THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Influence of thermal mass on the heating and cooling demands of a building unit

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ABSTRACT

The purpose of this work is to find to what extent the thermal properties of the building materials, the allowed indoor temperature swing, determined by the comfort interval, and, to some extent, the ventilation strategy can affect the heating and cooling demand of a building.

It is well known that a thermally heavy building, that is a building with a high heat capacity, often demands less energy for heating and cooling and have a more stabile indoor temperature due to heat storage in the building structure. A great number of studies have been done in this area and it is often debated to what extent the heat capacity of the building structure can be used as heat or cool storage.

The heat storage potential of a building structure has been analysed using analytical solutions for both sinusoidal variation and a unit step of the indoor temperature. In three case studies, numerical calculation programs have been used to analyse the thermal behaviour of a building unit. The first case study focuses upon the influence of the building's thermal mass and of the comfort intervals upon the heating and cooling demand during a 24-hour period. The second case study focuses on how different ventilations strategies can influence the heating and cooling demands of a building during a 24-hour period. The third case study compares the heating and cooling demand during one year for four buildings, each with a heavy and a light construction, respectively.

Apart from the main task, two complementary projects are presented. In the first project, heat and moisture conditions are simulated in an earth-tube system designed to pre-heat the inlet air to a terrace building using the thermal mass of the ground surrounding the building. In the second complementary project, the energy use during the life cycle of four buildings is assessed.

By choosing the right material in the building structure and adjust the comfort interval and ventilation to the current internal heat gain it is possible to decrease the heating and / or cooling demand of the building when part of the surplus heat is stored in the building structure. However, the amount of heat stored is small compared to the total energy use of a regular building. According to this study, the most important material parameter regarding heat storage is the thermal effusivity.

Keywords: heat storage, building energy use, thermal mass, building structure, heavy or light buildings, earth tube heat exchanger, thermal comfort, environmental impact, life cycle, comfort interval

LIST OF PUBLICATIONS

This thesis consists of an introductory text together with six research articles. The main part of the thesis concerns dynamic analysis of a building unit. A short presentation of two complementary studies is done in Chapter 6 ‘Preheating of air through an earth-tube system’ and in Chapter 7 ‘The effect of thermal mass on the energy use during the life cycle of a building’.

The research articles listed below will be referred to in the text as Paper I to Paper VI.

I. **Ståhl F**. Thermal properties of building materials and their influence on the energy efficiency. Proceedings of the 5th Nordic Symposium on Building Physics, Gothenburg 1999. p. 153-160. ISBN 91-7197-795-3.

II. **Ståhl F**. Potential influence of the heating demand by choice of thermal mass and comfort interval. Submitted to Journal of Building Physics, 2009.

III. **Ståhl F**. Influence on the heating demand by choice of ventilation strategy. Proceedings of the 7th Nordic Symposium on Building Physics, Reykjavik 2005. p. 1025-1032. ISBN 9979-9174-5-8.

IV. **Claesson J., Hagentoft C-E.** and **Ståhl F**. Thermal buffering capacity of interior walls – Handy formulas from step-response analysis. Submitted to Journal of Building Physics, 2009.

V. **Ståhl F**. Preheating of supply air through an earth tube system – Energy demand and moisture consequences. Proceedings of the 6th Nordic Symposium on Building Physics, Trondheim 2002. p. 913-920. ISBN 82-91412-02-2.

VI. **Ståhl F**. The effect of thermal mass on the energy use during the life cycle of a building. Proceedings of the 6th Nordic Symposium on Building Physics, Trondheim 2002. p. 333-340. ISBN 82-91412-02-2.

Not included in this thesis is publication VII, which is the background report to Paper I, V and VI.

VII. **Ståhl F**. Lic. Thesis: The effect of thermal mass on the energy use during the life cycle of a building, System and component analysis. (Inverkan av termisk massa på en byggnads energibehov under dess livscykel, System- och komponentanalys). Department of Building Physics, Chalmers University of Technology. 2000. (In Swedish).

PREFACE

The work presented in this thesis has been carried out at the Division of Building Technology at Chalmers University of Technology. This work is a merger of several larger and smaller projects focusing on thermal heat storage in buildings. The Swedish Council for Building Research, Industrins byggmaterialgrupp (the Swedish Building Materials Industry Group), Chalmers University of technology and SP Technical Research Institute of Sweden have financed different parts of this work.

First, I would like to thank my supervisor Carl-Eric Hagentoft and assisting supervisor Johan Claesson. Parallel to my PhD studies I have been working as a building consultant for more than 7 years. Still my supervisors never failed to encourage me to complete the work even though they did not see me or any progress in the work for several months sometimes.

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Fredrik Ståhl

Göteborg, november 2009

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PAPER IV.	Thermal buffering capacity of interior walls – Handy formulas from step-response analysis.
PAPER V.	Preheating of supply air through an earth tube system – Energy demand and moisture consequences.
PAPER VI.	The effect of thermal mass on the energy use during the life cycle of a building.

1 INTRODUCTION

1.1 Background

The energy used in buildings accounts for about 35 percent of Sweden's total energy consumption (Swedish Energy Agency 2008). About 80 to 90 percent (Adalberth 2000, Swedish Energy Agency 2008) of this energy use occurs when the building is occupied, and is due largely to the heating or cooling of the building. Thus, one way to lower energy consumption in Sweden is to lower heating and cooling demand. Certainly, Sweden has a cold climate, but with good insulation the heat losses and thus the heating demand can be minimised. Another way to lower the heating and cooling demand is to utilise the internal heat gain, that is, the heat generated within the building. Internal heat gain varies with building type: In domestic buildings the heat generated by people and appliances is fairly modest, although on sunny days indoor temperatures may exceed what is considered comfortable. In commercial buildings, the internal heat gain due to people, machinery and the sun is so large that cooling is required. In both commercial and domestic buildings the heat gain varies throughout the 24 hours of the day, and by storing some of the surplus heat generated during the day (to be released at night when gains are low) the need for cooling or ventilation is lessened. The surplus heat can be stored in the structure of the building during shorter periods, such as a day, if the structure includes a layer of material with good heat storage capacity exposed to the interior of the building.

1.2 Hypotheses

The first hypothesis is that by choosing the right material, thickness and exposed area of the building structure, together with a suitable comfort interval and ventilation strategy, it is possible to reduce the energy demand of a building by storing heat in the building structure, or by cooling, on a diurnal basis.

The second hypothesis is that the need for heating and cooling is decreased when the inlet air passes through an earth tube system buried in the ground before it is brought into the building.

The third hypothesis is that it is possible to reduce the energy demand in the occupational phase of a building through heat storage in the building structure and thereby decrease the energy use in a building during its whole life cycle.

1.3 Scope

The main task of this thesis is to assess the heating and cooling demand of a unit of a multi-storey building. This unit represents two apartments or part of an office floor. The internal heat gains depend on the use of the building unit. The parameters of the building have been varied to assess their influence on the building energy demand.

The varied parameters are:

- Material parameters describing the heat transfer and storage capacity of the building structure: thermal conductivity, thermal effusivity and specific heat capacity.
- The thickness of the building structure and the area of the structure that is exposed to the interior of the building.

