A parameter study of the energy use in an office building

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Report from the project: IDEEB
Intelligently Designed Energy Efficient Buildings
–assessment and control by an Eco-Factor system

EUROPEAN COMMISSION
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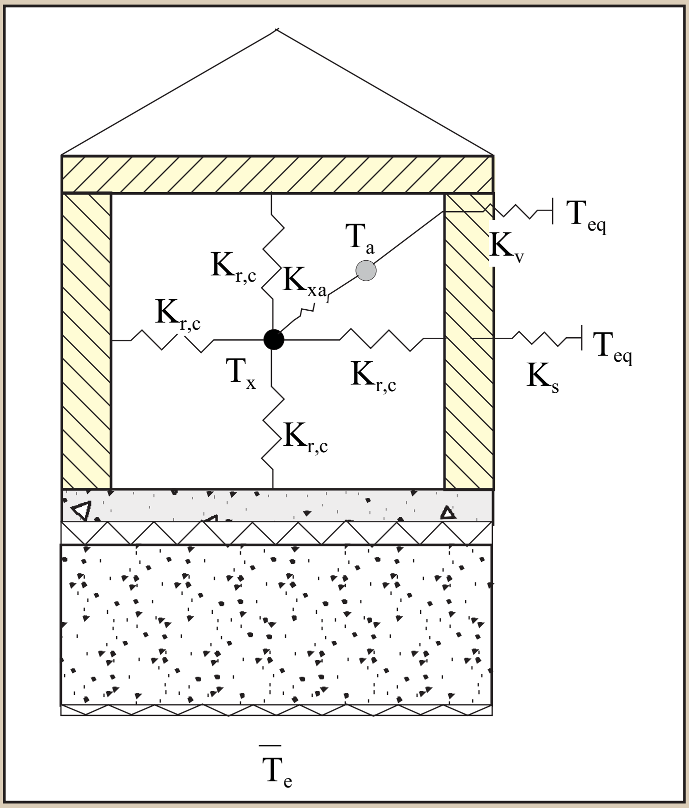

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Preface

This report is produced as part of the work of the research project, IDEEB, Intelligently Designed Energy-Efficient Buildings - assessment and control by an Eco-factor system.

The holistic approach of the IDEEB project is to adopt a comprehensive view, considering the building itself and its installations as a single energy system to achieve the required indoor climate, at the same time as reducing the building's environmental impact. Since each building is unique, there are no all-encompassing solutions, and therefore the project aims to develop a concept (based on a Eco-factor) that describes the way of working to reach the goal.

The IDEEB project consists of three parts:

1. *A theoretical part*, with separate developments of new guidelines and methods for the building process and design of a control system.
2. *A demonstration and improvement part*, in which it was intended that the results from the first part should be tested, improved and extended in the construction of four office buildings in different European climates.
3. *An evaluation and connection part*, in which all the improved results from the second part were to be combined into a concept that would describe a way of working to achieve energy-efficient buildings with good indoor climate and low environmental impact.

Unfortunately, the market situation for the construction of office buildings changed after the start of the project, so that only the first part of the project could be performed. This means that the total project result consists of nine separate reports containing theoretical backgrounds for guidelines and methods that are ready to be tested in practice for improvements and extensions into a new way of working.

One part of the project involves developing an assessment concept, which supplies an integrated design process with engineering methods for the design of office buildings with low energy-related environmental impact and with a satisfactory indoor climate. This report gives guidance to a building designer on how to design an energy-efficient building through appropriate design of the thermal characteristics of the building envelope, and is intended to assist the assessment concept. A sensitivity study has been undertaken in order to determine how different parameters of the thermal characteristics of the building envelope affect energy use for conditioning the indoor air.

The work has been performed in cooperation with Aalborg University, and the author would like to thank Henrik Brohus and Erik Bjørn

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Summary

This report is a part of the EU IDEEB 'Intelligently Designed Energy-Efficient Buildings' project. Part of the project involves developing an assessment concept for an iterative design process of office buildings with integrated energy solutions. The concept concentrates on the design of office buildings with low energy-related environmental impact and with the required indoor climate (Brohus et al., 2004). The results from this report are intended to assist the assessment concept.

This study investigates how thermal characteristics of the building envelope affect the building's energy use. Theoretical simulations are undertaken for office buildings in different climate conditions (cold, temperate and warm), and the results are intended as support in an early design phase of the building.

Theoretical simulation has been undertaken in Matlab, Simulink in order to determine the energy use in an office building. The simulations have been performed for non-steady state conditions and for different characteristics of the building envelope.

The simulations have used mean U-values of 0.3, 0.6 and 1.0 W/m^{2}K for the building envelope, i.e. to cover representation of light or heavy buildings (the thermal capacity). Window area has been varied between 10, 30 and 50 % of the wall area, and ventilation air flow rates have been 0.5, 1.5 or 3.0 air changes per hour. Three climates have been considered: cold (Sweden), temperate (Great Britain) or warm (Greece).

The *thermal resistance* of the building envelope has a considerable influence on the energy use. In most cases in cold and temperate climates, **the energy use reduces with increasing thermal resistance and is independent of other parameters**. However, for a building in a warm climate, minimum energy use is achieved if the U_m-value (the mean U-value of the building envelope) is 0.6 W/m^{2}K. Energy use increases with higher or lower values.

The *thermal capacity* of the building envelope has affects the energy use. In most cases, the energy use of a building with low thermal capacity is about 5 to 10 % less than that of a building with a high thermal capacity. In a temperate climate, energy use in light and heavy buildings varies when the window area varies. Optimum window area is about 30 % in a building with high thermal capacity. In a light building, increasing the window area always increases energy use.

The *ventilation air flow rate* increases the energy used in most cases when the air flow rate increases. However, for a building in a warm climate, there is a case when the energy use is almost constant with increasing air flow rate.

The *window area* affects the energy use in different ways. Heat loss increases with a higher window area, but the heat gain through insolation increases. Making use of daylight is another aspect: optimising the design for maximum daylight reduces the energy requirement for artificial lighting. The results from the simulations show that 30 % window area is an optimum area in respect of energy use for buildings in cold and temperate climates. In buildings in warm climates, energy use increases with increasing window area.

If greater variations in *indoor comfort level* can be accepted, energy use can be reduced by up to 30 %. The magnitude of this reduction depends on the magnitude of the acceptable variation of indoor temperature.

How the *parameters in combination* affect the energy use is as discussed above. For example, reducing the U_m-value will result in a lower energy use with different windows area etc. for buildings in cold and temperate climates, but further investigation is needed for buildings in a warm climate.

The simulations also show that the geometry of the building affects the energy use. An energy-efficient building should have a low value of the relationship between floor area and volume.

Key words: Office building, energy use, thermal capacity, U-value, ventilation air flow rate, building geometry, window area.

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1 Introduction

1.1 Background

One objective in the EU IDEEB project is to develop an assessment concept for an iterative design process of office buildings with integrated energy solutions (Brohus et al., 2004). It focuses on the energy-related environmental impact in the operation phase indoor climate control, and the design of the building is of particular interest for optimisation of energy use and indoor comfort. Below is a short summery on how the assessment concept works.

The assessment concept is divided into two levels. The first and 'simplest' level, the **concept design level**, is used to produce a rapid overview of, and intelligent suggestions for, alternative building designs. This level consists of guidance for scanning, overview methods, principles, catalogues etc., that will help to give intelligent design suggestions for the building without doing any detailed simulations. The suggestions are sketches/scenarios of the building design. The intention is that the architect, client and builder cooperate and together decide the design of the building with the aim of minimising the environmental impact caused by energy use in the operation phase. This allows for consideration of aspects such as whether the building envelope should have a high thermal capacity, whether it should be well insulated, the required window area, use of shading etc. However, it is difficult to predict the energy use, since many parameters both affect the energy use and interact with each other. There is a need for a table or figures that show how different parameters affect the energy use, which this work aims to provide. Sensitivity studies of the effects of parameter variations on net heating and cooling use over a period of one year have therefore been performed for a reference building.

Input from the parameter sensitivity studies in the present work, together with parameter sensitivity studies for indoor comfort and installation energy efficiency and choice of energy sources, give an estimate of indoor comfort and energy use, which is described by an Eco-factor (Brohus et al., 2004). The results provide guidance of how different parameters affect indoor comfort, energy use and the Eco-factor for a reference case, but cannot indicate directly how these parameters will influence a specific building.

The second and 'advanced' level, the **detailed design level**, is intended for consultants to prepare detailed designs with advanced theoretical simulations of two or three chosen designs in order to predict the energy use for the building.

Each level consists of two phases, a **design phase** and an **assessment phase**. The assessment phase evaluates the building suggestions using the Eco-factor method (Bjørn et al, 2004), and a prepares a life cycle cost analysis. A high Eco-factor score indicates that the building has good indoor comfort, low environmental impact or uses renewable energy sources, or a combination of these factors.

If the suggested building design and technical features give satisfactory results in the assessment phase, the concept proceeds to the next level: if not, the process returns to the design phase. This process continue in an iterative manner until a desirable Eco-factor is achieved for a suggestion with reasonable costs. The concept can be summarised as shown in the illustration in Figure 1.

The assessment concept and calculation of the Eco-factor require information on net energy use and indoor climate. The level of detail depends on the stage of the design process, as indicated in Figure 1.

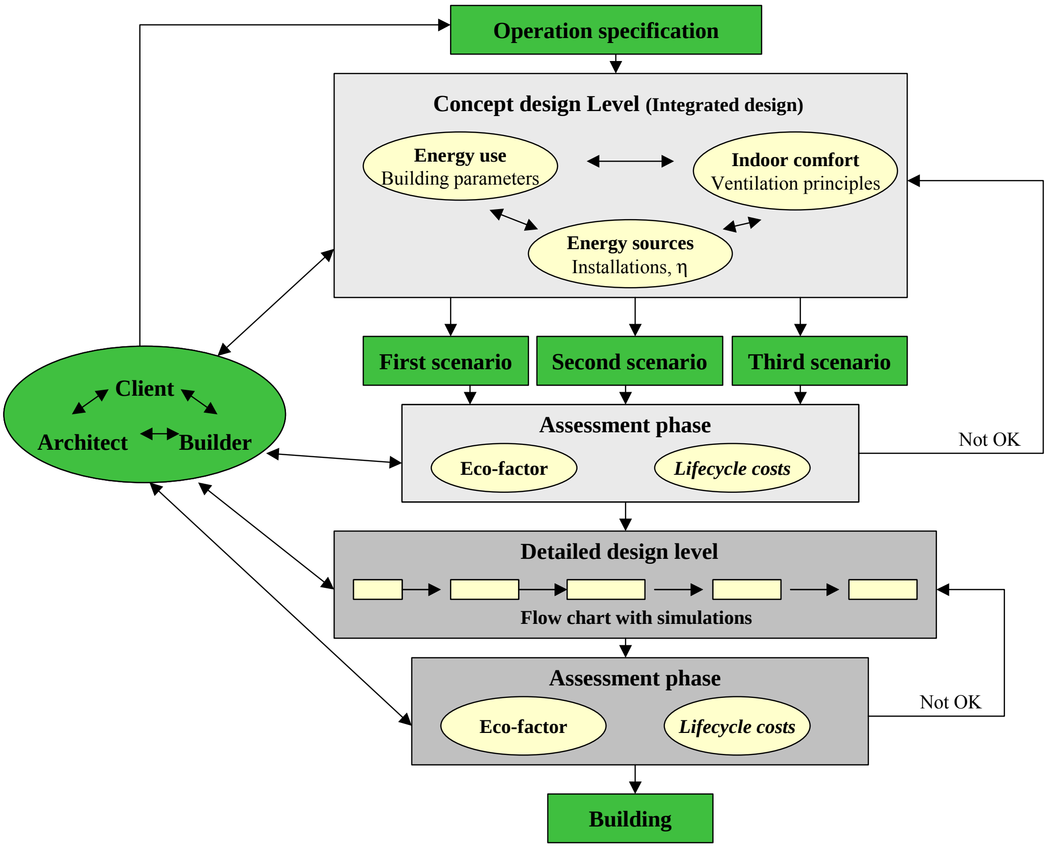

Figure 1 Illustration of the assessment concept.

1.2 Objective

The objectives of this study are to quantify the effect on the energy consumption of an office building of different measures for controlling the indoor environment. Both heating and cooling demand are simulated for a reference building for a year. The results help to indicate how different parameters affect the energy use for a reference case, but can give actual figures for changes in energy use only for a specific building.

1.3 Limitations

This study concentrates on how the thermal characteristics of a building envelope affect the energy use for conditioning the indoor air. A simplified theoretical mode is used, i.e.:

- A duration diagram based on non-steady-state simulation is used for calculation of energy use.
- The HVAC-system is assumed to work perfectly.
- The detailed characteristic of the HVAC system is not taken into account.
- Only feed-forward control strategy is considered.
- The thermal capacity of indoor equipment is lumped into one cell.
- Only one room is simulated.

2 Simulation of energy use for an office building

Simulating the energy use of a building is complex. Many parameters affect the energy use and, as the climate varies with time, we have a non-steady-state case. Another aspect is that the building must been seen as a whole energy system, i.e. the building and its services systems must be treated as a single integrated energy system.

The indoor climate of a building is controlled by using energy for heating, cooling, electricity for machines such as fans, pumps etc. In order to minimize energy use for conditioning the indoor air, all energy use for operation of machines, heating, cooling etc. must be taken into account. If all the energy use is not taken into account, the building may not be energy-efficient. For example, a building can be designed to be energy-efficient, but if the building services systems are not compatible with the building's characteristics, the indoor climate may be sub-standard, yet with high-energy use.

In most cases, the building services systems' characteristics can be obtained from their manufacturers. The building's characteristics are more difficult to obtain, and complex simulations must be undertaken in order to obtain the necessary data for energy simulations.

2.1 Energy use - calculation

Energy use for conditioning the indoor air can be determined by using a duration diagram. Figure 2 shows an example of how the heating supply power varies over a year for a well-insulated building. During the summer, there is no heating demand: the sun and internal heat gains provide the required heating power supply.

The difference between heat gains (internal and insolation) and the heat loss during the year is the same as the yearly energy demand for heating the building, see Figure 2.

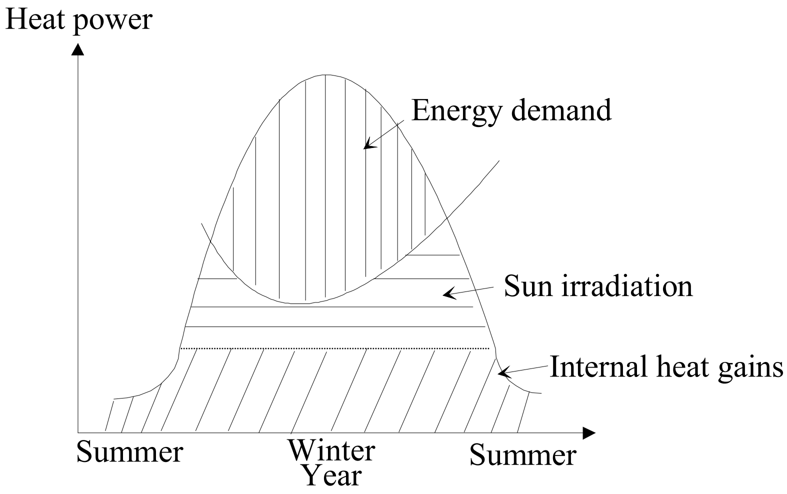

Figure 2 An example of a diagram that illustrates how heat gains and heat losses could vary during a year from winter to summer. The energy demand for heating is the same as the difference between heat loss and heat gains.

