination with other passive techniques it can have a negative impact on building's energy performance.

Conclusively, passive design helps the building take advantage of the climate when it is advantageous, and protects the building from the climate when it is not. This requires good knowledge of local climate, occupants thermal comfort requirements and a greater sophistication on the part of the designer. The designer must therefore have adequate tools for this sophisticated task of passive design

4.8 Recommendations for future research

The proposed passive techniques in this thesis focus to the renovation of a building without modification of the footprints. The effects of major changes to the building configuration in terms of building shape and form, orientations, and different window sizes and proportions are not investigated. Simulation results suggest that natural ventilation is a very important function for the simulation of a high thermal mass building, where indoor comfort mostly depends on ventilation to help remove heat from the building. With the help of CFD, simulations of airflow across the building, and the indoor thermal performances, due to different building shapes, forms, or windows could performed. Therefore, it is recommended that the thermal/CFD analysis of the office building with major architectural changes in design is a topic for future study.

The strategies investigated in the thesis focused on the evaluation of techniques to improve the overall thermal performance and comfort condition of the buildings using only passive cooling and heating systems. This research does not investigate the effects of using a hybrid-cooling system, which involves a combination of passive designs and a complex HVAC system. However, there is the possibility that some buildings could install such HVAC systems in the future to alleviate comfort problems. Therefore, future research concerning the use of hybrid systems is also recommended.

In terms of a thermal comfort assessment, this research uses the universal comfort zone recommended by ASHRAE as indicator of how comfortable the indoor conditions are. It does not investigate the comfort preferences of Greek people in particular. This research assumes that universal human comfort preferences are based on a worldwide research can be appropriately applied to this group of occupants. Therefore, field studies on the thermal comfort preferences of the occupants of Greek buildings can also be a topic for future research.

As simulation results indicated, thermal insulation is inadequate on the most of the building's surfaces such as the roof, walls, floor and windows. Therefore, it is recommended as a topic for further investigation the study of different major changes to the type, installation and quantity of thermal insulation as well as the interaction with the outdoor climate.

In the preceding analysis, there was no investigation regarding financial aspects of the proposed strategies. Therefore, a cost benefit analysis on short-term and long-term of these strategies would also be important.

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Appendix A

This appendix provides normalized definitions to frequently used terminology in this thesis. This facilitates referencing and prepares the reader for the subsequent analysis sections, where a clear understanding of the terms and metrics would prove highly beneficial.

New buildings	New buildings are considered to be buildings either: (i)in the process of being build or (ii)completed buildings that are less than 3 years old
Existing buildings	Existing buildings refer to the total existing building stock, discounting the new buildings
Building envelope	This consists of the walls, windows, roof, floor, doors and foundations of the building. The external skeleton, which determines a significant portion of the cooling and heating load, contains conditioned air for the health and comfort of the occupants. In summer, the heat transfer is through the building envelope and into the building, while in winter the reverse occurs.
Energy performance of a building	This refers to the amount of energy consumed, or estimated to be consumed, to meet the demand of energy required with the standard use of the building.

Energy efficiency	Energy efficiency refers to products or systems designed to use less energy for the same or higher performance than regular products or systems.
Whole-building design	Whole-building design is the integration of a building's elements and systems to maximize its energy, environmental, and financial performance. A critical element of this approach is the integration of energy systems to maximize efficiency and reduce the need for electricity, heating, and cooling technologies. The whole-building approach also considers construction materials, indoor environmental quality, acoustics, and other building factors like design and siting to minimize a building's impacts on its surroundings and improve its performance for occupants.

Table A-1. Standard building definitions

Annual final energy consumption	kWh/year	Applied in general calculations summing both electricity and heat energy consumption in final energy use
Annual electricity consumption	kW_eh/year	For the quantification of electricity use in electrical applications within a building's final energy use

Annual heat consumption	kW_th/year	For the quantification of heat use in non-electrical applications within a building's final energy use
Sensible heat gain	kWh	The sensible component is the sum of : • Heat transmission through opaque building envelope(due the combined effects of temperature difference and absorbed solar radiation) • Outside air(both infiltration and ventilation) • Solar gains through glazing(windows and skylights) • Internal sensible heat gain(due to people, lights and equipment)
Latent heat gain	kWh	The latent(moisture-related) component of the cooling load is the sum of: • People • Appliances • Outside air (both

		infiltration and ventilation)
Heating loads	kWh	The heating loads (heat loss) of a building are expressed as total load coefficients. There are two components: transmission load, which includes all heat transfer through the building envelope itself, and infiltration load, which includes heat lost by means of indoor/outdoor air exchange through cracks and normal door operation.
Cooling loads	kWh	The building cooling load consists of sensible and latent heat gains.
Annual final energy consumption	kWh/year	Applied in general calculations summing both electricity and heat energy consumption in final energy use