- The internal heat gain is varied to represent different uses of the building. Low internal heat gain represents residential buildings, and high internal heat gain represents office buildings.
- Different comfort intervals have been used to assess the connection between comfort interval and energy use.
- The ventilation rate has been constant in most cases, but one part of the work is focused on varying the ventilation rate during the day to find a ventilation strategy that will decrease the energy use.

By analysing the relation between different parameters we can develop general rules in the shape of formulas and ‘rules of thumb’ in order to estimate the heat storage potential of different buildings and parts of buildings. Both periodic sinusoidal and step response solutions have been used.

Apart from the main task, two complementary projects are presented. In the first project, heat and moisture conditions are simulated in an earth-tube system designed to pre-heat the inlet air to a terrace building using the thermal mass of the ground surrounding the building. In the second complementary project, the energy use during the life cycle of four buildings is assessed. The energy use of a terrace house, a block of flats, an office building and a school is compared when designed with a heavy or a light building structure, respectively.

1.4 Limitations

The energy consumption of a building is to a large part influenced by the habits of its users, but in this work these habits are not considered directly. Instead, varying thermal gains and ventilation rates represents the function of the building and the habits of the users. Airing of the building has not been studied per se, but is included in relevant ventilations strategies. Three different comfort intervals have been used to represent the users’ tolerance to temperature variations. Energy used to evaporate or condense moisture in the building has not been considered. Different heating systems using heat exchangers or heat pumps have not been considered. Boundary conditions such as external temperature and internal gains have in some sections of the study been simplified to sinusoidal oscillations, temperature pulses or to synthetically generated climate data. The results from the simulations have not been verified by measurements in actual buildings.

The study is only concerned with the energy demands of a building for heating and cooling in order to achieve a specific indoor temperature interval. What kind of energy and what kind of heating system that would be best is not part of the study.

The project about air pre-heating via earth-tubes is mainly concerned with a terrace house with heat recovery from exhaust air to inlet air; and the scope of the study is limited.

The project analysing the energy consumption during the life cycle of a building, uses only a few of the possible constructions that can represent a heavy and a light building, respectively. The analysis is based on measurements of energy and hot water demands by Boverket (1994), Nilson et al. (1996) and Aronson (1996). These values vary markedly in actual buildings.

1.5 Method

With the help of analytical solutions simplified tools and formulas have been developed to determine the heat storage potential in a building or in a part of a building. The analytical solutions point out important factors and parameters – and their relation – for heat storage in the building's structure and thus increase our understanding of this phenomenon.

Numerical calculation programs have been used in three case studies. The first case study (Paper II) focuses upon the influence of the building's thermal mass and of the comfort intervals upon the heating and cooling demand during a 24-hour period. The structure is not made of a specific material; instead, the material parameters vary from an extremely high to a low heat storage capacity. These parameters do not refer to actual materials, but the values used lie within the limits of common materials.

The second case study (Paper III) focuses on how different ventilations strategies can influence the heating and cooling demands of a building during a 24-hour period. On the whole, this is based on the same model as in the first case study, with the difference that specific materials are used in the building structure: granite (with a good heat storage capacity), wood (intermediate capacity), and mineral wool (low capacity).

The first two case studies use the International Buildings Physics Toolbox (IBPT), a Simulink-based tool which handles heat and moisture transport in buildings and parts of buildings. In these studies moisture is not accounted for. The external climate is given by hourly temperature values taken from a synthetically generated reference year in Copenhagen.

The third case study (Paper VI) compares the heating and cooling demand during one year for four buildings, each with a heavy and a light construction, respectively. The different building types are: a terrace house, a block of flats, an office, and a school. Internal heat gains and building structures are chosen to be as realistic as possible. The block of flats and the office contain largely the same building volume as in case studies one and two, but have a different heat gain. In this third case study, Derob-LTH has been used to calculate the heating and cooling demands. Climate data, recorded in Lund in 1988, where used.

In the additional project concerned with pre-heating of inlet air via earth-tubes, both analytical and numerical solutions have been used. In order to determine the heat and moisture conditions in a buried pipe, a numerical computer program based on the finite difference method (Eftring 1990, Blomberg 1996) has been developed in Pascal and transferred into Delphi. Climate data are based on measurements recorded during a cold year in Bromma

In the study of the energy life cycle of buildings, the methodology developed by Adalberth (2000) has been used to determine the energy demand during the construction and demolition of buildings.

1.6 Structure of thesis

The thesis is divided into three parts:

I. Dynamical analysis of a building unit
The first part of the thesis focuses upon periodic heat storage in the structure of a building and its influence upon the heating and cooling demands of the building. This work, in turn, is divided into analytical solutions and three case studies with results and analysis:

1. **Analytical solutions for heat storage in materials and in ventilated areas**

   This study presents three simplified tools to assess the potential for periodic heat storage in a building structure. The first tool calculates the periodic heat storage in a building material induced by sinusoidal indoor temperature swing. The second tool calculates the heat recovery from an interior wall due to a unit step of the indoor temperature. The third tool assesses the amplitude of the indoor temperature in a building, which depends on the material used in the building structure.

2. **Case studies of heating and cooling demands in parts of a building**

   The first case study focuses upon the influence of important parameters that characterise the building thermal mass and of the comfort interval on the heating demands during one 24 hr period.

   The second case study focuses upon how different ventilation strategies can influence the heating and cooling demands during one 24 hr period.

   In the third case study the heating and cooling demand during one year are compared in a building with a heavy and with a light structure, respectively. Four different building types are used: a terrace house, a multi-storey residence, an office building, and a school.

II. Preheating of air through an earth-tube system
The second part of the thesis demonstrates how the heat storage capacity of the ground around a building can be utilised (by circulating the inlet air through an earth-tube) to affect the heating and cooling demand of the said building.

III. The effect of thermal mass on the energy use during the life cycle of a building
The final part compares the energy use in heavy and light buildings, respectively, during their whole life cycle. Again, four different building types are used: a terrace house, a block of flats, an office building, and a school.

1.7 Literature survey

I. Dynamic analysis of a building unit

Mathematical models

Carslaw and Jaeger (1946) uses a matrix method to solve problems concerned with periodically varying temperatures in a composite layer.

Granholm (1971) shows how the heat capacity of a wall influences the heat flow through the wall when the temperature on either side varies periodically. Larsson (1984) builds on Granholm's ideas about heat flow through a building component and adds variations in the indoor climate due to other building parts such as windows and adherent solar radiation. This is done using Carslaw and Jaeger's matrix calculations.

The mathematical models of Claesson and Hagentoft (1994) use heat capacity nodes in a mesh and complex value conductance meshes to describe the heat flow and heat storage properties of a building component. Both step-change and periodic solutions have been investigated.

Circuit models

Mathews et. al. (1994) present a first order circuit model where a layer in a building component is represented by two conductive resistances and the component's heat storage capacity by a capacitance. Several layers can be combined using Carslaw and Jaeger's (1946) matrix method. Lombard and Mathews (1999) let a two-port solution be represented by matrices, one for each frequency of interest, in order to describe to the whole range of the behaviour of the building envelope. Coley and Penman (1996) model the thermal response of a building using a second order RC-mesh with five characteristic parameters.