Energy use can be calculated by using a duration diagram, based on a model that shows how the temperature varies during a year. The temperature is plotted hourly in a duration diagram, from which the degree-days over the year can be calculated. The calculation method is described below.

Figure 3 is a plot of the outdoor temperature, expressed as a duration diagram. It can be seen that the outdoor temperature is below 15 °C for 6000 hours of the year in this example.

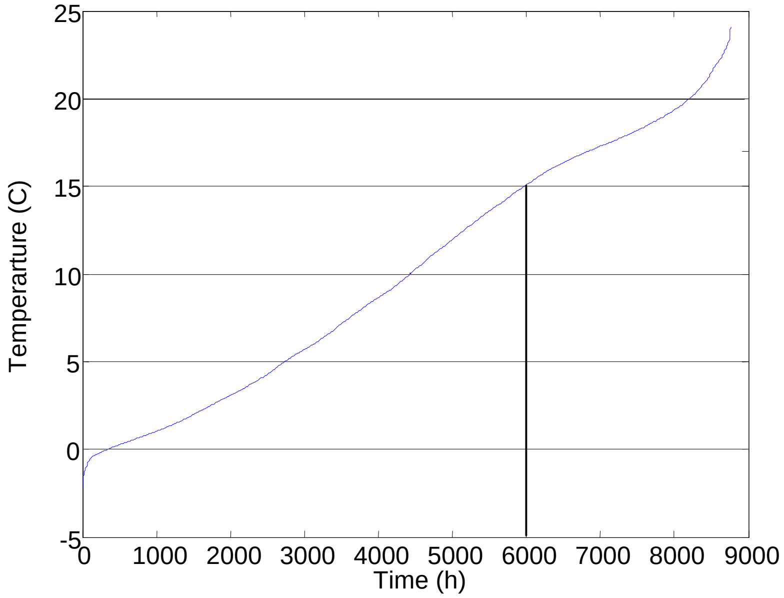

Figure 3 Example of a duration diagram for outdoor temperature. It can be seen that, for example, the outdoor temperature is below 15 °C for about 6000 hours of the year

The heat loss from a building can be calculated by following relationship:

$$\int_{t_1}^{t_2} \left(\sum (U \cdot A) + m \cdot c \cdot (1-\eta)\right) \cdot (T_i - T_e) \cdot dt$$

or

$$\left(\sum (U \cdot A) + m \cdot c \cdot (1-\eta)\right) \cdot \int_{t_1}^{t_2} (T_i - T_e) \cdot dt$$

Where U = U-value (W/m²K)
A = Area (m²)
m = Air flow rate (kg/s)
c = Specific heat capacity of air (kJ/kgK)
T_i = Interior temperature (K)
T_e = Exterior temperature (K)
t_1 = Time when heating period start (s)
t_2 = Time when heating period stop (s)
η = Performance factor of the heat exchanger (-)

The integral in the equation above is defined as the degree-days. Normally, in Sweden, the setpoint for indoor temperature is 20 °C. We assume that the internal and external heat gains raise the temperature by 3 °C, and heating is assumed to start when the outdoor temperature is below 17 °C. The degree-hours are then represented by the area below 17 °C, as shown in Figure 4. The cooling demand is the same as the area above 17 °C, again as shown in Figure 4.

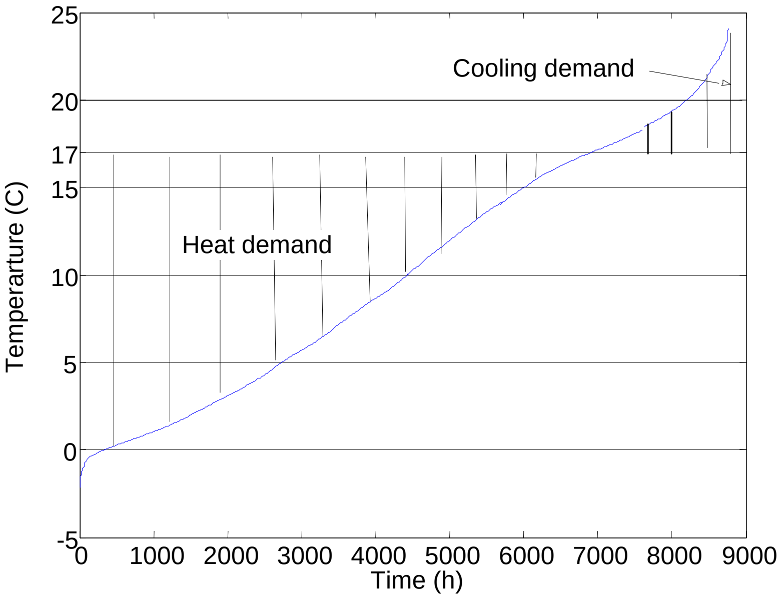

Figure 4 The heating and cooling demands can be calculated bys using degree-hours. In this example, with an indoor setpoint temperature of 20 °C, the degree-hours for heating are represented by the area below the outdoor temperature of 17 °C. The cooling demand energy is indicated by the area above the setpoint of 17 °C.

Heating and cooling energy requirements in terms of degree-hours vary with the location of the building and the indoor temperature. Most energy use calculations assume that the number of degree-days per year is constant, although in practice the number will vary. A well-insulated building will have fewer degree-days than a poorly insulated building. The reason for this is that the well-insulated building requires a lower heat power to maintain the indoor temperature than does a poorly insulated building. The heating season will start later in the autumn and stop earlier in the spring for a well-insulated building than is the case for a poorly insulated building. The impact of the thermal capacity of the building envelope is not included in the degree-days.

A PC-program that simulates the heat transfer through the building envelope can be used in order to determine the degree-days requirement when including the effect of thermal capacity, internal heat gains, external heat gains etc. The indoor temperature is simulated in one or many zones in a building in the non-steady-state case. The program takes the effects of internal and external (insolation) heat gains, outdoor climate, orientation of the building, window area and other factors that affect the indoor temperature into account. The result from the simulation is a *fictitious indoor temperature*, that is also referred to as *the balance temperature*.

The simulated fictitious temperature is plotted in a duration diagram, as can be seen in the example in Figure 2. The degree-hours for heating are shown by the area C in Figure 5, and those for cooling by area B. The energy use, E, for air conditioning can now be calculated by using the conductance (K) and the degree-days (C and B) in the following relationship:

Heating demand:

$$Eh = K \cdot C \quad \text{(Wh)}$$

Cooling demand

$$Eh = K \cdot B \quad \text{(Wh)}$$

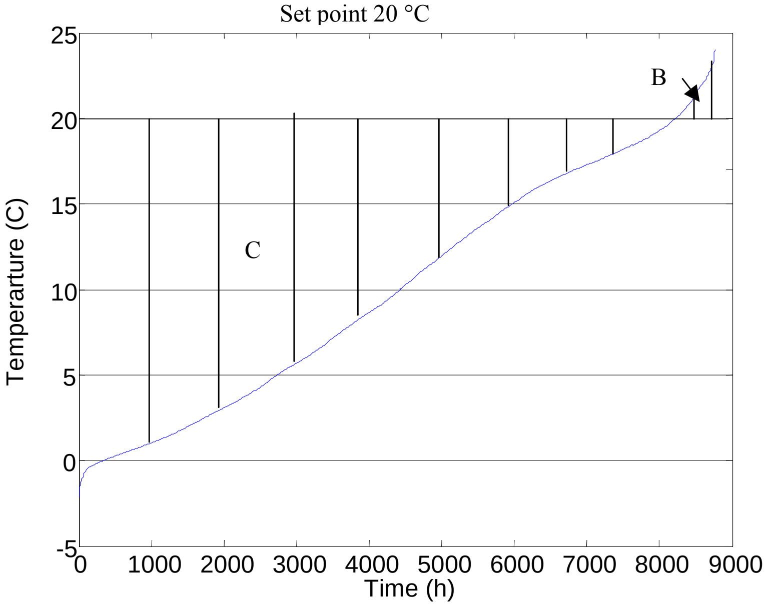

Figure 5 The simulated fictitious indoor temperature plotted in a duration diagram. Internal heat gains and gain from insolation are taken into account. Area C represents the degree-hours for heating demand, and area B that for cooling.

The indoor climate can be divided into different levels. According to CR 1752, indoor comfort for an office is divided into three levels:

Level	Summer (cooling season)	Winter (heating season)
A	24.5 ± 1.0 °C	22.0 ± 1.0 °C
B	24.5 ± 1.5 °C	22.0 ± 2.0 °C
C	24.5 ± 2.5 °C	22.0 ± 3.0 °C

Energy use increases with a higher level. Level A gives the highest energy use due to conditioning the indoor air.

In the degree-hours calculation method, the area that corresponds to the temperature variation is subtracted from the heating and cooling load.

2.2 Building - simulation model

The theoretical model that is used is based on a model developed by Hagentoft CE et al. in 2002, where the model is compared and validated against other theoretical models.

The energy use for conditioning the indoor air is simulated in a simplified model. The effect of the following parameters on energy use is investigated (with internal heat capacity lumped into one cell):

- Thermal resistance of the building envelope
- Location - climate
- Internal heat gains
- Thermal capacity of the building envelope
- Different levels of indoor climate
- Window area
- Heating and cooling loads
- Air change rate

Based on these parameters, a theoretical model of a building has been developed in SIMULINK from Matlab (a mathematical computing program from Mathworks Inc). Simulink is an interactive tool for modelling, simulating and analysing dynamic systems. Simulink blocks for one-dimensional heat transfer components have been defined and developed for foundations and single- and multi-layer walls, based on finite difference methods.

The considered building has a slab-on-grade (100 mm concrete) foundation. The ventilation system is a simple mechanical exhaust ventilation system. The geometry of the building is 12 x 8 x 2.4 m (l x w x h), i.e. the floor area is 96 m^2.

The main simulation model is shown in Figure 6, in the form of a building with a single zone (room). The model can be easily extended to include more than one room. The model is based on a two-node simulation model, see Figure 6.

A 1 m thick layer of soil is included below the floor in order to simulate the one-dimensional dynamic behaviour of the ground thermal mass. Below the soil layer there is a thermal resistance.

The heat flows are represented by using thermal conductance, denoted K. $K_{r,c}$ represents the thermal conductance due to radiation and convection between the surfaces and the room node at temperature T_x. The thermal conductance, K_v represents the coupling between the air node and the exterior air (i.e. ventilation), and K_s represents the conductance of the building envelope.

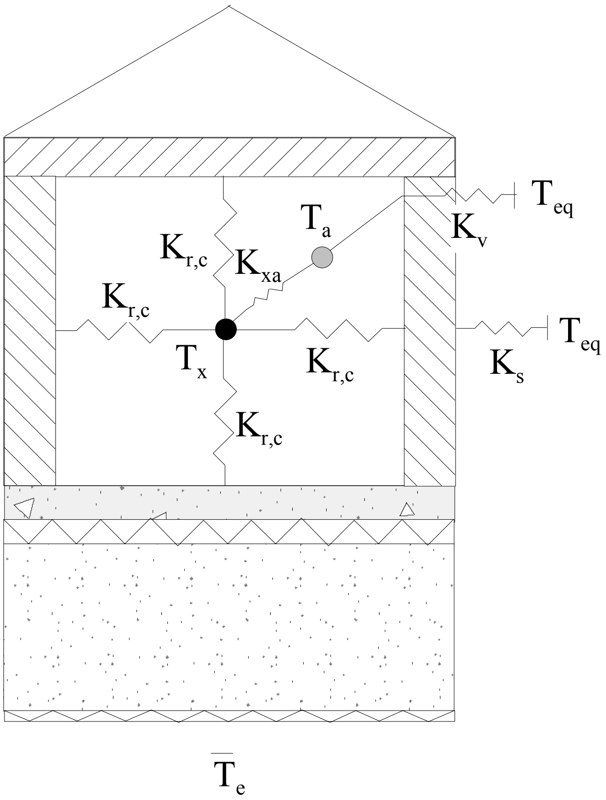

Figure 6 The two-node simulation model. $K_{r,c}$ represents the thermal conductance due to radiation and convection between the surfaces and the room node at temperature T_x. The thermal conductance K_v represents the coupling between the air node and the exterior air (i.e. ventilation), and K_s represents the conductance of the building envelope. A 1 m layer of soil is included below the floor in order to represent the one-dimensional dynamic behaviour of the ground thermal mass. Below the soil layer there is a thermal resistance to produce the correct overall U-value from the interior to the exterior.

Insolation

Insolation is assumed to irradiate 75 % of the total wall area. The assumption is based on meteorological data. By calculating the annual insolation on the building walls, it is found that approximately 75 % of the wall area is irradiated. The total incident insolation, I_{tot}, on the surface of the building (see Figure 7) is the sum of:

$$I_{tot} = I_{sr} + I_{dr} + I_{rd} \quad (\mathrm{W/m^2})$$

Where I_{sr} = Sky radiation (W/m²)
I_{dr} = Direct radiation (W/m²)
I_{rr} = Reflected radiation (W/m²)

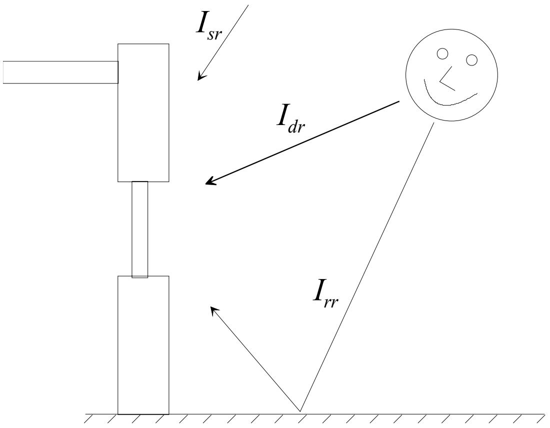

Figure 7 Insolation on a buildings surface.
I_{sr} = Sky radiation, I_{dr} = Direct radiation, I_{rr} = Reflected radiation (W/m²)

Incident sun radiation on the building depends mainly on:

- The altitude of the sun
- The azimuth
- Shading
- Location
- Cloudiness

Hourly insolation on a vertical wall for different locations has been simulated using the Meteonorm program, which calculates solar irradiation based on meteorological data, and is validated against measured data.

Heat gain through windows

The window area of a building varies, and affects the heat balance of the building. The window area of the model has been varied between 10 and 50 %.

The heat transfer through the window, I_w, can be calculated by:

$$I_w = \tau \cdot I_{tot} \quad (\mathrm{W/m^2})$$

Where τ = Transfer coefficient for the window

It is assumed that 75 % of the total window area receives solar radiation.

Equivalent outdoor temperature

Insolation on walls and roofs affects the surface temperature, which in turn affects the heat transfer through the building structure. This effect can be taken into account by calculating an equivalent outdoor temperature. The equivalent outdoor temperature, T_{eq}, is defined as:

$$T_{eq} = T_a + \frac{1}{\alpha_e} \cdot \left(I_{tot} \cdot \alpha_{sun} + \left(T^{r} - T_a \right) \cdot \alpha_r \right) \quad (\mathrm{K})$$

$$\alpha_e = \alpha_c + \alpha_r$$

Where T_a = Ambient temperature (K)
T^r = Sky temperature (K)
α_{sun} = Absorption factor (W/m²K)
α_r = Radiative heat transfer coefficient (W/m²K)
α_e = Convective heat transfer coefficient (W/m²K)

Energy balance for a room

The energy balance simulation for the ventilated building is based on a two-node model, (Wit M. de, 1987), using both the interior air temperature and an environmental temperature, T_x, (Danter E, 1973). For the cases presented in this paper, the temperature T_x is a weighted average determined by the surface temperatures and areas (including radiators), the air temperature and the surface heat transfer coefficients due to radiation and convection. The radiative part of the internal gains also contributes to this temperature.