Table A-2. Standard energy definitions

Air Temperature	^{o}C	*Air temperature* is a measure of the heat content of the air

Radiant Temperature	°C	Mean Radiant Temperature (MRT) is the uniform surface temperature of a black enclosure with which an individual exchanges the same heat by radiation as the actual environment considered. It describes the radiant environment for a point in space.
Operative Temperature	°C	The mean of the zone air and radiant temperatures.
Outside Dry-Bulb Temperature	°C	The dry-bulb temperature is the temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture. In construction, it is an important consideration when designing a building for a certain climate
Relative Humidity	%	Relative humidity is a term used to describe the amount of water vapor that exists in a gaseous mixture of air and water.
Wind		At local level wind is the most irregular and varying component of the climate. It is affected by topography,

		vegetation and surrounding buildings; closeness to the sea may create on and offshore winds. Wind is described by its speed and direction and is measured with an anemometer.
Solar radiation and sky conditions		Short-wave solar radiation is divided into direct (ID) and diffuse (Id) and the sum of these is global radiation (IGL).Humid air or overcast skies increase the diffuse part. Overlays to the solar diagram may give data on solar radiation on horizontal or other surfaces, but corrections for cloudiness and humidity must always be considered. Reflections from the ground and adjacent buildings, and shading from adjacent buildings and vegetation, affect the total solar radiation. Energy is also dissipated from the earth to the sky by long-wave heat radiation. This is affected by air and sky conditions, such as cloudiness and

		pollution.
Fanger PMV (Predicted Mean Vote)	-	The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. Fanger (1970) related PMV to the imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort at the specified activity.
Discomfort hrs (all clothing)	hrs	The time when the zone is occupied that the combination of humidity, ratio and operative temperature is not in the ASHRAE 55-2004 summer or winter clothes region.
Air Temperature	°C	Air temperature is a measure of the heat content of the air

Table A-3. Environmental / Comfort definitions

Windows	kWh	the total heat flow to the zone from the glazing, frame and divider of exterior window excluding transmitted short-wave solar radiation
Walls	kWh	Heat gain due to conduction through all external walls, including the effect of solar radiation and longwave radiation to the sky.
Roofs	kWh	Heat gain due to conduction through all external roofs, including the effect of solar radiation and longwave radiation to the sky.
Ceilings (int)	kWh	Heat conduction gain through internal ceilings (e.g. zone above is colder).
Floors (int)	kWh	Heat conduction gain through internal floors (e.g. zone below is colder).
Floors (ext)	kWh	Heat conduction gain through external floors (not ground floor, e.g. floor in cantilevered space, roof eaves etc).
Partitions (int)	kWh	Heat conduction gain through all internal

		partitions (e.g. adjacent zone is colder).
Doors and Vents	kWh	Conduction heat gain through doors and vents.
External Infiltration	kWh	Heat gain through air infiltration (non-unintentional air entry through cracks and holes in building fabric)
External Natural Ventilation	kWh	heat gain due to the entry of outside air through natural ventilation
Internal Natural Ventilation	kWh	heat gain from other zones due to air exchange through open internal windows, doors, vents, holes and virtual partitions.
External Mechanical Ventilation	kWh	heat gain due to the entry of outside air through the air distribution system
External Air	kWh	heat gain due to the entry of outside air through external windows, vents, doors, holes and cracks
Mixing Air	kWh	heat gain due to the entry of inside mixing air through internal windows, vents, doors and holes

Table A-4. Fabric and ventilation heat gain definitions

Task Lighting	kWh	heat gain due to task lighting.
General Lighting	kWh	heat gain due to general lighting.
Miscellaneous	kWh	heat gain due to miscellaneous equipment.
Process	kWh	heat gain due to process equipment.
Catering	kWh	heat gain due to cooking.
Computer and Equipment	kWh	heat gain due to computer and other IT-related equipment.
Occupancy	kWh	sensible gain due to occupants
Solar Gains Exterior glazing	kWh	The total short-wave solar radiation from glazing to the zone

Table A-5. Internal gains definitions

CO_2 - total CO_2 emissions mass	Total carbon dioxide emission from building

Table A-6. CO_2 production