Dynamic thermal behavior of building components

Davies (1994) shows the relationship between temperature and heat flow at the surface of a material at a sinusoidal change and summarizes the characteristic that affects the temperature and heat flux through the surface of a material into two components: characteristic admittance and cyclic thickness. Davies (1994) links the one-dimensional heat flow through a material to heat flow through multi-layer structures and to temperature variations in a ventilated space.

Wentzel (2005) illustrates the thermal behavior of building components and buildings using dynamic thermal networks that are based on step-response functions.

Holford and Woods (2007) examines the role of thermal mass in buffering the interior temperature of a naturally ventilated building and use four dimension resolve parameters to describe the thermal heat storage in buildings (with natural ventilation). They also investigate when the thermal mass of a building can be modeled as a lumped mass.

Jóhannesson (1981) describes and evaluates non-stationary heat transfer in building components and building envelopes; he also develops simplified methods to calculate these non-stationary transfers using a parameter called 'active heat capacity' to represent the specific building component. Cammarata, Fichera and Marletta (1993) developed 'sensitivity coefficients' to assess how variations of a building parameter's nominal value influence the thermal gain. Burmeister and Keller (1996) define a function they call "a climate surface" which represents a building's heating or cooling demands. Mao (1997) uses a frequency-response method to predict heat losses from thermal bridges in the building envelope of a building.

Fernández et. al (2005) calculates the thermal mass of a un-ventilated and un-heated building based on measurement of the indoor and outdoor temperature. The inside temperature attenuation and time delay forms the basis of the calculations.

Computer models
Today, there are a lot of computer models that analyse the thermal performance of buildings and only a few will be mentioned in this thesis. Månsson (1997) summaries the work by International Energy Agency In Annex 21 Calculation of Energy and Environmental Performance of Buildings (Lomas et. al.1994) and Task 12 Subtask Building Energy Analysis and Design Tools for Solar Applications where a direct comparison of several different thermal computer models is done. Brown (1990) shows how the simulation program BRIS is constructed and how the program handles the different parameters that influence the heating balance in a building. CHEETAH is another computer program that has been developed to determine the thermal properties of a building (Delsante 1987). The program is a development of the research program ZSTEP3 and uses a frequency-response method as the basis for its calculations (Walsh and Delsante 1983), a method that differs from the z-transform method advocated by ASHRAE (1997). Kalema et al. (2008) compare heating and cooling energy in well insulated buildings with heavy or light structures in Nordic climate. The calculations of six simulation programs are compared. The reliability of ISO 13790 is evaluated, especially the gain utilization factor.

Simple hand calculations
Jensen (1992) predicts the heating demand of a building, in respect of solar radiation, with the help of a simplified calculation. Elmarsson (1998) shows how one can use some simplified calculations to study the effects of a heavy wall and of a light wall, both with the same U-value, and also demonstrates the dampening effect of heavy walls on variations in room temperature.

Heat and cool storage in building structure
Isfält (1977) discusses the energy savings that can be made through storage of surplus heat in heavy structures and under what conditions the storage does or does not work. Betongindustrins Samarbetsråd (1982) describes, in a small pamphlet, how a heavy structure, made of concrete, can be used to store surplus heat and thus reduce the energy consumption. Bergqvist et. al (1995) present indoor climate calculations for a typical office room in order to show how different parameters affect indoor climate. The compared parameters are, among others, heavy and light structure, heat storage capacity of the furnishings, the window area and the internal heat gains. Hagentoft (1996, 1997) shows in two reports the theoretical advantages of a heavy, well-insulated building with respect to lessened energy consumption and a more stable indoor climate.

Walsh et. al (1982) used the computer program ZSTEP to simulate a both heavy and a light building in seven Australian localities. Goodwin et. al (1979) investigate the effect of a building's mass upon its heating and cooling requirements in different climates.

Snyder and Newell (1990) have developed a model with the help of which the cheapest cooling strategy for a building with a large thermal mass can be worked out. This is done using a simplified thermal mesh, and the strategy includes actual cooling of the building's structure in order to allow large amounts of internal surplus heat to be absorbed.

Active use of thermal heat storage

Brandemuehl et. al. (1990) examine the effects of structural thermal mass in the above-ceiling unducted return air plenum on the air temperature returning to the HVAC equipment. Amato et. al. (1998) discuss cooling of the floor structure in commercial buildings; they discuss both passive – with sufficiently exposed ”thermally transmitting” surface – and active systems.

Andersson and Pal (1980) describe a building with hollow floor structure moulded in situ, where hot or cold air can pass through pipes. Bergkvist (1990) presents the Strängbetong Termodeck climate control system, an active heating and cooling storage system in hollow floor structure. Meierhans (1993) takes a step further and uses cold water in pipes to cool the ceiling during nights and weekend, when energy prices are low; the ceiling then cools the room during the day.

IEA Annex 44 (2009) identifies Thermal Mass Activation as one of five responsive building element technologies with future potential.

Interaction between thermal mass and HVAC

In many papers, Athienitis (1988, 1993) and Athienitis and Stylianou (1990) has described his work to simulate the interaction between the thermal mass of a building and its HVAC (air treatment) system. Isfält (1972) uses computer programs to analyse how different factors influence indoor climate.

Optimisation

Nielsen (2002) develops a methodology to optimise the life cycle cost of a building with respect to other performance aspect such as energy use, thermal indoor environment and daylight conditions. The developed design methodology is implemented in a design tool that utilizes an optimisation method to perform automatic parameter variations of the design variables. The goal is to minimize the life cycle cost with respect to energy use and thermal indoor environment.

Henze et.al (2007) evaluate the benefits of optimal control for passive thermal energy storage to reduce utility costs. Sensitivity analysis of parameters important in reducing the energy(/utility) costs by pre-cooling the thermal mass of a building.

II. Preheating of air through an earth-tube system

Claesson and Dunand (1983) have analysed heat extraction from the ground using analytical solutions to the heat conduction equation in the ground. Their report provides basic mathematical methods to assess the heat extraction potential of the ground by using steady-state and time-dependent solutions put together by the principle of superposition to dynamical, multidimensional processes in the ground. Nilsson (1991) has dealt with the thermal processes, which influence the design of an earth-tube preheating system for cold climates. His work is based on analytical solutions of the heat equation taking latent heat and natural frost penetration into consideration. The theoretical analysis is compared with a full-scale test of a preheating system located in Boden, Northern Sweden. Mihalakakou et. al. (1994) have studied the cooling potential of an earth-tube system using both numerical simulations and field measurements. Mihalakakou et. al. (1996) have investigated the heating potential of an earth-tube system discuss the need to incorporate the latent heat into the model to predict the heat transfer of the earth-tube system.

Previous research into earth-tube systems has dealt with the latent heat of an earth-tube but has not presented the high relative humidity of the air from an earth-tube and has not dealt with the important combination of high relative humidity and the growth of mould and fungus. Mihalakakou et. al. (1994) have discussed the importance of incorporating the latent heat gains into their simulation of an earth-tube system (to preheat or precool the ambient air before the air is used in the building). In a recent article, Hollmuller and Lachal (2001) question whether or not an earth-tube system is a good investment considering the heating potential of the earth-tube system. They conclude that the cooling potential is good and that stagnant water in the earth-tube system enhances the performance of the system. Unfortunately, the quality of the outlet air of earth-tube systems is not discussed in most articles. One report by Blomsterberg et al. (1998), deals with passive stack ventilation in three newly built Swedish schools. In two of the schools' earth-tube system there was mildew formation. All three schools were built only a few years previous to the inspection. It is vital to investigate the moisture content of the air that passes through an earth-tube system because air with a high relative humidity in contact with organic material will increase the risk of the formation of mildew (Hallenberg and Gilert 1993).