The two-node model assumes that:

- The room air is at uniform temperature
- All radiation (short wave and emitted long wave) is distributed in such a way that all surfaces absorb the same amount per unit of surface area
- The surface coefficients for convection and radiation are the same for all surfaces.
- The assumption of uniform temperature is reasonable for the considered insulated and airtight buildings.
- All interior thermal capacity is lumped into the air node.

The operative temperature, T_{op}, is calculated by a weighting of the T_x temperature and the air temperature, T_a, (Wit M. de 1987):

$$T_{op} = \frac{2 \cdot T_x + T_a}{3} \quad (°C) \tag{1}$$

The simulated weighted temperature, T_x, and air temperature, T_a, is plotted in a duration diagram for a year. The total heat and cooling demand can be calculated by adding the transmission and ventilation losses by using the following relationship:

$$E = K_T \cdot \int_{t1}^{t2} \left(T^s{}_x - T{}_x(\tau) \right) d\tau + K_v \cdot \int_{t1}^{t2} \left(T^s{}_a - T_a(t) \right) d\tau \quad (\text{Wh}) \tag{3}$$

Where $T^s{}_x$ = set point for weighted temperature (K)
$T^s{}_a$ = set point for air temperature (K)

In the equations, the conductance for ventilation, K_v, and transmission, K_T, is defined as:

$$K_v = \frac{n}{3600} \cdot V \cdot c \cdot \rho \quad (\text{W/K}) \tag{4}$$
$$K_T = \sum U \cdot A$$

Where T_a = Air temperature (°C)
T_e = Outdoor temperature (°C)
U = U-value (W/m²K)
A = Surface area (m²)

n = Specific ventilation air flow rate (1/h)
V = Ventilated volume (m^3)
c = Specific thermal capacity (Ws/kgK)
ρ = Density of the air (kg/m^3)

Internal casual heat gains are simulated as a pulse (see Figure 8), occurring between 08:00-17:00 from Monday to Friday. The amplitude of the pulse varies, depending on the number of occupants, the type of lighting system, electric equipment such as computers, fax, copiers etc. The heat gains are assumed to vary with the number of occupants, at between 200-300 W per person, which includes electric equipment etc. Each occupant is assumed to occupy 10 m^2, which means that heat gains vary between 20 and 30 W/m^2.

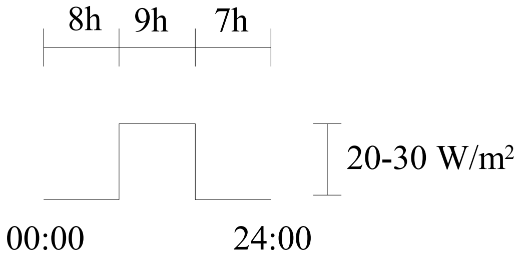

Figure 8 The internal heat gains (occupants, electric equipment etc.) are simulated as a pulse from Monday to Friday between 08:00 to 17:00. The amplitude of the heat gain varies between 20 and 30 W/m^2.

The energy use for different levels of indoor climate is defined in Section 2.1. The duration diagram shows the temperature intervals. An example for level A is shown in Figure 9. The degree-hours for the winter and summer case for level A are plotted in the duration diagram. When the energy use for cooling is calculated, the degree-hours for these levels are subtracted from the total degree-hours for cooling for the year. This is done for each indoor climate level (A, B and C).

The behaviour of the occupants is not taken into account. For example, windows may be opened when it get too hot indoors. Another factor is shading, which requires a more complex model for simulation.

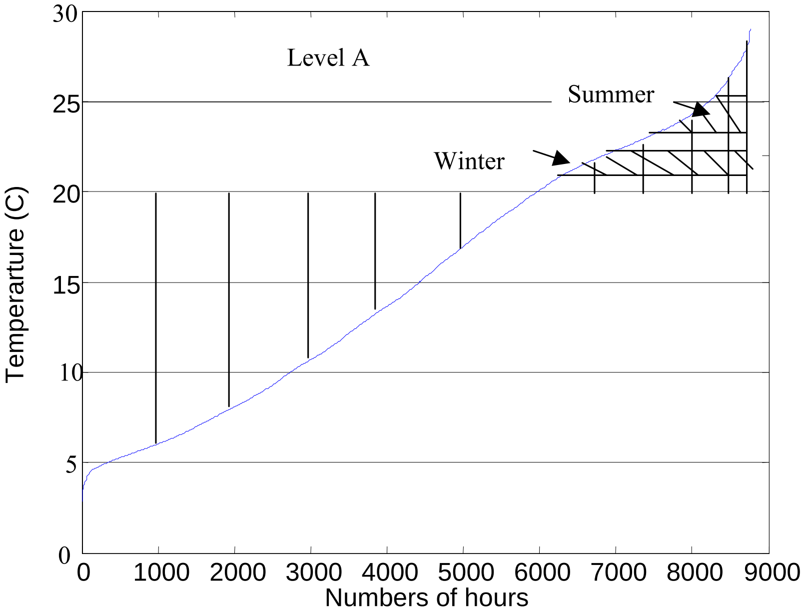

Figure 9 In the indoor level Class A is a temperature variation on winter and summer seasons accepted. The total cooling load for a year can thereby be reduced with the degree-hours corresponding to the summer and winter cases in the diagram.

2.3 Case studies

The parameter study concentrates on how the thermal characteristics of the building envelope affect the energy use for conditioning the indoor air. The following parameters have been studied:

- Thermal capacity of the building envelope
- Thermal resistance of the building envelope
- Window area
- Varying indoor climate
- Internal heat gain
- Climate
- Ventilation air change rate

Thermal capacity
Using a building with concrete as an inner surface and insulation on the outside will simulate a building with high thermal capacity. a building with low thermal capacity is simulated by constructing the building envelope solely of insulation: for example, mineral wool. Figure 10 shows the cases in schematic form.

The effective thermal capacity of the concrete layer in the wall and ceiling depends on the fluctuations of indoor temperature. On a daily basis, only a small part of the thermal capacity may be ‘active’.

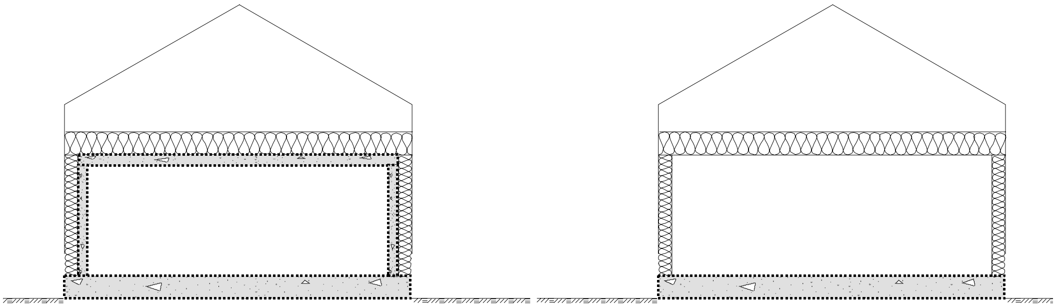

Figure 10 The left-hand figure represents a building with a high thermal capacity. The walls and ceiling consist of concrete, with insulation on the outside. The right-hand building has low thermal capacity, with no concrete in the walls or ceiling.

All the internal thermal heat capacity is lumped into one air node. We assume that the weight of material (books, furniture etc.) per person is 20 kg/m^2, and that the mean thermal heat capacity of the material is 1000 J/kg.

Well or poorly insulated building envelope

The mean U-value of the building envelope is assumed to vary within the interval 0.3-1,0 W/m^{2}K. However, building regulations vary for different countries in Europe. The interval of chosen mean U-value may cover a large part of the office buildings in Europe.

Internal heat gain

The internal heat gain in an office in Sweden varies normally over the range 20-30 W/m^2. These values will be used for all climates.

Climate

The climate is modelled for three zones: warm, temperate and cold climate. The hourly climate for these locations has been calculated by the Meteonorm program.

Air change rate

The ventilation air flow rate is modelled over the interval 0.5-3 air change rates per hour on all days, i.e. with no reduction for weekends.

U-value for windows

The U-value of the windows varies between 1, 2 and 2.9 W/m^{2}K for mean U-values of the building envelope of 0.1, 0.6 and 1 W/m^{2}K respectively.

3 Results

The energy use is presented in normalised form. The normalised energy use, *E**, in each diagram has been calculated by the following relationship:

$$E^* = \frac{E_i - E_{\min}}{E_{\max} - E_{\min}} \quad (-)$$

Where E_i = Actual energy use (Wh/m²)
E_{min} = Lowest value of energy use (Wh/m²)
E_{max} = Highest value of energy use (Wh/m²)

Note that the normalised values can be compared only with each other within the diagram. A normalised value cannot be compared with a value from another diagram.

The study simulates a single-storey building and its floor area. In addition, in one case, the geometry of the building has also been investigated.

The results are presented for the different climates.

3.1 Cold climate

3.1.1 Insulation

The U_m-value of the building envelope has a considerable influence on the energy use. The energy use increases with the U_m-value, see Figure 11. The thermal capacity and internal heat gains influence the energy use, but the U_m-value dominates.

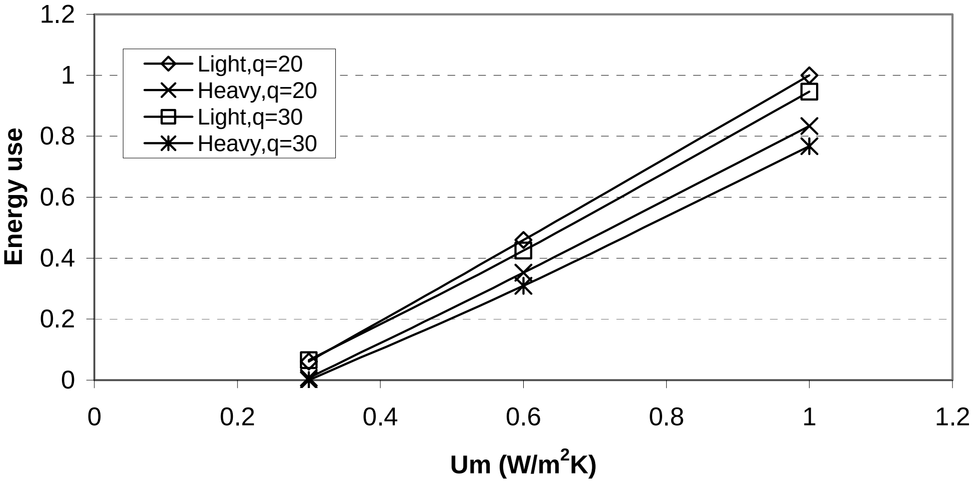

Figure 11 Normalised energy use for conditioning for U_m-value (U) and a heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

The heating load constitutes a major part of the energy use for conditioning the indoor air (see Figure 12) for U_m-values above 0.3 W/m²K. The reason for this is that the heating demand is greater than the cooling demand for a building in a cold climate. However, in a well-insulated building, the cooling load is approximately the same as the heating load. The results also indicate that the heating load is approximately constant for a U-value of 0.6 and higher.

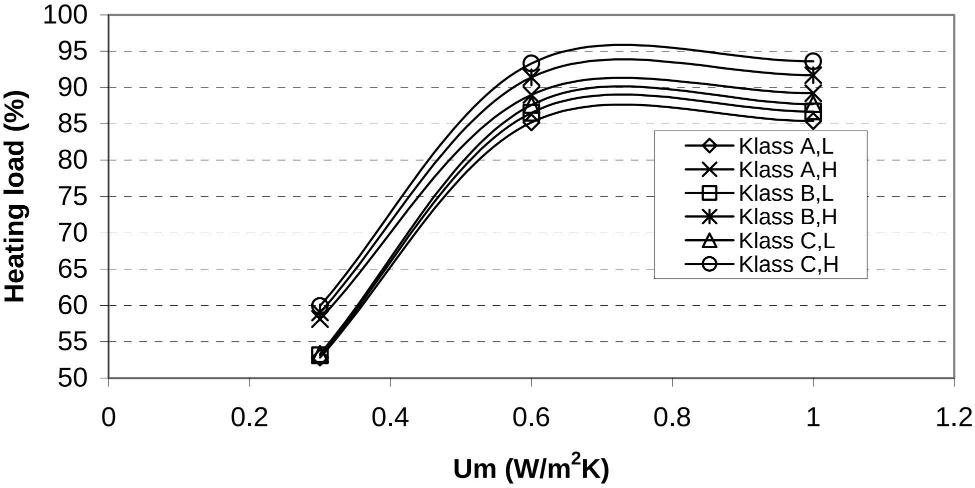

Figure 12 Normalised energy use for heating of the total energy use for U_m-value (U) and a heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 W/m^2. The window area is 30 % of the wall area.

The tendency for the cooling load is opposite in comparison with the heating load (see Figure 13). The cooling load is about 50 % of the total energy use with low U_m-values. If the U_m-value increases, the cooling load reduces (see Figure 13). The results also tell us that the cooling load portion of the total energy use is approximately constant for U_m-values of 0.6 and 1.

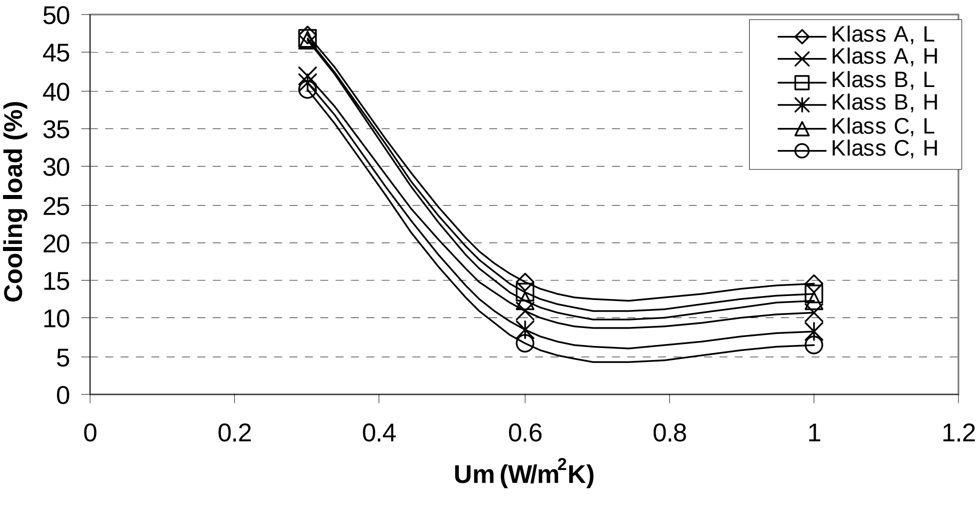

Figure 13 Normalised energy use for cooling of the total energy use for U_m-value (U) and a heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 W/m^2. The window area is 30 % of the wall area.

3.1.2 Thermal capacity

The thermal capacity of the building envelope has little effect on the energy use when the internal heat gains are the same. The results in Figure 14 show that the difference is about 8 % in energy use between buildings with high or low thermal capacity of the building envelopes. The heavy building has the lower energy use. However, the difference is greater between the cases with 20 or 30 W/m^2 internal heat gains.

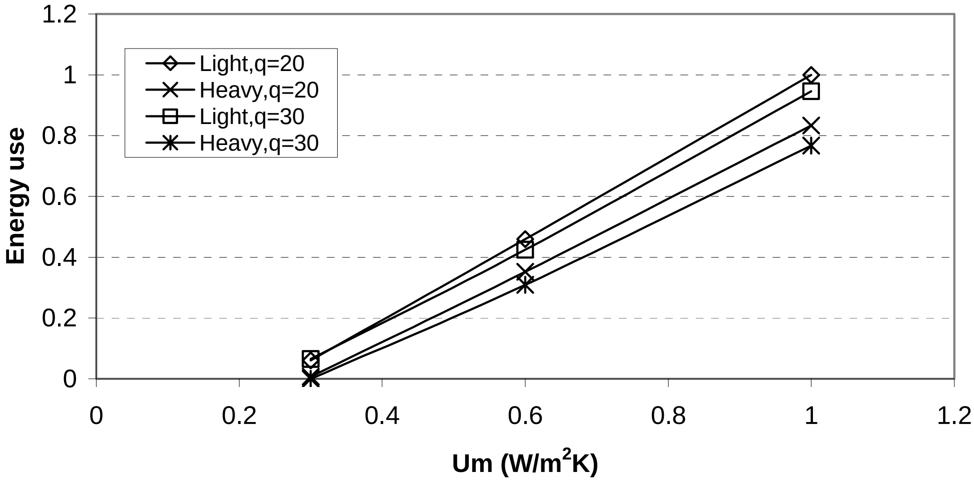

Figure 14 Normalised energy use for U_m value (U) and a heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

Figures 15 and 16 illustrate the simulated results for indoor classes B and C. The results show the same tendency as above, i.e. that a heavy building can reduce energy use.

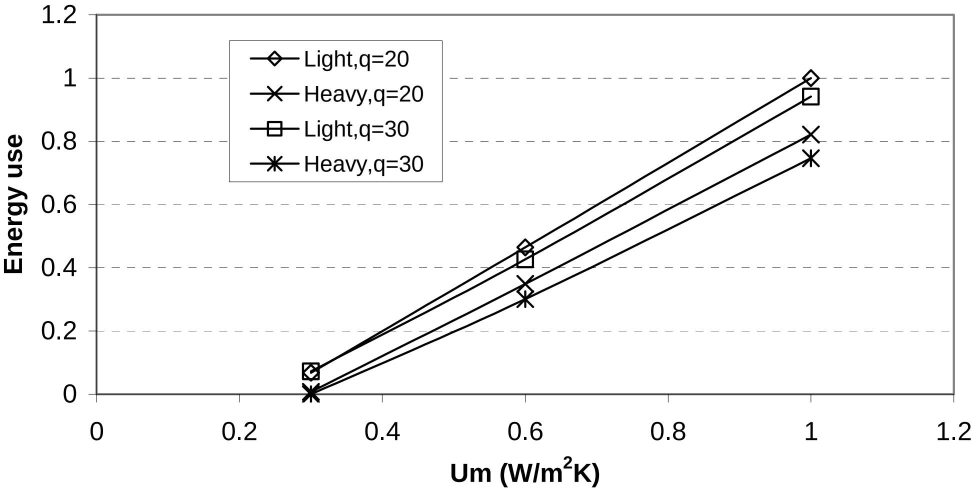

Figure 15 Normalised energy use for U_m-value (U) and a heavy (H) or light (L) building. The indoor comfort level is B. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

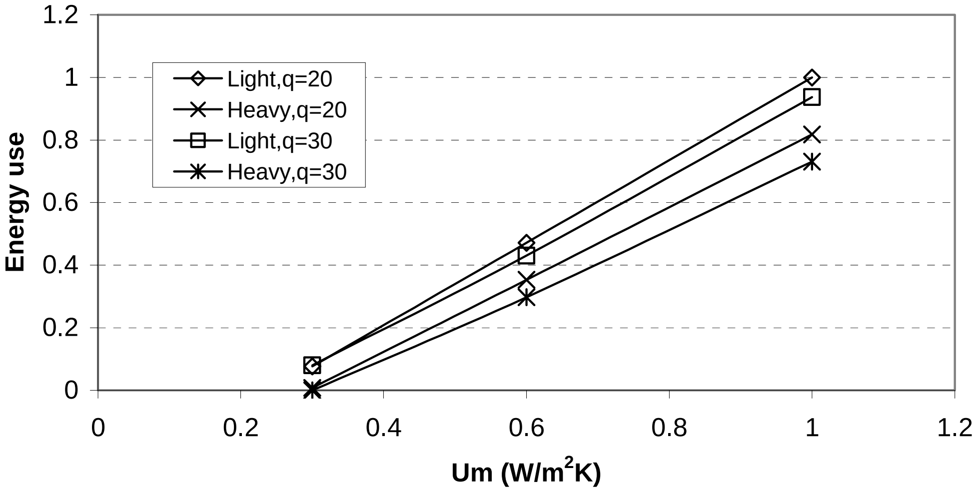

Figure 16 Normalised energy use for U_m-value (U) and a heavy (H) or light (L) building. The indoor comfort level is C. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

3.1.3 Ventilation air change rate

Energy use always increases with increasing air change rate (see Figure 17), and the thermal capacity of the building has no or little effect. The thermal resistance of the building envelope (U_m value) has a slight influence. The conclusion is that a higher ventilation air change rate will always result in higher energy use.

However, in this case, a heat exchanger has not been used, which is normal in Sweden. How this affects the energy use will be discussed in a later paragraph.

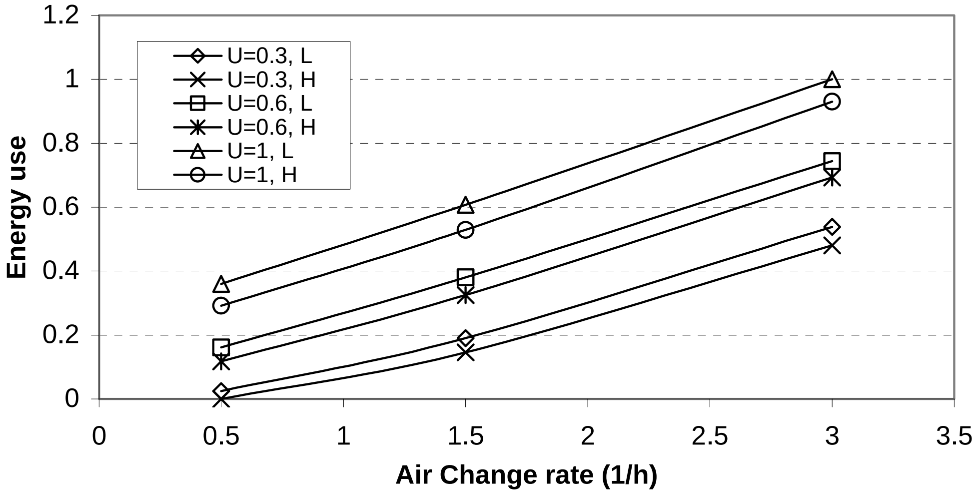

Figure 17 Normalised energy use for different air change rate and U_m-values (U). The indoor comfort level is A, light (L) or heavy (H) building and the U_m-value is 0.6 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 30 W/m^2. The window area is 30 % of the wall area.

3.1.4 Heat gains – Shading

The internal heat gains are assumed to vary over the range 20 to 30 W/m². If the internal heat gains increase, energy use decreases, due to the fact that the heating load constitutes the major part of the total building energy use (see Figure 12).

A shading factor is defined as how large a part of the window area is shaded. In Figure 18 shows energy use as a function of the shading factor. As expected, energy use is reduced when the shading factor increases, i.e., less insolation to the room.

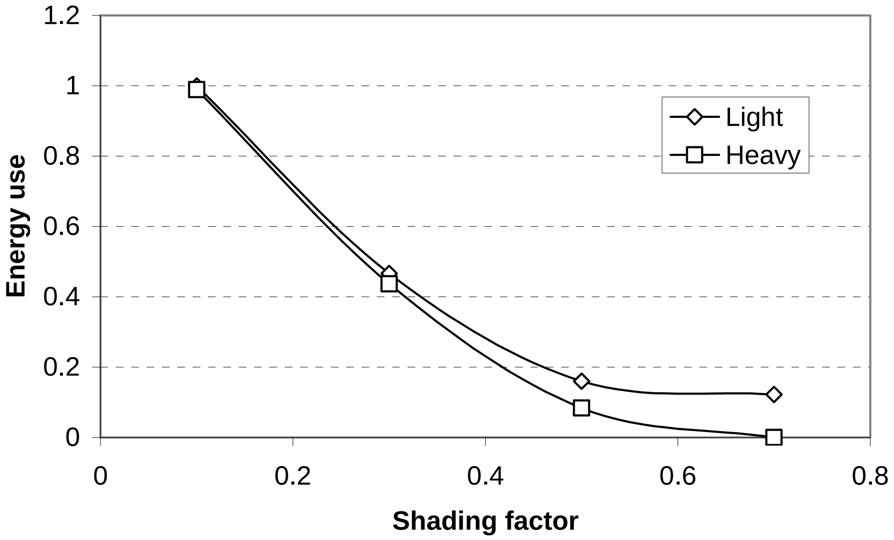

Figure 18 Normalised energy use when the shading factor varies. The indoor comfort level is A, light or heavy building and the U_m-value is 0.3 W/m^2K. The air change rate, n, is 0.5 air change rates per hour. The internal heat gain, q, is 20 W/m^2. The window area is 30 % of the wall area.

The magnitude of the insolation heat gain to the room depends on the window area and the properties of the window etc. Figure 19 tells us that:

- In well-insulated buildings (U_m = 0.3 W/m²K) with high ventilation air flow rates, energy use will decrease with increasing window area, see Figure 19.
- With a normal ventilation air flow rate (air change rate = 0.5 air changes per hour) energy use will increase with window area. The reason for this is that the cooling load increases. In the case with 50 % window area, the cooling load constitutes a major part of the total energy use. This means that shading will reduce the energy use for well-insulated buildings with a normal air change rate.

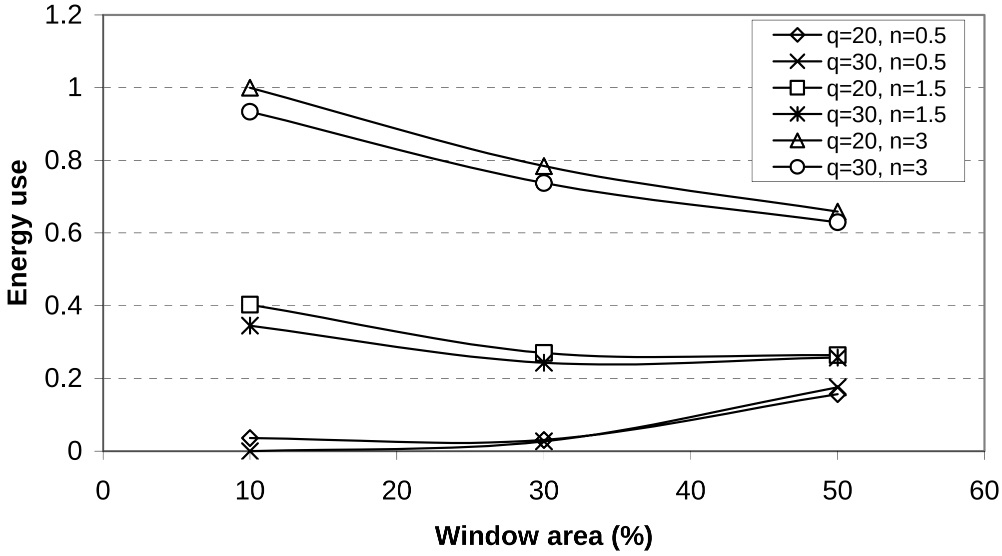

Figure 19 Normalised energy use when window area is varied. The indoor comfort level is A, heavy building and the U_m-value is 0.3 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

Figures 20 and 21 show the energy use for buildings with U_m-values of 0.6 and 1,0 W/m²K. The results show that, with a normal air change rate, the energy use is nearly constant for a window area of 30 % or larger.

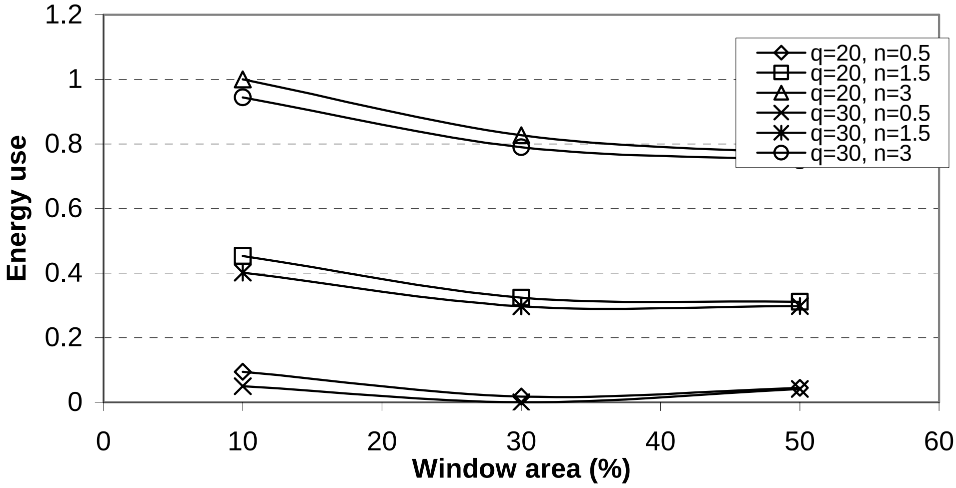

Figure 20 Normalised energy use when window area is varied. The indoor comfort level is A, light building and the U_m-value is 0.6 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

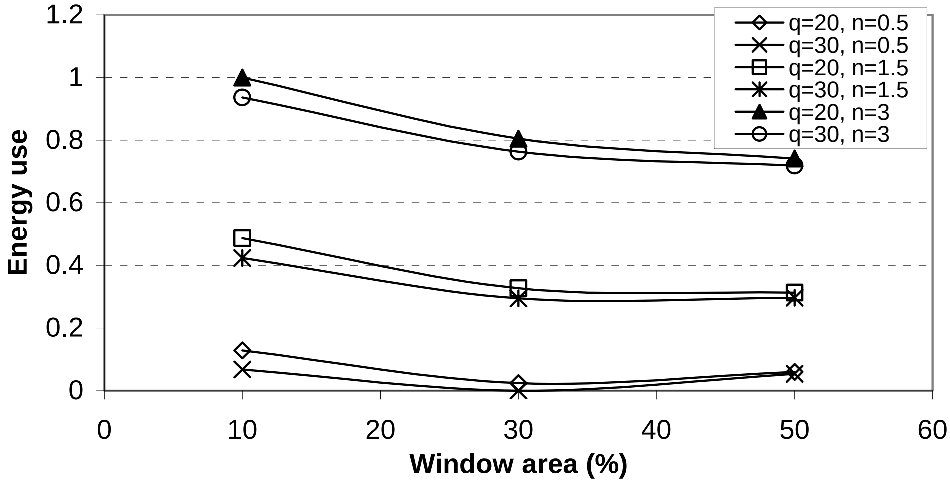

Figure 21 Normalised energy use when window area is varied. The indoor comfort level is A, light building and the U_m-value is 1 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

3.1.5 Indoor climate

Accepting a lower requirement for the indoor comfort level can reduce energy use. As shown in Table 1, the energy use increases by approximately 10 % with higher levels of indoor comfort level (A, B or C). The variation of energy use seems to be independent of U-value.

The thermal capacity of the building envelope may increase the energy use slightly, as can be seen in Table 1.

Table 1 Energy saving in percent for one example. The numbers gives the energy saving for a lower level of indoor comfort. Consider, for example, a building with U_m = 0.3 W/m²K and with a light structure. Reducing comfort level from Class A to Class B reduces energy use by 10 % according to the table.