Samuelsson et al. (2007) present three cases where the combination of an earth-tube system and the building ventilation system proved difficult to realize and at the same time be beneficial to the indoor environment and the energy demand. Both the benefits and drawbacks of an earth-tube system are discussed.

IEA Annex 28 (2001) presents an early design guide for (low energy) cooling by ground coupled air systems. IEA Annex 44 (2009) identifies Earth Coupling (Earth to Air Heat Exchanger) as one of five responsive building element technologies with future potential.

III. The effect of thermal mass on the energy use during the life cycle of a building

Energy use in the occupational phase of a building

Hagentoft (1997) shows the different thermal behaviours of a heavy and a light building, respectively. The study demonstrates the interaction between the structure of a building and the indoor temperature variations and how these variations influence the heating and cooling demands of a building. Adamson (1989) points out the importance of letting indoor temperature vary over a 24 hr period to allow heat storage (and extraction) in the building's structure. In a building where the structure consists of a material with a high heat capacity and where this structure is exposed to the interior, it is normally sufficient to allow the temperature to vary by a few degrees for the surplus heat to be stored (Hagentoft and Svensson 2000).

In different investigations, the energy demand of a building has been simulated to throw light on the difference between heavy and light structures. Isaksson and Kellner (1984) compare a light building with active heat storage with a thermally heavy building. They concluded that the internal heat gain is of great importance to whether the building's heat capacity can be used to store heat, as the internal heat gain must exceed 25 W/m² to give a considerable heat saving.

Södergren et al. (1992) are simulating the energy demands in warehouses with structures of different heat capacities. They conclude that the heat capacity of the building structure has almost no influence on the energy demands of the simulated buildings. More important factors are insulation, window area, sunscreens, ventilation etc.

Norén et al. (1999) calculate the annual energy demand for three types of building constructions with different thermal inertia. They use three simulation programmes TSBI3, BRIS and EN 832 and conclude that "the highest thermal inertia has the lowest energy demand and a small change in the thermal inertia has a relatively large influence" on the energy use.

Akander (1999) reaches the conclusion that the heating energy can be reduced by up to 15 percent in a building with a heavy structure compared to a building with a light structure. The compared buildings comply with the Swedish building regulations from 1995 (Boverket 1995). The saving is 5.6 percent of the purchased energy if heating, appliances, ventilation fans, and heating of water are included. Akander (1999) also calculates the equivalent U-value of similar buildings with different building envelopes. The equivalent U-value of a heavy building is higher compared to the U-value of a building with a light structure due to the expected heat storage. Akander used prEN 832 to calculate the energy demand; prEN 832 is a pre-version of the former European standard EN 832 that calculates the average monthly energy demand. prEN 832 uses the degree to which the internal heat gain has been used to estimate the buildings heat capacity. This variable shows how much of a possible heat surplus can be stored in the structure and then used when there is no surplus, e.g., from day to night.

Akander (2000) presents a new method in deciding the effective heat capacity that gives a more reliable result compare to the then suggested method of prEN ISO 13786. Akander models the thermal performance of multi-layer building components using optimised RC-networks.

Weber (2004) questions the reliability of the utilization factor of the European standard EN 832 when comparing it to measured energy use of a great number of low energy houses in Sweden and Germany. The calculated utilization factor had a better fit when the contribution of the time constant of the building is neglected. Jokisalo and Kurnitski (2007) adapt the reference numerical parameter α_0 and the reference time constant τ_0 to Nordic climate using the dynamic simulation tool IDA-ICE. These parameters are essential when calculating the utilization factor of ISO 13790.

Cole and Kernan (1996) are of the opinion that the energy use in an office building depends more on the internal heat gains than on how well it is insulated. They also think that it is the inner lining that is the most importance factor for the thermal properties of the building. An estimate of the magnitude of the interior surface resistance due to object such as carpets and bookshelves have been made by Hagentoft and Svensson (2000).

Energy use during the life cycle of a building

Many studies have been made of a building's energy demands, but only a few of the environmental impact of a building. To calculate a building's energy demands before it is built is quite a simple process, but the assessment is made more difficult by the fact that the habits of its users have a large impact on the energy consumption (Lundström 1982). The assessment and analysis of the environmental impact of a building during its whole life cycle is a comparatively new and complex science, but the tools and techniques are constantly improving.

Björklund and Tillman (1997) compare the environmental impact of structural concrete and wooden frames in dwelling and warehouses. They use three Life Cycle Assessment tools: Environmental Priority System for product design (EPS), Environmental Themes and Ecoscarcity. The estimated energy demand in the user phase is the same regardless of the heat capacity of the framework. Adalberth (2000) estimates the total energy use for seven residential buildings during their life cycle. The energy use in the occupational phase is calculated using ENORM, a non-dynamical but often-used calculation program. The conclusions were that the parameters that greatly influence the energy use of the studied building are: the choice of windows, the use of hot water and appliances, heat recovery from the exhaust air, and, if possible, reduced indoor temperature.

Burström (1999) has compiled available information regarding the length of life of different building materials. The work is primarily intended to be used in life cycle analyses and contains rules of thumb that can be used where well-defined length of life information is missing.

Cole och Kernan (1996) study the energy use in an office building during its whole life cycle, using three types of structure: concrete, steel, and wood. Nilson and Hjalmarsson (1993) and Nilson, Hjalmarsson and Uppström (1996) also study the energy use in office buildings of different age, locality, size and HVAC systems. One of their conclusions is that energy use is much lower in the newer buildings compared to the older, although, at the same time the use of electric energy has increased. The studies also show that the energy for lighting, office equipment, heating, ventilation and sanitary installations etc. can vary strongly in different buildings.

2 PERIODIC HEAT STORAGE IN A BUILDING UNIT – AN INTRODUCTION

In order to create a good indoor climate it is often necessary to heat or cool the building. The amount of heating or cooling that is required depends upon the local climate. It also often depends on the season, the time of the day, and the user's personal preferences. It is possible to store surplus heat in a building from one time of the day to another and thus lessen its heating and/or cooling demands and, at the same time, the indoor temperature variations. How much of the surplus heat that can be stored depends, among other things, upon the heat storage capacity of the building.

The heat capacity of the indoor air is far less than the heat capacity of the material of the surrounding floor, walls and ceiling. Therefore the indoor air temperature change~~s~~ more rapidly than the temperature of the surrounding surfaces. The difference in temperature will generate a heat transfer that will dampen the rapid change of the indoor temperature. In buildings, there is often a surplus of heat during daytime due to solar irradiation, household appliances and human activity. The indoor temperature rises due to the surplus of heat and thus the temperature of the building structure will also rise. During the night the surplus of heat will be less and the indoor temperature will decrease. The decrease in indoor temperature will be counteracted due to the fact that the temperature of the building structure now is higher than the indoor temperature. Heat is transferred from the building structure to the indoor air.