Level		Um = 0.3	Um = 0.6	Um = 1
a→b	Light	10.5	11.4	11.4
a→c	Light	23.4	24.2	24.2
b→c	Light	11.7	11.4	11.5
a→b	Heavy	13.0	13.1	13.1
a→c	Heavy	28.5	27.4	27.5
b→c	Heavy	13.7	12.7	12.7

3.1.6 Cold climate comments and summary

The energy use in an office building located in a cold climate varies, depending on the design of the building and, of course, the thermal characteristics of the building envelope. If a heat exchanger is not used, the results from simulations tell us that:

- A well-insulated building requires less energy than a poorly insulated building. This is independent of the thermal capacity of the building envelope and heat gains (external and internal).
- The heating load dominates the energy use if the mean U-value of the building envelope is 0.6 W/m^2K or above. With a lower U-value, the cooling load and the heating load are nearly the same.
- Increasing ventilation air flow rate always results in increasing energy use.
- A building with a high thermal capacity building envelope may reduce the energy use slightly, 0-10%.
- An optimum window area is about 30 %.
- If greater variation of the indoor climate can be accepted, the energy use will be reduced.
- Shading may increase the total energy use. This depends on the fact that solar heat gains may contribute to heating the building and reducing the heating load at times when the heating load dominates energy use.
- If a heat exchanger is used, the energy use for heating will be reduced.

Another aspect to take into account is whether or not the incoming ventilation air is preheated. In the model, the temperature of the incoming air is assumed to be the same as the outdoor temperature. In practice, there is a requirement for the temperature of incoming ventilation air. It cannot be too low, as this can cause draughts and reduce the indoor comfort. The ventilation air may therefore be pre-heated (by a heat exchanger or similar). With pre-heated ventilation air, the internal heat gains may cause a higher temperature in the room and thus lead to a demand for cooling. The result of pre-heating can therefore lead to an increase in energy use due to increasing cooling demand, especially in the case when the building heating load constitutes the major part of the energy use for conditioning the indoor air.

3.2 Temperate climate

In this context, a temperate climate lies between cold and hot. The simulation has been undertaken for climate in London, Great Britain.

3.2.1 Insulation

The thermal resistance of the building envelope reduces energy use as shown in Figure 22, regardless of whether the building has a high thermal capacity or not. The tendency is the same as in a building located in a cold climate.

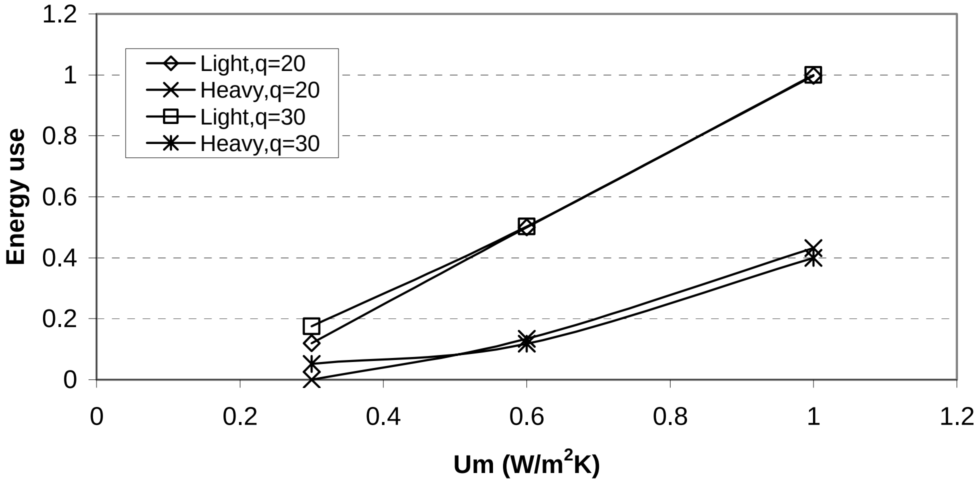

Figure 22 Normalised energy use for conditioning for U_m-value (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m². The window area is 30 % of the wall area.

Heating energy dominates the energy use for conditioning the indoor air for U_m values above 0.3 W/m²K, see Figure 23. An increasing U_m value results in higher energy use, which was expected. However, the heating load is up to 80 % of the total energy use for poorly insulated buildings.

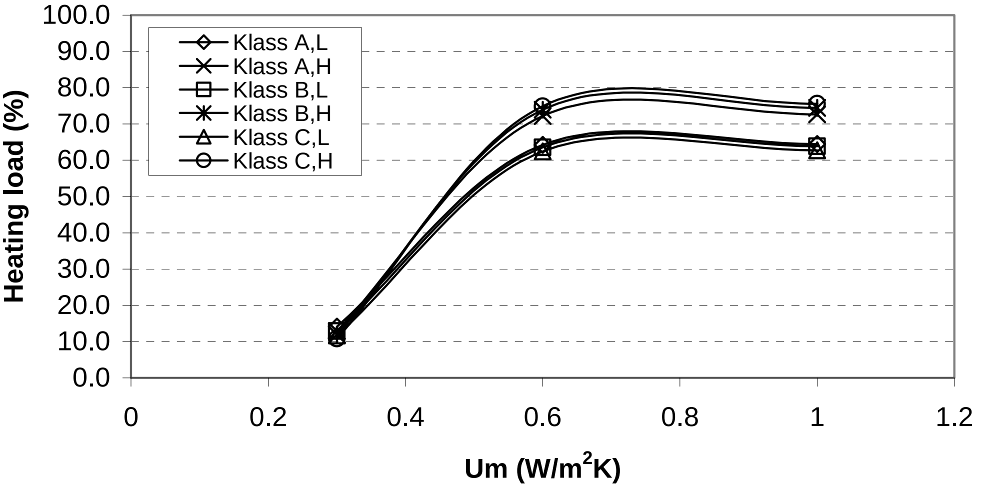

Figure 23 Normalised energy use for heating as a percentage of total energy use for U_m-value (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

The characteristics of the cooling load are opposite to the heating load, as can be seen in Figure 24. In a well-insulated building, a major part of the energy use is for cooling. It decreases rapidly with increasing U-value.

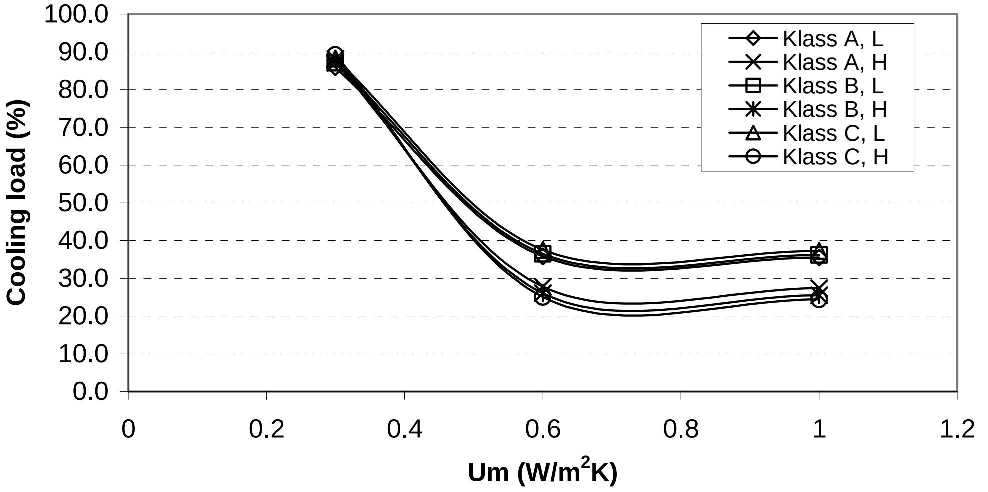

Figure 24 Normalised energy use for cooling as a percentage of total energy use for U_m-value (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m². The window area is 30 % of the wall area.

3.2.2 Thermal capacity

The thermal capacity of the building envelope has a considerable influence on the energy use. Figure 25 shows that there can be a large relative difference between low and high thermal capacity as a function of the U_m-value. The results also show that the relative difference in energy use increases with a higher U_m-value. A building with high thermal capacity in the envelope can result in lower energy use in comparison with an identical building having a low thermal capacity.

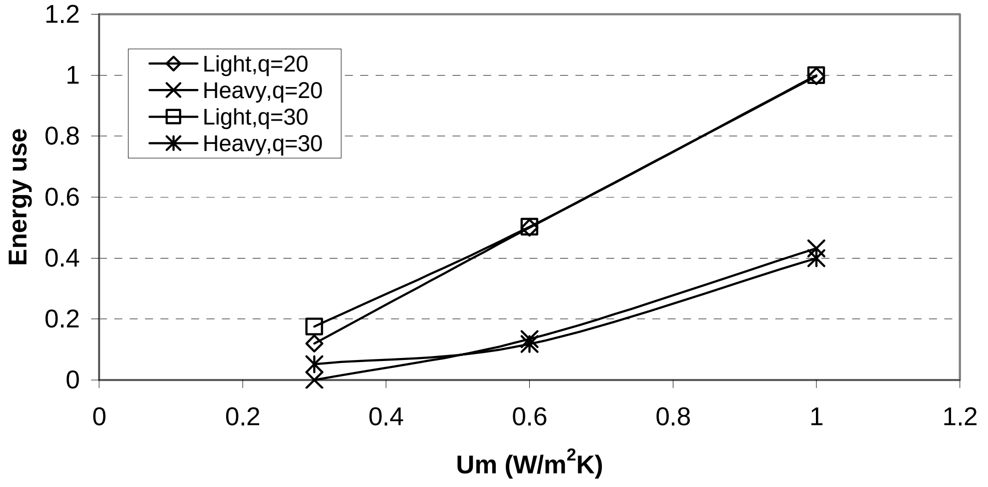

Figure 25 Normalised energy use for conditioning for U_m-value (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m². The window area is 30 % of the wall area.

3.2.3 Ventilation air change rate

As expected, the energy use increases with increasing ventilation air change rate, see Figure 26. Changes in the U-value etc. have no effect.

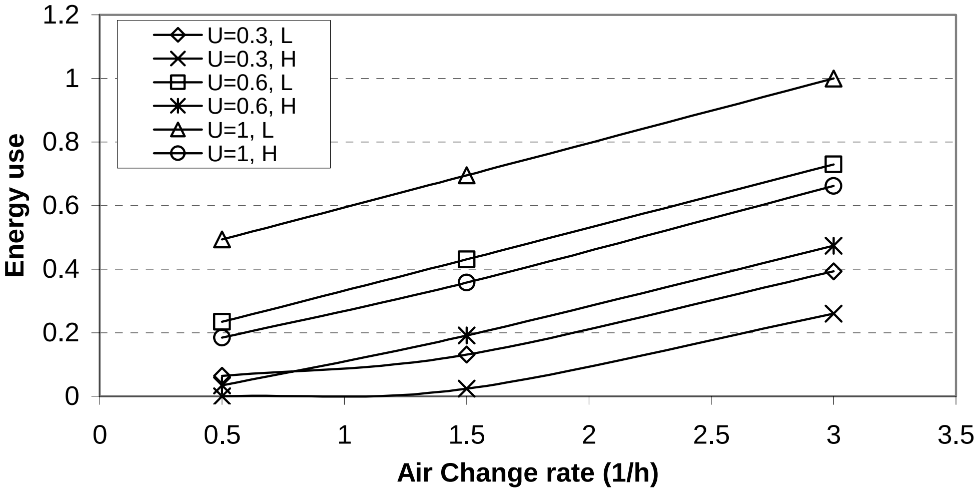

Figure 26 Normalised energy use for different air change rate and U_m-value (U). The indoor comfort level is A, light (L) or heavy (H) building and the U_m-value is 0.6 W/m²K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 30 W/m^2. The window area is 30 % of the wall area.

3.2.4 Heat gains – Shading

In a temperate climate, there seems to be an optimum shading factor. In Figure 27 it can be seen that energy use is a minimum with a 0.3 shading factor.

However, the greatest effect on energy use is seen with a low U_m-value.

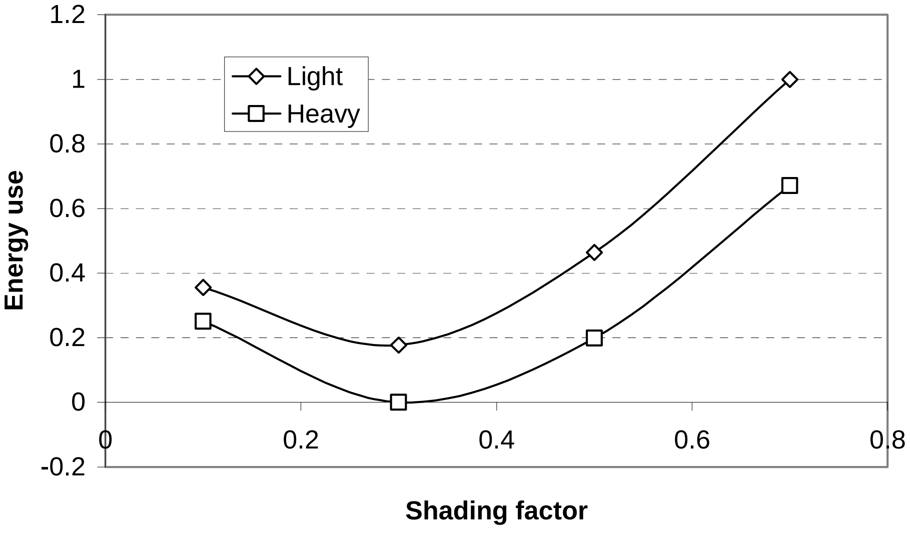

Figure 27 Normalised energy use for s shading factor and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 W/m^2. The window area is 30 % of the wall area. The U_m-value is 0.3 W/m^2K.

Energy use as a function of window area shows that high ventilation air flow rates (3 air changes per hour) always increase the energy use *for a well-insulated building* with high or low thermal capacity, see Figures 28 and 29. With a normal ventilation air flow rate (0.5-1.5 air changes per hour), energy use reaches a minimum with 30 % window area or a U_m-value of 0.6 W/m^{2}K and high thermal capacity.

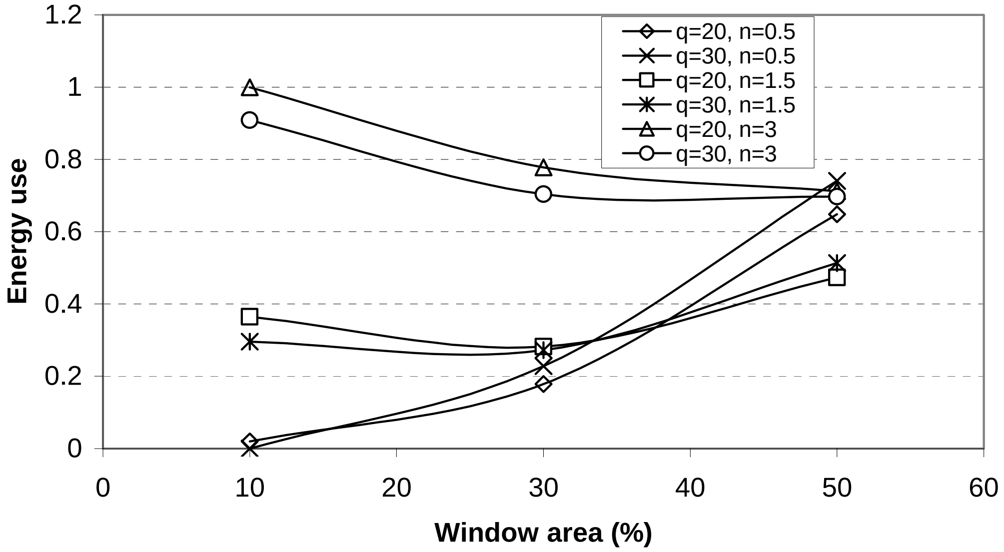

Figure 28 Normalised energy use when window area varies. The indoor comfort level is A, heavy building and the U_m-value is 0.3 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m².