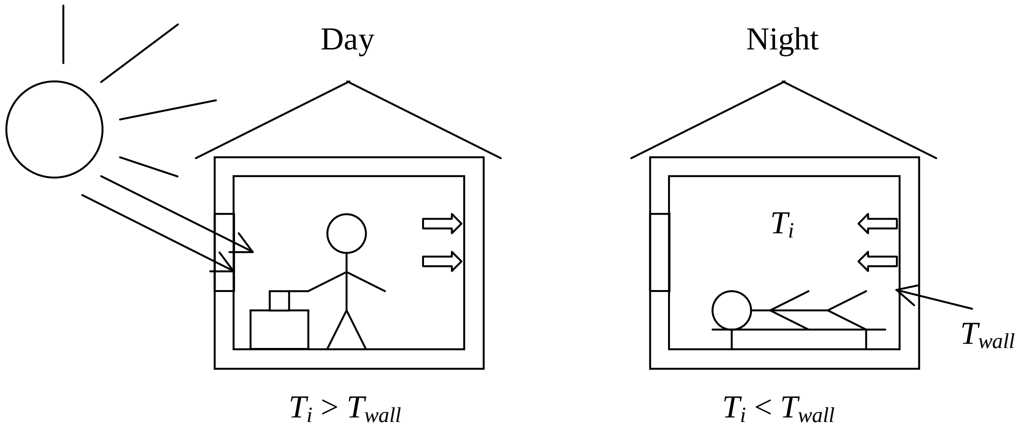

Figure 1. Part of the surplus heat during the day is stored in the building structure. The stored heat will heat the interior of the building during the night. The indoor temperature is denoted T_i and the temperature of the wall is denoted T_{wall}.

Heat storage in buildings is generated by heat transfer due to the temperature difference between the interior of the building and the building structure.

2.1 Heat balance of a building

Heat balance of a building is achieved when the heat gains equal the heat losses in the building.

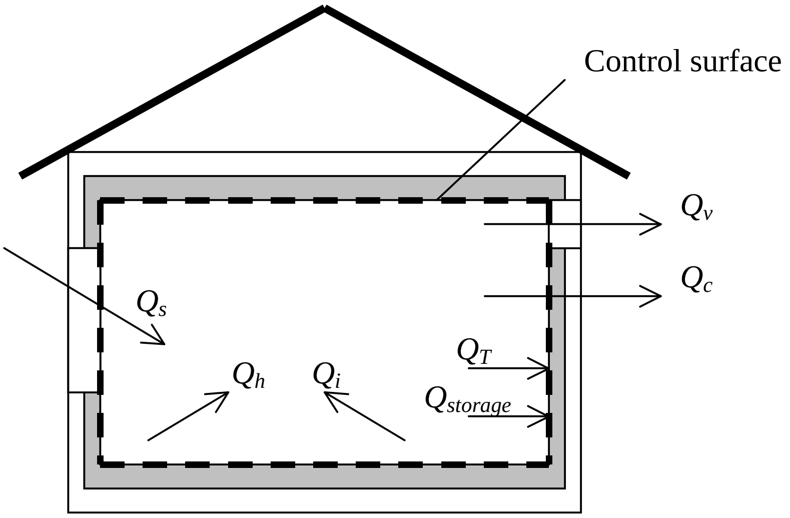

Figure 2. Heat balance of a building. The heat balance of a building is given by:

$$Q_h + Q_s + Q_i = Q_T + Q_v + Q_c + Q_{storage} \qquad (1)$$

where

Q_h	net heat use for space heating (W)
Q_s	solar gains (W)
Q_i	internal heat gains (metabolic heat and energy from appliances) (W)
Q_g	total heat gains ($Q_g = Q_i + Q_s$) (W)
Q_T	transmission losses (W)
Q_v	ventilation losses (W)
Q_c	heat losses through cooling or enhanced ventilation (W)
$Q_{storage}$	heat storage (W)

If the heat gains are greater than the heat losses the indoor temperature will rise. In the same manner the indoor temperature will decrease when the heat losses are greater than the heat gains.

2.2 The free-running indoor temperature in a heavy and in a lightweight building

The indoor temperature in a building, when the heating and cooling system is turned off, is denoted as the free-running (or undisturbed) indoor temperature. If there are no internal heat and solar gains in the building the average indoor temperature will be equal to the average outdoor temperature. In Figure 3 the free running temperature is shown for two simulated buildings. In the first building, left, the interior structure is made of a material with low thermal effusivity, which represents a light building. The thermal effusivity is a measure of the heat uptake capability of the material when the air temperature increases. The thermal effusivity is denoted by b ($W \cdot \sqrt{s}/m^2 \cdot K$) and is given by $b = \sqrt{\lambda \cdot \rho \cdot c}$. The thermal conductivity is denoted by λ (W/m K) and the volumetric heat capacity by $\rho{\cdot}c$ (J/m^3·K). In the second building, the thermal effusivity is much higher, which represent a heavy building.

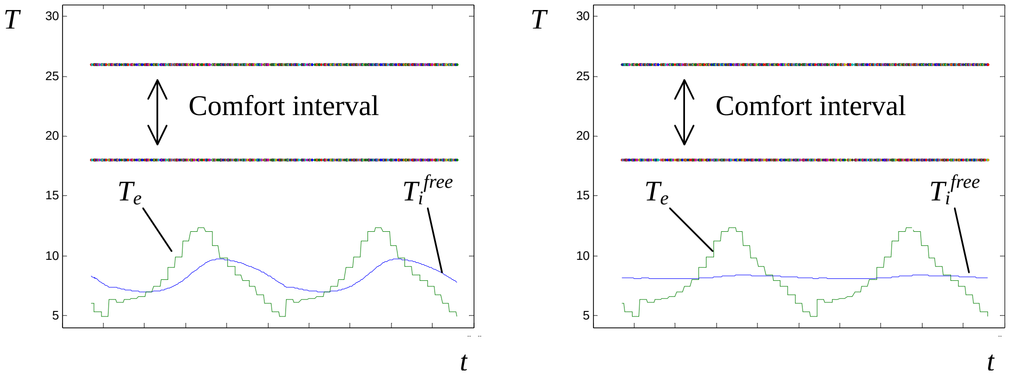

Figure 3. The simulated free running temperature T_i^{free} for a light (left) and a heavy (right) building. The outdoor temperature is presented as hourly values T_e. The comfort interval is 18 to 26°C. With no internal heat gain, the average indoor and outdoor temperature is 8.2 °C.

The U-value of these simulated buildings is the same in both cases. In the left-hand part of Figure 3 the free running indoor temperature is slightly dampened and delayed compared to the outdoor temperature. In the right-hand part of Figure 3, the free running temperature is strongly dampened and almost equal to the average outdoor temperature throughout the period. The two lines show the comfort interval at 18 and 26°C. The energy required for heating is equal in both cases but the maximum power of the heating system needs to be higher in the building with low thermal effusivity.

Figure 4 shows the same simulated buildings as in Figure 3, but, in this case, there is also a modest sinusoidal internal heat gain, superimposed on the average internal heat gain, with low amplitude bringing the average indoor temperature to 15°C.

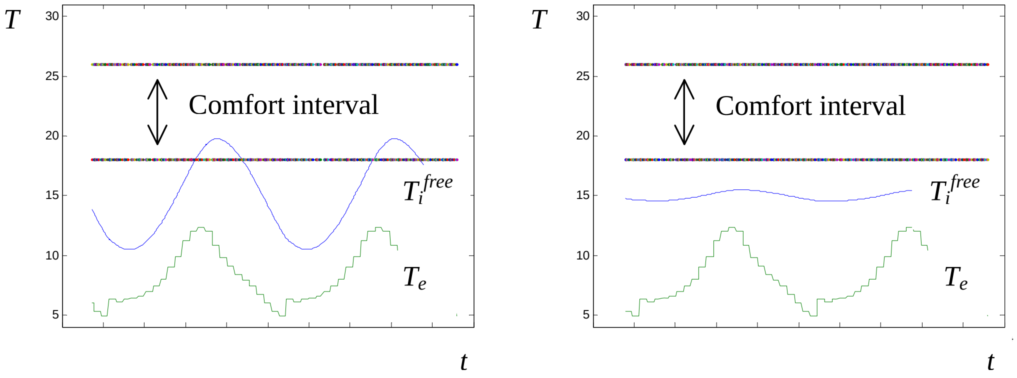

Figure 4. The simulated free running temperature T_i^{free} for a light (left) and a heavy (right) building. The average indoor temperature is 15 °C, with a sinusoidal internal heat gain.

The heating demand of the buildings in Figure 4 is less than in Figure 3, but the heating energy is still equal for both buildings. As before the power peaks will be higher in the building with low thermal effusivity.

In Figure 5 the sinusoidal internal heat gain is increased, which will bring the average indoor temperature to 22°C, the centre of the comfort interval. Due to symmetry the heating and cooling needs will be equal. The building with a low heat capacity structure, Figure 5 left, will need both heating and cooling. In contrast, the heavy building does not need any heating or cooling at all.

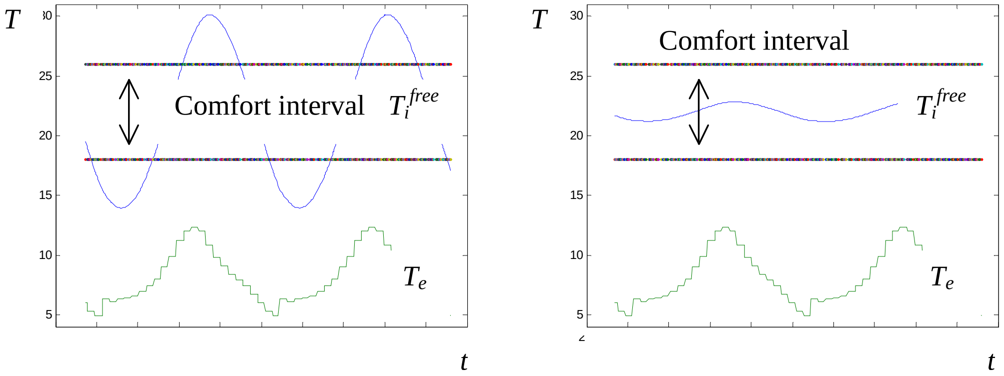

Figure 5 The simulated free running temperature T_i^{free} for a light (left) and a heavy (right) building. The average indoor temperature is 22 °C, with a sinusoidal internal heat gain.

3 ANALYTICAL MODELS FOR PREDICTING HEAT STORAGE IN A BUILDING STRUCTURE

Paper I presents two simplified tools to assess the potential for periodic heat storage in a building structure. Paper IV presents formulas based on the thermal response of a wall to a unit step of the indoor temperature. An overview of these tools is presented in this chapter: the first tool calculates the potential of periodic heat storage in a building material. The second tool analyse the heat recovery from an interior wall after an indoor temperature pulse. The third assesses the amplitude of the indoor temperature due to the material used in the building structure.

3.1 Superposition of periodic temperature processes

To be able to analyse heat storage in a building structure, the temperature variations have been simplified to periodic sinusoidal processes. The outdoor temperature T_e (°C) and indoor temperature T_i (°C) are given by:

$$T_e(t) = \overline{T}_e + T_e^A \cdot \sin\left(2 \cdot \pi \cdot t / t_p\right) \tag{2}$$

$$T_i(t) = \overline{T}_i + T_i^A \cdot \sin\left(2 \cdot \pi \cdot \left(t - t_{delay}\right) / t_p\right) \tag{3}$$

Where $\overline{T}_e$ (°C) is the daily, average outdoor temperature and T_e^A (°C) is the diurnal outdoor temperature amplitude. The time is represented by t (s) and t_p (s) the time period, i.e. 24 hours. The indoor temperature can be described in the same manner assuming that there are periodically varying heat gains. The time delay, in relation to the outdoor temperature variation, is denoted by t_{delay} (s).

These sinusoidal temperature variations can then be divided into simpler ones by the use of superposition techniques. In Figure 6 the temperature process is divided into one stationary case and two periodic cases with a pure sinusoidal temperature variation one side and zero temperature on the other side.

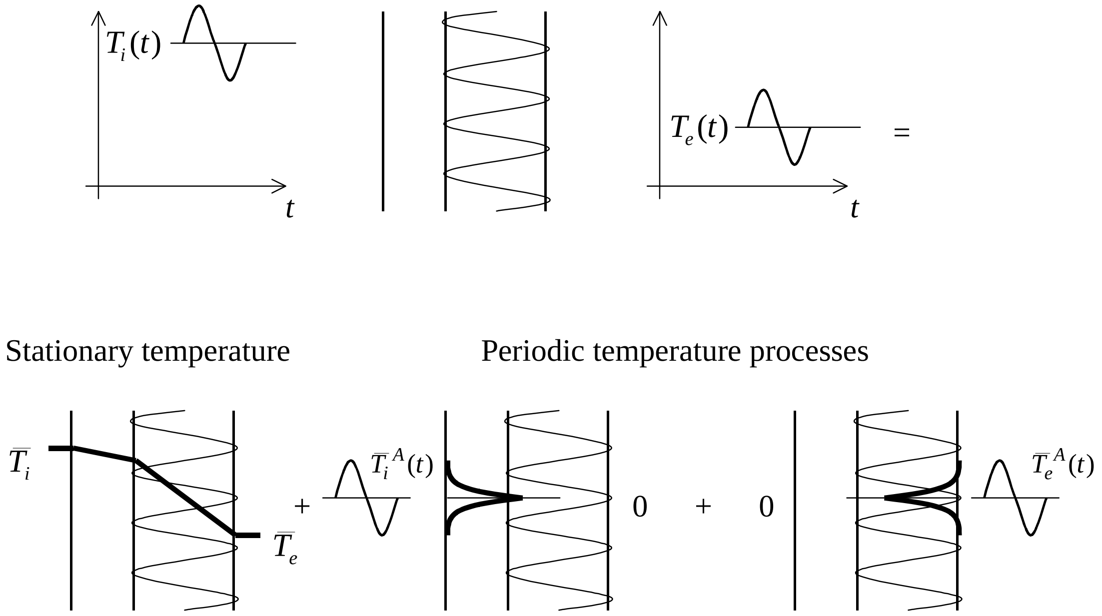

Figure 6. The temperature through the outer wall of a building is divided by superposition technique. The indoor temperature is denoted T_i and the exterior temperature is denoted T_e. The left bottom figure shows the average temperature distribution throughout the wall as a thick line. In the graphs in the middle and to the right the thick line shows how the maximum amplitude of the periodic temperature oscillations are dampened in the building component's inner and the outer layer.