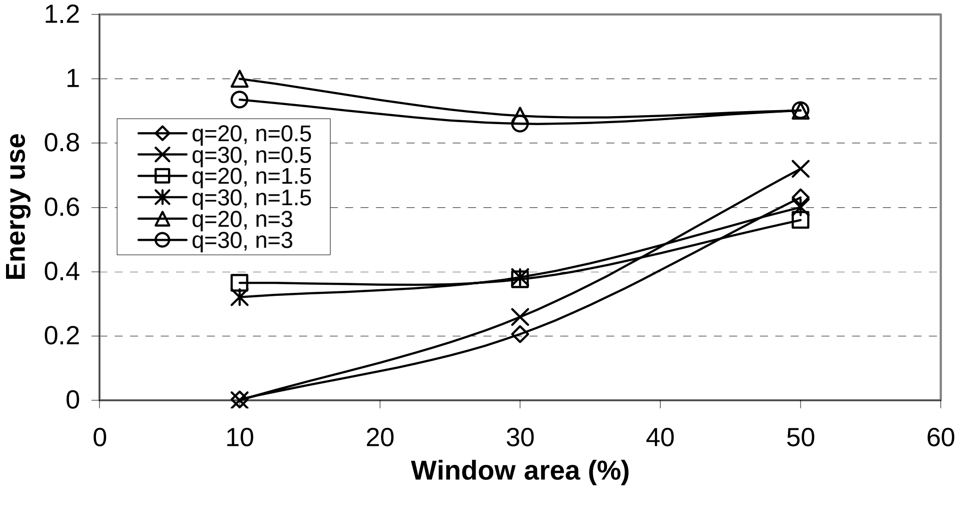

Figure 29 Normalised energy use when window area varies. The indoor comfort level is A, light building and the U_m-value is 0.3 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m².

Energy use in a building with *high thermal capacity* is a minimum with about 30 % window area, see Figures 29 and 33.

Energy use as a function of window area shows that high ventilation air flow rate (3 air changes per hour) always increases the energy use in a building with low thermal capacity, see Figures 30 and 32.

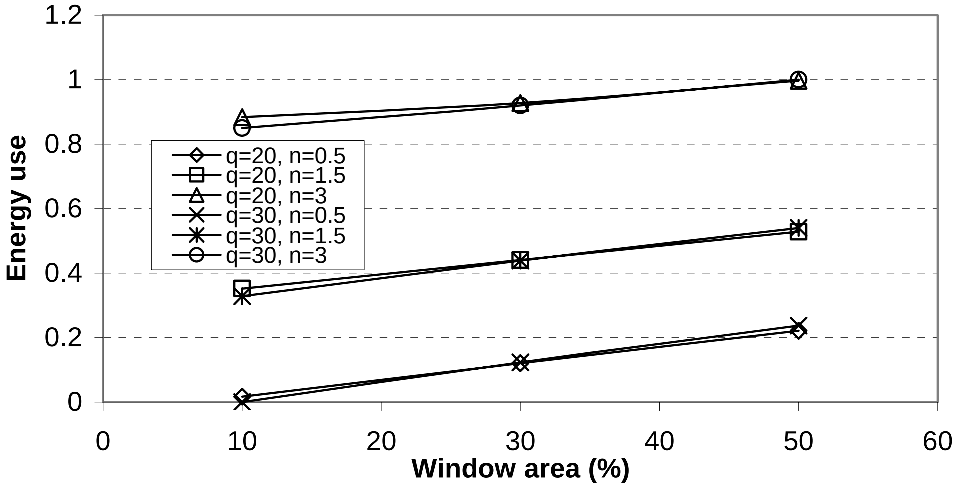

Figure 30 Normalised energy use when window area varies in the building. The indoor comfort level is A, light building and the U_m-value is 0.6 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m².

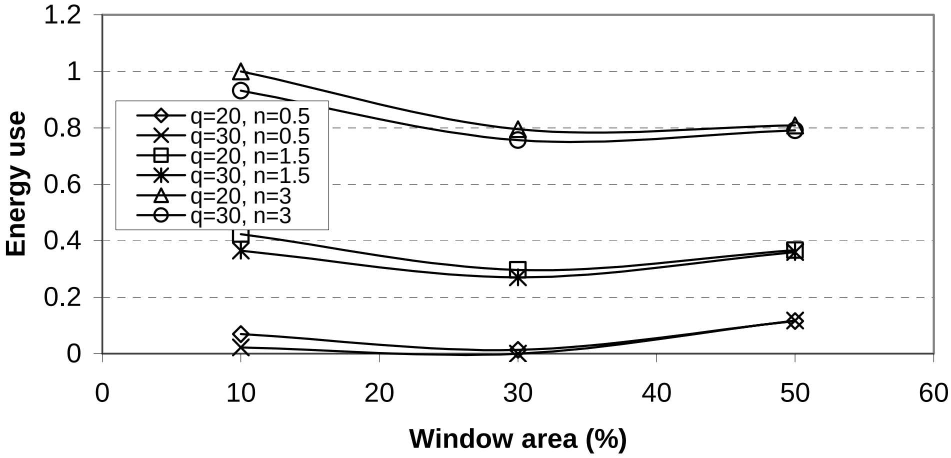

Figure 31 Normalised energy use when window area varies in the building. The indoor comfort level is A, heavy building and the U_m-value is 0.6 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m².

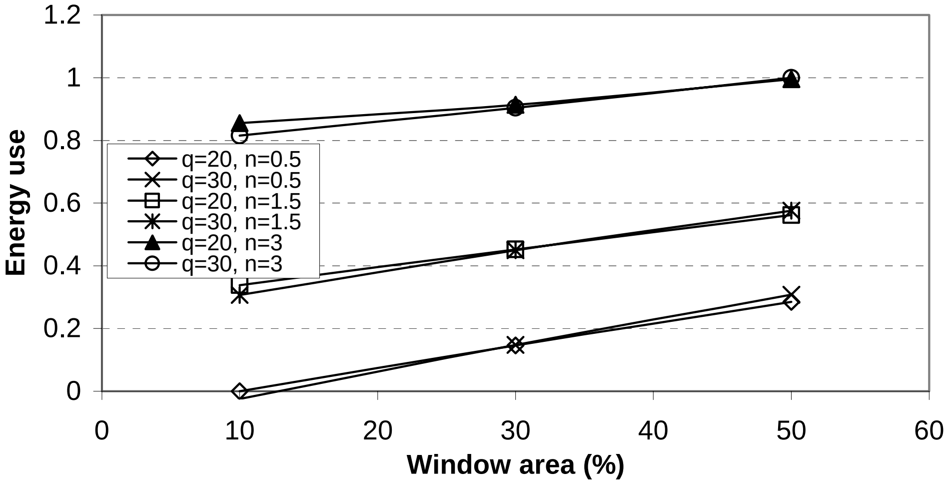

Figure 32 Normalised energy use when window area varies in the building. The indoor comfort level is A, light building and the U_m-value is 1 W/m^2K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m².

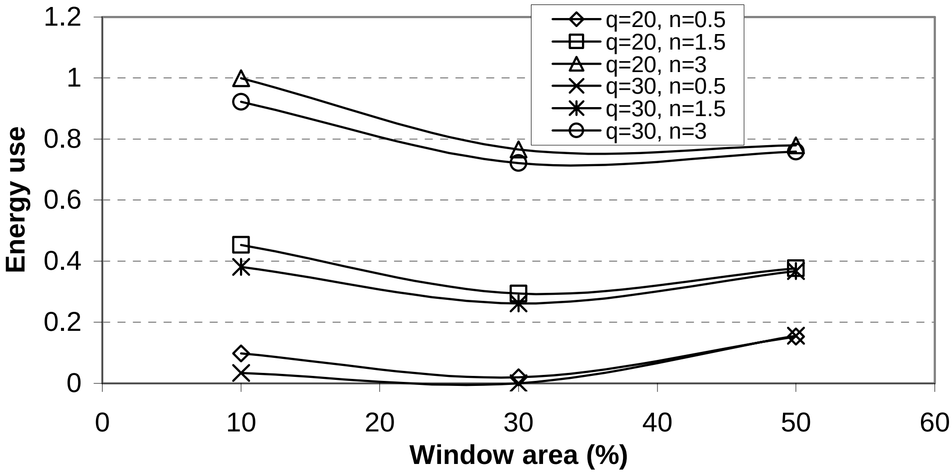

Figure 33 Normalised energy use when window area varies in the building. The indoor comfort level is A, heavy building and the U_m-value is 1 W/m^2K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m².

Figures 28 to 33 illustrate the ventilation air flow rate for different U-values and thermal capacities. The result show the same tendency as in a building with low thermal capacity (Figures 29, 30 and 32): i.e. that energy use increases with higher window area and air change rate, with the U-value making little difference. In a heavy building (Figures 28, 31 and 33), energy use is at a minimum with 30 % window area. But energy use always increases with higher air change rate, as expected

3.2.5 Indoor climate

A higher indoor comfort results in higher energy use. Table 2 shows the energy use for different levels of indoor comfort. It can be seen that the energy saving can be up to 50 % if a lower indoor comfort level is accepted.

Table 2 Percentage energy saving for one example. The numbers show the energy saving for a reduced indoor comfort class. For example, consider a building with $U_m = 0.3$ W/m^{2}K and with a light structure. Reducing the comfort level from Class A to Class B reduces energy use by 10 %. (See Class A-B, light, $U_m = 0.3$.)

Level		U_m= 0.3	U_m= 0.6	U_m= 1
a→b	Light	11.4	13.0	13.1
a→c	Light	23.8	28.4	28.5
b→c	Light	11.1	13.6	13.6
a→b	Heavy	14.7	22.2	21.3
a→c	Heavy	31.5	50.1	49.1
b→c	Heavy	14.7	22.9	23.0

3.2.6 Temperate climate comments and summary

The energy use in an office building in a temperate climate is varies depending on the design of the building and, of course, the thermal characteristics of the building envelope. If a heat exchanger is not used, the results from simulations tell us that:

- A well-insulated building requires less energy than a poorly insulated building. This is independent of the thermal capacity of the building envelope and heat gains (external and internal).
- The heating load dominates the energy use if the mean U-value of the building envelope is 0.6 W/m²K or above. With a lower U-value, it is the cooling load that dominates.
- Increased ventilation air flow rate always result in increased energy use.
- Thermal capacity has only a minor influence on energy use.
- In a well-insulated building with a ventilation air flow rate of 0.5 air changes per hour, increasing the window area increases the energy use. For higher ventilation air flow rate, an optimum window area is about 30 %.
- For a building with a U_m-value of 0.6 W/m²K or higher, the energy use increases with a higher window area for a light building. For a building with high thermal capacity, optimum window area is about 30 %.
- If greater variation of the indoor climate can be accepted, the energy use will be reduced.
- Shading may increase energy use, due to the fact that internal heat gains may contribute to heating the building and reducing the heating load.

If a heat exchanger is used, energy use will be reduced.

3.3 Warm climate

The simulation has been undertaken for a building with a climate typical of Greece, Athens.

3.3.1 Insulation

For a building located in a warm climate, the thermal resistance of the building envelope affects the energy use. Figure 34 shows that the energy use reaches a minimum for a mean building envelope U-value of 0.6 W/m²K.

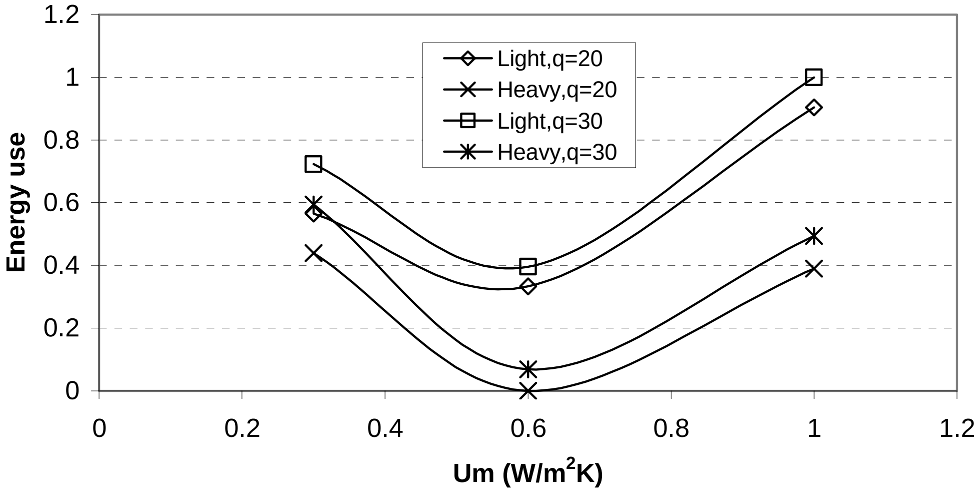

Figure 34 Normalised energy use for conditioning for varying U_m-values (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

The cooling load constitutes a major part of the energy use for conditioning the indoor air, see Figure 35. The heating load constitutes up to 16 % of the total energy use, see Figure 36.

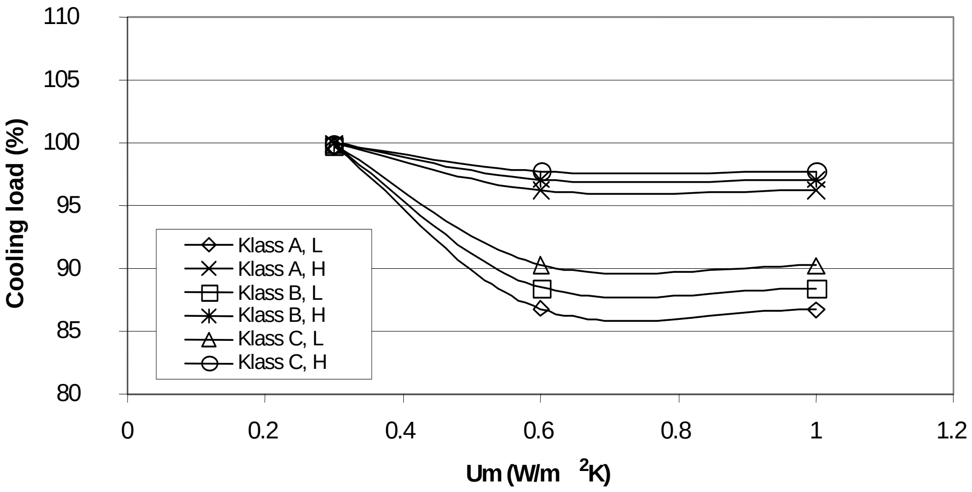

Figure 35 Normalised energy use for cooling as a percentage of the total energy use for varying U_m-values (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

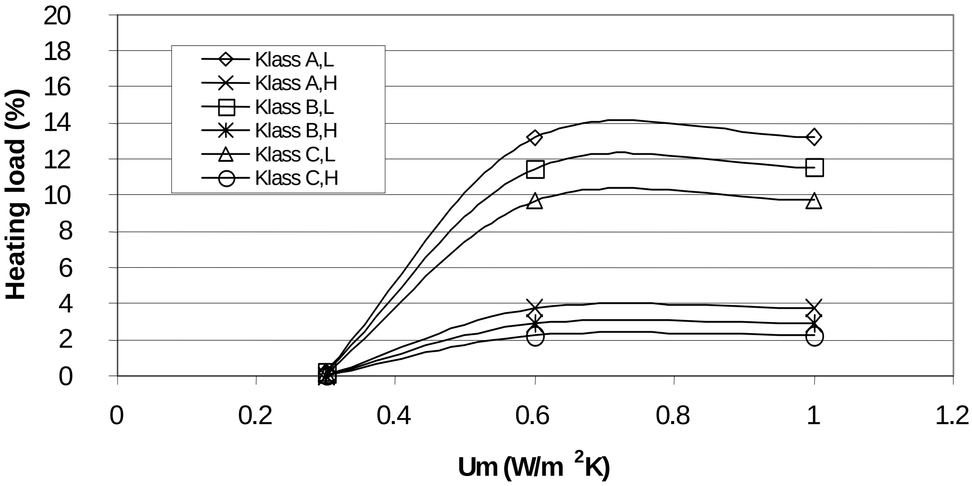

Figure 36 Normalised energy use for heating as a percentage of the total energy use for varying U_m-values (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

3.3.2 Thermal capacity

A building with a high thermal capacity has a lower energy use in comparison with an otherwise identical building, but having low thermal capacity, see Figure 37.

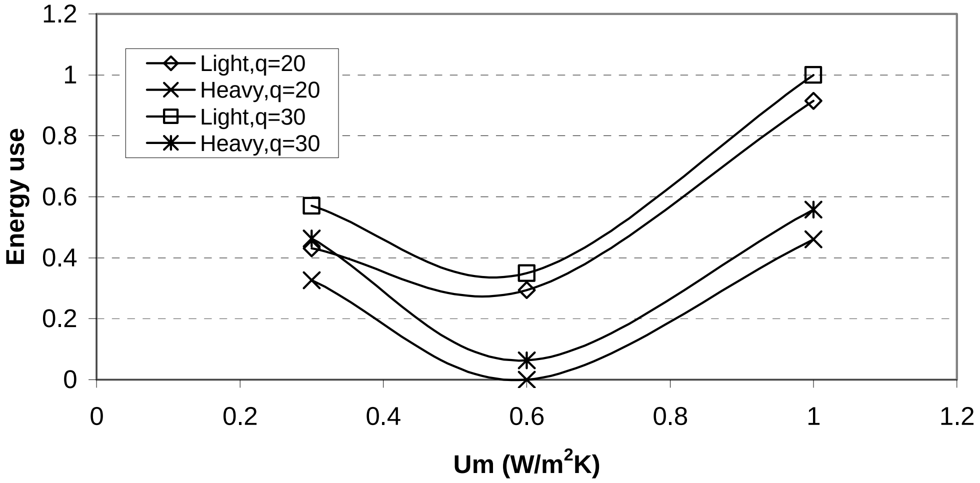

Figure 37 Normalised energy use for conditioning for varying U_m-values (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2. The window area is 30 % of the wall area.

3.3.3 Ventilation air change rate

The ventilation air flow rate has a varying influence on the energy use, as can be seen in Figure 38. It is difficult to identify a general conclusion based on the simulation results. However, in well-insulated buildings, a minimum can be reached at a ventilation air flow rate of 1.5 air changes per hour. In poorly insulated buildings, the energy use can increase with increasing ventilation air flow rate.

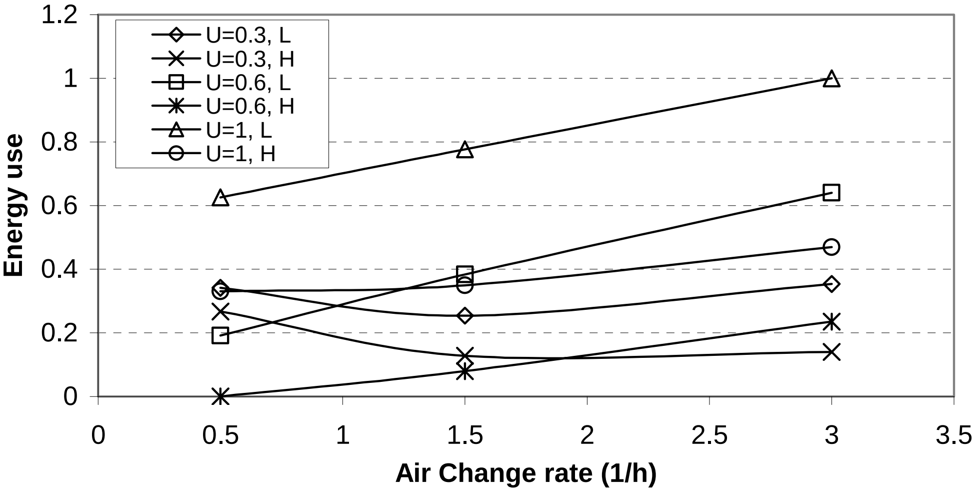

Figure 38 Normalised energy use for different air change rates and U_m-values (U). The indoor comfort level is A, light (L) or heavy (H) building and the U_m-value is 0.6 W/m^2K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 30 W/m^2. The window area is 30 % of the wall area.

3.3.4 Heat gains – Shading

Internal heat gains increase the energy use, as shown in Figure 39. This means that shading will reduce energy use, as the cooling load will be reduced.

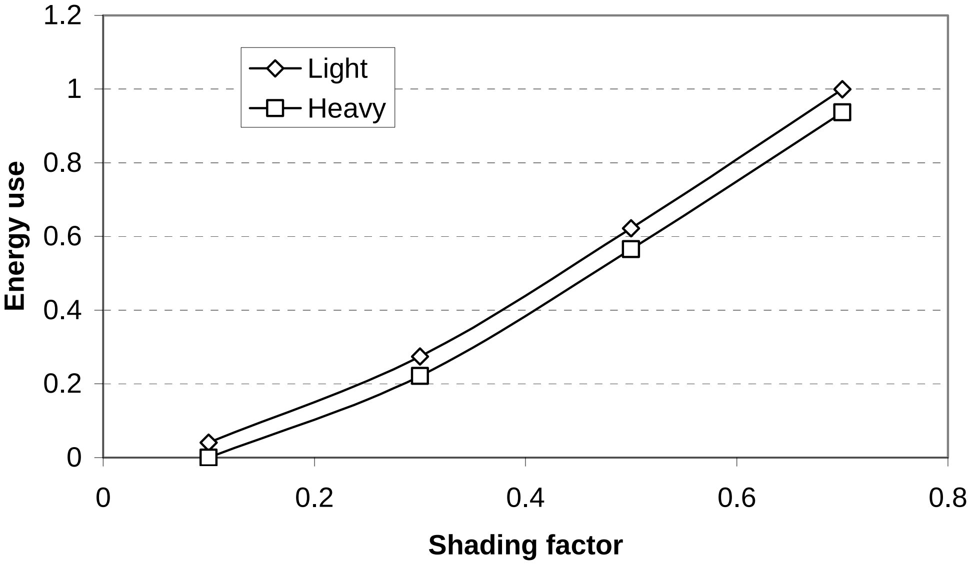

Figure 39 Normalised energy use for conditioning for Um-value (U) and heavy (H) or light (L) building. The indoor comfort level is A. The air change rate, n, is 0.5 air changes per hour. The internal heat gain, q, is 20 W/m^2. The window area is 30 % of the wall area. The U_m-value is 0.3 W/m^{2}K.

With increasing ventilation air flow rate, energy use will increase for all indoor levels and thermal characteristics of the building envelope (window area etc.). See Figures 40 - 45.

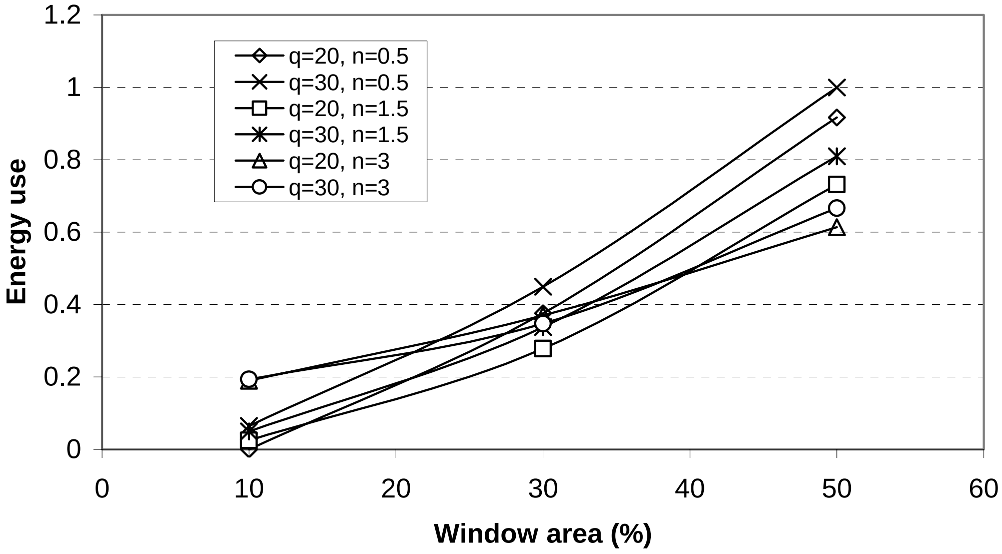

Figure 40 Normalised energy use with varying window area. The indoor comfort level is A, heavy building and the U_m-value is 0.3 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m².

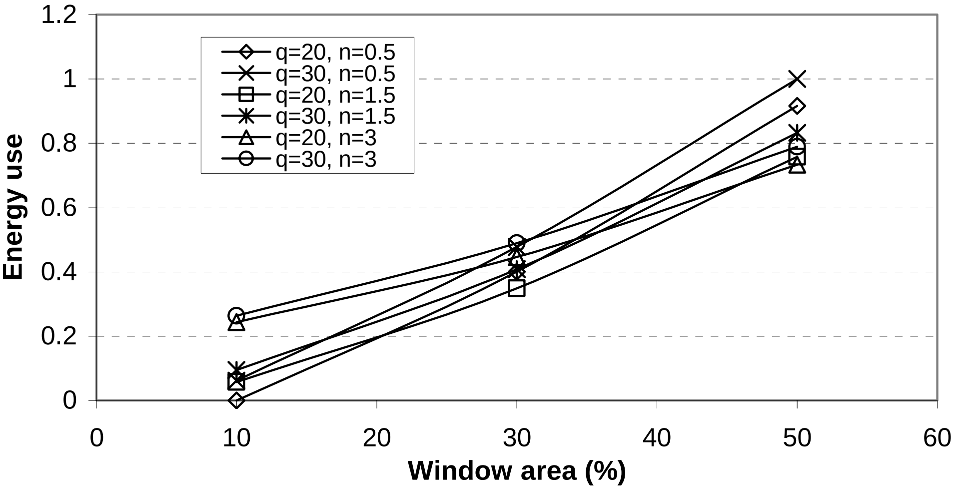

Figure 41 Normalised energy use with varying window area. The indoor comfort level is A, light building and the U_m-value is 0.3 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

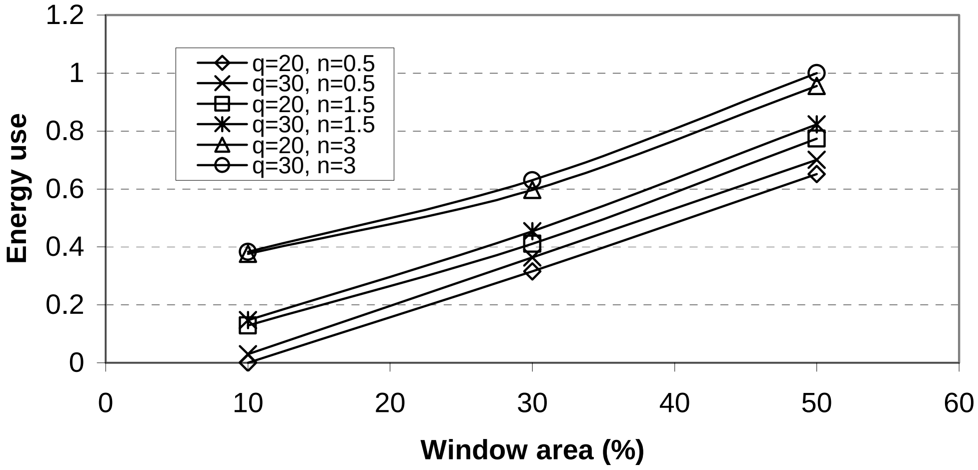

Figure 42 Normalised energy use with varying window area. The indoor comfort level is A, heavy building, and the U_m-value is 0.6 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

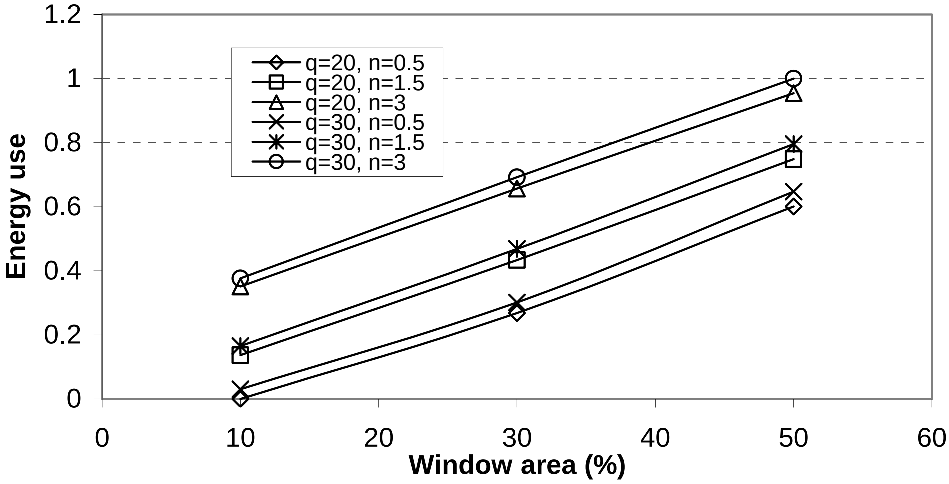

Figure 43 Normalised energy use with varying window area. The indoor comfort level is A, light building, and the U_m-value is 0.6 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

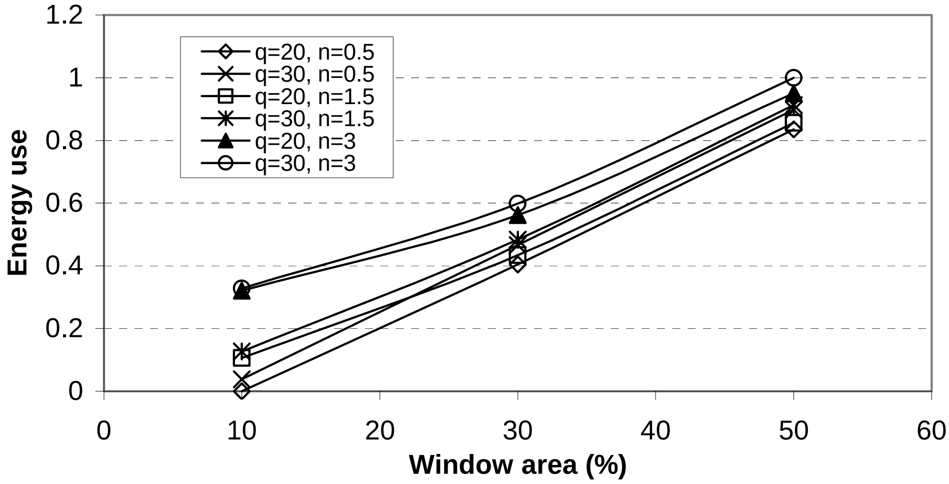

Figure 44 Normalised energy use with varying window area. The indoor comfort level is A, light building, and the U_m-value is 1 W/m^{2}K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

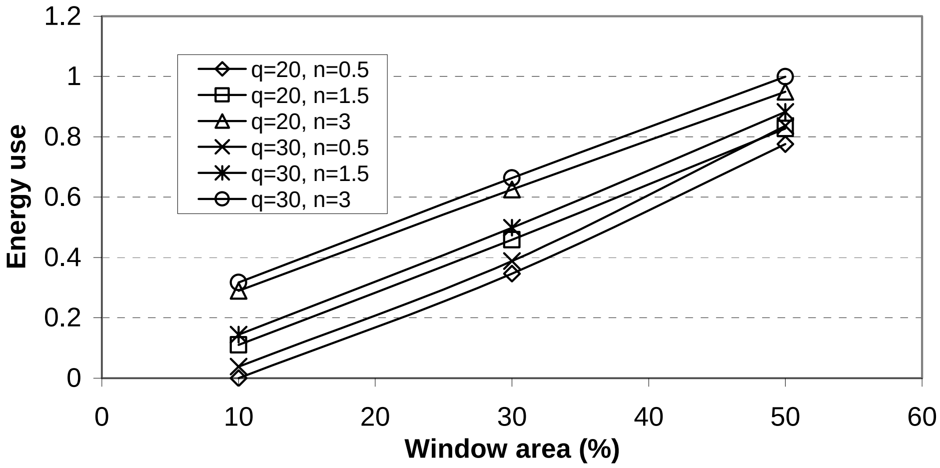

Figure 45 Normalised energy use with varying window area. The indoor comfort level is A, heavy building, and the U_m-value is 1 W/m^2K. The air change rate, n, varies between 0.5 and 3 air changes per hour. The internal heat gain, q, is 20 or 30 W/m^2.