The top graphs in Figure 6 show the outdoor and indoor temperature as simplified sine shaped oscillations with a 24 hr period. The left bottom figure in Figure 6 shows the average (stationary) temperature distribution throughout the wall as a thick line. In the graphs to the right the thick line shows how the maximum amplitude of the periodic temperature oscillations are dampened in the building component's inner and the outer layer, respectively.

3.2 Stationary heat balance – energy balance over a long time period

To calculate the energy demands of a building for periods much longer than its characteristic time, t_c (s), the average indoor and outdoor temperatures can be used. The characteristic time of a building is the time it takes for a temperature change inside a building to reach its stationary equilibrium.

$$t_c = \frac{\rho \cdot c \cdot V_s}{\left(A_e \cdot U + n \cdot V \cdot \rho_a \cdot c_a\right)} \tag{4}$$

Where

$\rho \cdot c$	volumetric heat capacity of the interior structure of the building (J/m^3·K)
V_s	the total volume of the interior structure (m^3)
A_e	the area of the external facing building envelope (m^2)
U	over-all thermal transmittance (U-value) (W/m^2·K)
n	air exchange rate (s^{-1})
V	the internal air volume of the building (m^3)
$\rho_a \cdot c_a$	the heat capacity of the air per unit volume (J/m^3·K)

The energy balance of a ventilated space over a long period of time is defined in Paper I. The heating demand E_h is given by:

$$E_\mathrm{h} = \left(A \cdot U + n \cdot V \cdot \rho_a \cdot c_a\right) \cdot \left(\overline{T}_i - \overline{T}_e\right) \cdot \left(t_b - t_a\right) + E_c - E_s - E_i \qquad (5)$$

$\overline{T}_i$	the average indoor temperature for the considered period (°C)
$\overline{T}_e$	the average outdoor temperature for the considered period (°C)
t_a	the beginning of the period (s)
t_b	the end of the period (s)

A (m²) denotes the envelope area, E_c (J) the cooling demand, E_s (J) the solar gains and E_i (J) the internal heat gains. This is often a good approximation to use, for example, to calculate the energy required to heat a building during the cold season.

3.3 Periodic penetration depth

Temperature oscillations at the surface of a material are increasingly dampened as they penetrate the material.

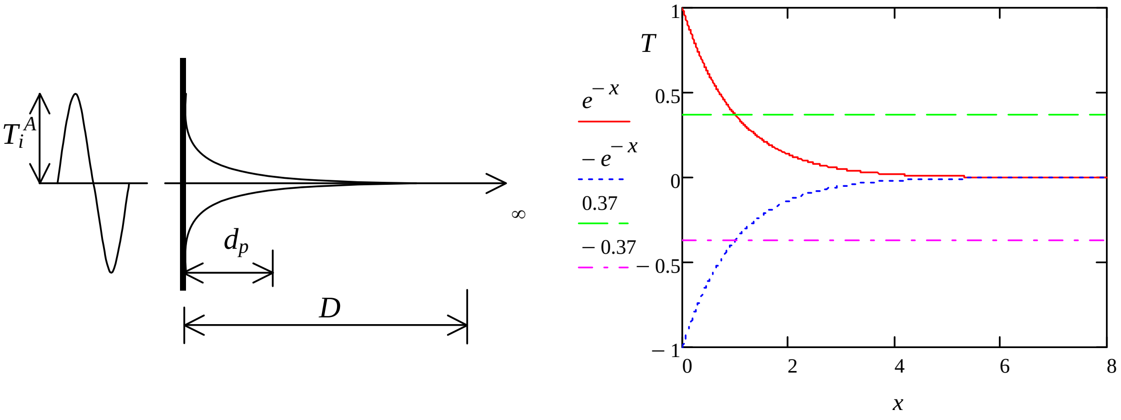

Figure 7. A temperature oscillation at the surface is dampened as it penetrates the material.

The period penetration depth is defined as that depth at which an oscillation at the surface has been reduced to 37 percent of its original amplitude; if sinusoidal, it can be described by the following formula:

$$d_p = \sqrt{\frac{\lambda}{\rho \cdot c} \cdot \frac{t_p}{\pi}} \qquad (6)$$

The dampening depends upon the thermal diffusivity a (m^2/s) of the material, given by $a = \lambda / \rho c$.

3.4 Periodic heat storage in a building material

A temperature change at the surface of a material generates a heat flow q (W/m^2), which tries to level out the temperature difference between the surface and the interior. This heat flow results in a periodic storage and release of energy, shown schematically in Figure 8.

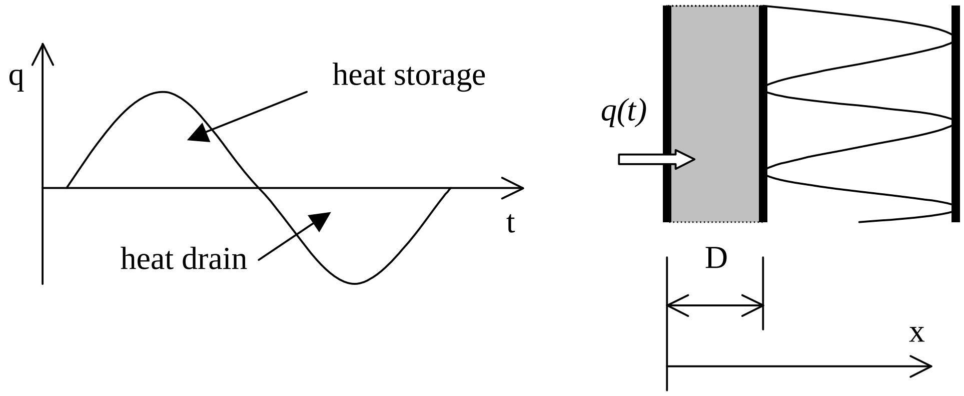

Figure 8. A changing heat flow generates a periodic storage and release of energy. The graph to the right shows a cross-section of a wall (right) where D is the heat-storing layer facing the interior followed by insulation.

In the simple drawing above, heat is stored in a building component (in this case, a wall) during the first half of the oscillation period. During the second half, heat is released from the component. Publication VII / Ståhl (2000) has shown that the effect of a temperature change at the exterior surface of a well-insulated construction on heat flow through the inner part of the construction is negligible compared to that of a temperature change at the interior surface. For this reason, this simplified model does not include any effects from external temperature changes.

3.5 Simplified models for predicting the heat storage in the interior structure of a building

Paper I and Publication VII / Ståhl (2000) presents a simplified model for predicting the heat storage in the interior structure of a building. For sinusoidal temperature variations the amount of energy E (J) stored in a material during one half of the cycle can be calculated by:

$$E = A \cdot T_i^A \cdot b \cdot \sqrt{\frac{2 \cdot t_p}{\pi}} \cdot \sigma^a\left(d/d_p, D/d_p\right) \qquad (7)$$

In Paper I the σ^a-factor is denoted by γ_a. The periodic penetration depth d_p (m) and the thermal effusivity b $(W \cdot \sqrt{s}/m^2 \cdot K)$ for some building materials are shown in Table 1 in

Paper I. The area of the building structure exposed to the interior of the building is denoted by A (m^2). The amplitude of the indoor temperature is denoted by T_i^A (°C) and the time period by t_p (s).