3.3.5 Indoor climate

The energy saving resulting from reduced indoor comfort level is not as great as in previous cases, see Table 3. However, energy saving can be up to 30 %.

Table 3 Percentage energy saving for one example. The numbers show the energy saving for a reduced indoor comfort class. For example, consider a building with $U_m = 0.3$ W/m^2K and with a light structure. Reducing the comfort level from Class A to Class B reduces energy use by 10 %. (See Class A-B, light, $U_m = 0.3$.)

Level		Um=0.3	Um=0.6	Um=1
a→b	Light	6.1	11.0	11.1
a→c	Light	12.7	22.8	22.9
b→c	Light	6.2	10.6	10.6
a→b	Heavy	6.7	14.9	15.1
a→c	Heavy	14.3	31.9	32.3
b→c	Heavy	7.1	14.8	15.0

3.3.6 Warm climate comments and summary

The energy use in an office building located in a cold climate varies, depending on the design of the building and, of course, on the thermal characteristics of the building envelope. If a heat exchanger is not used, the results from simulations tell us that:

- An optimum U_m-value is reached with 0.6 W/m^2K.
- The cooling load dominates the energy use.
- Increased ventilation air flow rate results in increased energy use in most cases.
- A building with high thermal capacity of the building envelope may have slightly lower energy use.

- Increased window area always results in increased energy use (when no shading is used).
- If greater variation of the indoor climate can be accepted, energy use will be reduced.
- Shading may decrease the energy use.

4 Night set back

Another way to reduce energy use is to have a strategy with night set back. The HVAC system is turned off at night. The ventilation air is not treated and is at the same temperature as the outdoor temperature, which means that the building is cooled by the ventilation air. The indoor temperature is allowed to be reduced to a certain level, below which the HVAC system will start and maintain this temperature. Depending on the building's time constant, the HVAC system starts to heat the building in order to get the required indoor temperature at the beginning of the working day.

The process is illustrated in Figure 46. A time cycle with night set back is presented. Two cases are illustrated. In Case One, the dashed line, the building may have a large thermal capacity. The time for cooling is shown by time t_1. The second case represents a light building, in which cooling reaches a set point for the temperature after time t_1. The HVAC system then starts to heat the building in order to maintain the room temperature at that level. After time t_2, the HVAC-system starts heating the building in order to achieve the required indoor temperature at time t_4.

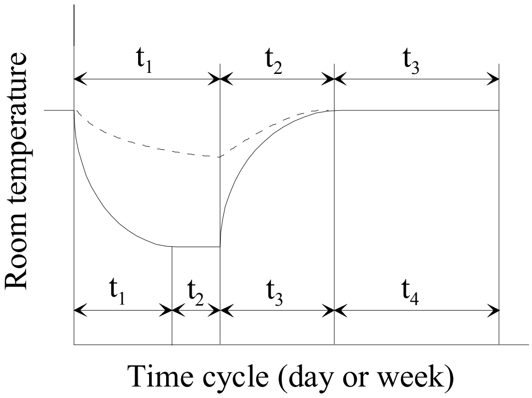

Figure 46 A time cycle with night set back. Two cases are illustrated. In Case One, the dashed line, the building has a large thermal capacity. The cooling of the building takes a long time, t_1. The second case represents a light building case, with the cooling indoor temperature reaching a set point at which the HVAC system starts to heat the building in order to maintain the room temperature at t_1, which is a shorter time compared with a heavy building.

Theoretical simulations by Nielsen A, 1983, show that the energy saving is larger in a light building than in a heavy building, see Figure 47. The result tells us that the saving can be up to 11 % with a light building, but less with a heavy building.

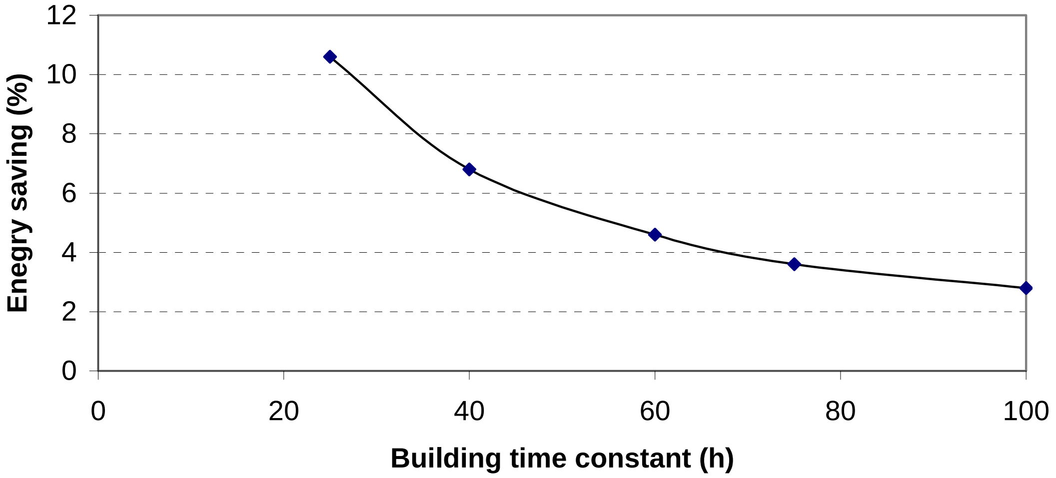

Figure 47 Energy saving in a building with varying time constant. The HVAC system has a 2 h time constant (Nielsen A, 1983). The night set back time is 16 h.

The duration of night set back will affect the magnitude of the energy saving. The results in Figure 48 show that, of course, the duration of night set back has a significant influence on the energy saving.

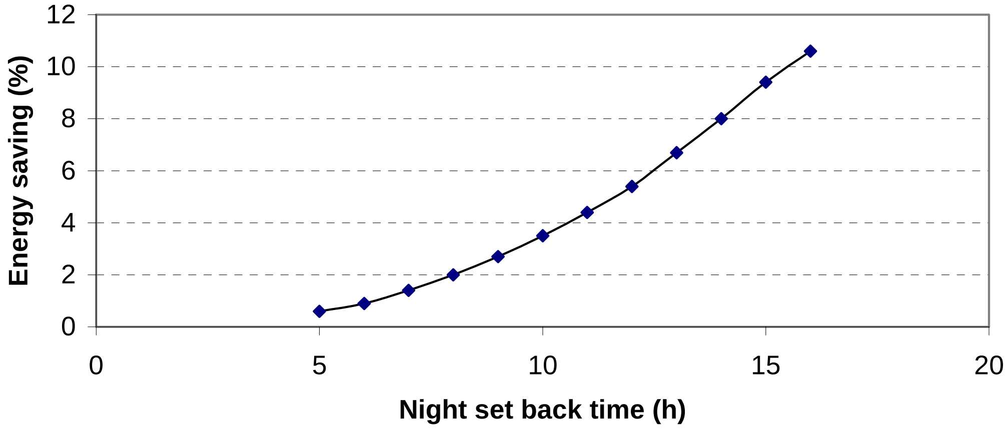

Figure 48 Energy saving in a building for different durations of night set back time (Nielsen A, 1983). The HVAC system has a time constant of two hours, while the building has a time constant of 25 hours.

Nielsen A, 1983, also shows that the HVAC system should have a short time constant in order to maximize the energy saving.

The results tell us that optimum energy saving is achieved in a light building with a short HVAC system time constant. However, in a light building, temperatures may rise too high when heat gains are large. Therefore a strategy is required to reduce the heat gains, for example sun shading, use of low energy office equipment etc.

5 Heat exchanger

Another aspect to consider is the temperature of the incoming ventilation air to the building. For good indoor comfort, the temperature difference between the ventilation air and the indoor temperature must not be too large. On the other hand, this can cause an increase of the use of energy. In a cold climate, the ventilation air is pre-heated. With high internal heat gains, the indoor temperature may increase the need for cooling. In other words, energy can be used for removing the energy used for pre-heating the ventilation air. In a cold climate, the optimum energy efficiency case may be that the ventilation air not is pre-conditioned.

The previous simulations have not modelled the use of a heat exchanger in the HVAC system. However, a simplified method can be used in order to simulate a heat exchanger. The heat exchanger influence can be estimated by using a fictitious air change rate, as follows:

$$n^* = n \cdot (1 - \eta) \quad \text{(air changes per hour)}$$

Where n = air change rate (air changes per hour)
η = performance factor of the heat exchanger

The fictitious air change rate is always lower than the real air change rate. Using the results from the simulations, it tells us that the decreasing air change rate reduces the energy use. The conclusion is that a heat exchanger should be used in cold and temperate climates. A more detailed study is needed in a warm climate in order to determine the effect of a heat exchanger.

6 Limitations and use of the results

The results in this report are meant to be used in the early design phase of a building before any building design parameters have been settled. The architect, designer etc. of the building can use the results in order to estimate how different versions of the building envelope and its thermal characteristics may affect the energy use: for example, a heavy or light building. Different design ideas may, in an energy use perspective, be evaluated and provide guidance for an energy-efficient design. The results should not be used for the final building. When the final design of the building is known, more advanced simulations must be undertaken in order to determine the energy use.

The results described here are based on a simplified model. The objective of the study was to determine how the thermal characteristics of a building affect energy use for indoor air conditioning. In practice, there are many other parameters that have not been considered, for example day lighting, control strategy, airtightness, occupants' behaviour, HVAC system characteristics etc. Another aspect is that the indoor climate in the model is uniform throughout the room, while in practice it will vary. **The results are therefore intended only as guidance to the designer in the early design phase of the building. They will provide an understanding of the studied parameters and the magnitude of their effect on energy use.** The results do not cover all cases that can occur in practice, and should therefore be used carefully.

The study is limited to how the thermal characteristics of the building envelope affect the energy use. The heating load used for the simulations represents the heating load without allowing for the performance of different components within the HVAC-system. This means that the results may produce an error if the energy use is compared for two different HVAC systems in otherwise identical buildings. Then the performance factor must be taken into account.

7 Discussion

The results from the simulations give an indication of how different parameters influence the energy use for indoor air conditioning. The study has concentrated on how the thermal characteristics of the building envelope affect the energy use. A simplified theoretical model has been used, and several parameters have not been taken into account, which should be born in mind when using the results.

The *thermal resistance* of the building envelope has a substantial affect on energy use. In most cases, in cold and temperate climates, **energy use reduces with increasing thermal resistance in most cases, and is independent of other parameters**. However, for a building in a warm climate, an energy use minimum is achieved if the U_m-value (mean U-value of the building envelope) is 0.6 W/m²K. Above or below this value, energy use increases.

The *thermal capacity* of the building envelope has an influence of the energy use. In most cases, the influence is about 5 to 10 % lower energy use for a building with high thermal capacity of the building envelope. In a building located in a temperate climate, there is a difference in energy use for light and heavy buildings when the window area varies. An optimum window area is about 30 % in a building with high thermal capacity. In a light building, increasing the window area always increases the energy use.

The *ventilation air flow rate* increases the energy use in most cases when the air flow rate increases. However, for a building in a warm climate, there is a case when the energy use is almost constant with increasing air flow rate.

The *window area* affects the energy use in different ways. Greater window area increases the heat loss, but the heat gain through insolation increases. Another aspect is day lighting. By optimise the use of daylight, energy for artificial lighting can be reduced. The results from the simulations show that 30 % window area is an optimum area for energy use for buildings in cold and temperate climates. In a building in a warm climate, energy use will increase with increasing window area.

The magnitude of irradiation on the vertical wall is assumed to be constant in all wall directions, i.e. south, west, north and east. Shading is a factor that can significantly reduce energy use for air conditioning. In buildings located in warm climates, it is important to reduce the irradiation from the sun. By designing shading, the cooling load can be reduced. A study by Bülow-Hübe, Helena 2001, shows that the cooling load reduces considerably if shading is used. The cooling power can be reduced up to 50 % or more for an office room in a building located in Sweden.

The results in this report show that shading of the window has an effect on energy use, although these effects are opposite, depending on whether the building is in a warm or a cold climate. In a cold climate, greater shading may increase energy use, because it is the demand for heating that dominates energy use. In a warm country, the tendency is opposite, with the demand for cooling dominating energy use. In a temperate climate, the results indicate that there may be a minimum for energy use as a function of the shading factor. However, it is difficult to determine how energy use will be affected. In practice, there are many parameters that affect the shading factor (other buildings, trees etc.), and it requires a more detailed simulation in order to determine how shading affects energy use.

If greater variations in *indoor comfort level* can be accepted, energy use can be reduced by up to 30 %. The magnitude of the reduction will depend on the magnitude of the variation of the indoor temperature.

How the *parameters in combination* affect energy use is as discussed above. For example, reducing the U_m-value will result in lower energy use for different window areas etc. for buildings in cold or temperate climates. In a warm climate, consult the diagrams for information.

Practical point of view
The simulation is based on a simplified theoretical model. It takes no consideration of:

- Pre-heating/cooling of supply air
- Insolation
- Internal heat capacity
- Day lighting
- Control strategy

In the model, supply air is not pre-heated or pre-cooled. In practice, the air must be pre-heated or pre-cooled in order to avoid draughts and poor indoor comfort. For a building in a cold climate, this can result in greater energy use. In the spring and autumn, when the outdoor temperature may be low and the insolation is high, pre-heating causes an increase of the cooling load. The supply air can be pre-heated from the outdoor temperature to 17 °C. The heat gains from the sun through the windows increase the indoor temperature. The temperature can increase to a level at which cooling is needed. Pre-heating the supply air may cause a cooling load. The same result can be achieved by using a heat exchanger. When designing the HVAC system, an analysis must be undertaken in order to minimise the energy use.

The internal heat capacity, such as books, furniture etc., is assumed to be constant, although in practice it varies.

Day lighting may affect the total energy use. Designs intended to increase the amount of daylight may make it possible to reduce electricity use for artificial lighting: see, for example, Kristensen P, 1997. Heberl J S, 1996, shows that well-designed buildings making good use of natural light can save 37 % of electrical energy use.

Control strategy is an important factor in the operation phase. For example, the control strategy is dependent on whether the building has high or low thermal capacity. In heavy buildings, the temperature variation is less than in a light building (see Hagentoft C E, 1997). It is difficult to change the indoor conditions quickly in buildings with high thermal capacity. Hagentoft also shows that well-insulated buildings with high thermal capacity of the building envelope have lower energy use during the operation phase of the building.

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