The simplified model above assumes zero heat flow through the outer insulation, which is replaced by an adiabatic layer. The heat flow q (W/m^2) is zero when $x = D$.

Figure 9 shows the factor σ^a (-) as a function of the thickness of the building structure D (m) divided by the periodic penetration depth d_p (m) for different values of d/d_p. The equivalent thickness of the surface resistance d (m) is given by $d = R_{si} \cdot \lambda$.

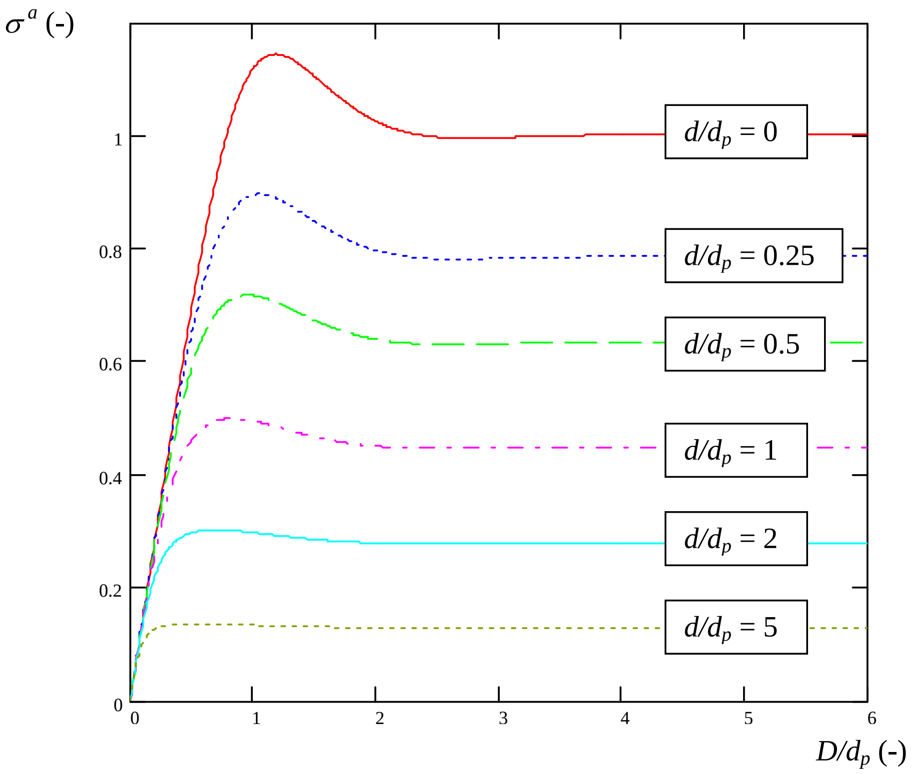

Figure 9. The factor σ^a (-) as a function of the thickness of the building structure D (m) divided by the periodic penetration depth d_p (m) for materials with different surface resistances, represented in the graph as the equivalent thickness of the surface resistance divided by the periodic penetration depth d/d_p.

As can be seen from Figure 9, the factor σ^a peaks when the thickness of the material about equals the penetration depth. Note, that any further thickening of the material does not improve its storage capacity. In the case where factor σ^a is greater than 1, this is due to mirror effects (reflexions) in the adiabatic layer.

The surface resistance is of great importance to how much energy can be stored. The top graph in Figure 9 shows the potential where there is no resistance (d/d_p=0). The surface resistance of concrete is 0.13 m^2·K/W, which gives a value of 1.47 for the factor d/d_p if the period is 24 hours; in this case, about 30 to 40 percent of the heat storage potential can be utilised.

Paper I presents a simplified model where the thickness D of the structure is assumed to be semi-infinite in which case the factor σ^s is given by Equation 6 in Paper I as:

$$\sigma^s\left(d/d_p\right)=1\Big/\sqrt{\left(1+d/d_p\right)^2+\left(d/d_p\right)^2} \qquad (8)$$

In Paper I the σ^s-factor is denoted by γ_S. The factors σ^s is a function of the dimensionless parameter d/d_p.

Example 1:

Let the exposed area A of the structure be 410 m², which is equal to the exposed area of the interior structure of the simulated cases in chapter 4. The surface resistance is 0.13 m²·K/W. The indoor temperature varies with amplitude T_i^A of 1°C and the period t_p is 24 hours. The penetration depth d_p and the thermal effusivity b can be taken from Table 1 in Paper I. Equation 7, where the insulation is approximated by an adiabatic layer, gives the amount of energy that can be stored in the structure. The corresponding thickness d (m) is given by $d = R_{si}\cdot\lambda$ for each material. The factor σ^a can be taken from Figure 9. Table 1 then gives the energy that is stored in the structure for some material.

Table 1. Heat storage potential for five building materials calculated using the semi-infinite E^s and adiabatic solution E^a of Example 1. The storage occurs during one half of the cycle and is driven by a temperature change of 1^o C.

Material	D (m)	E^s (kWh)	D (m)	E^a (kWh)
Concrete	∞	17.23	0.15	18.79
Brick	∞	13.05	0.15	14.01
Wood	∞	6.55	0.15	6.65
Lightweight concrete	∞	5.83	0.15	6.18
Mineral wool	∞	1.53	0.15	1.72

3.6 Thermal buffering capacity of interior walls – formulas from step-response analyses

In Paper IV a detailed and particular analysis of the thermal storage in internal wall structures is presented. Figure 10 illustrates the considered situation for a typical day. During the period of surplus heat, the indoor temperature is allowed to rise above T_{in}. The temperature $T_+(t)$ above T_{in} will provide an extra heating of the thermal envelope through the indoor surfaces. This injected surplus heat is in a dynamic way stored in the walls. The indoor temperature is kept at T_{in} after the injection period by heating when necessary. The required heating is reduced by the backflow from the walls of injected heat. Heating is most needed during the coldest period around midnight when the outdoor temperature $T_{out}(t)$ is low. There is an intermediate storage period essentially without heating during the time t_s. The required heating during the time t_r is diminished by recovered heat from the injection period.

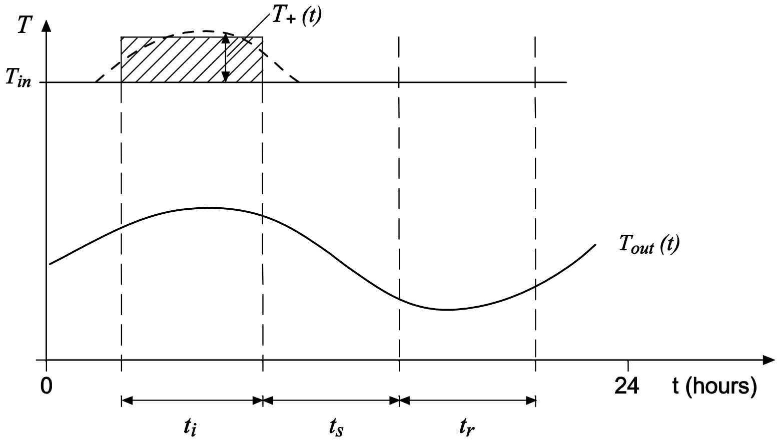

Figure 10 Indoor and outdoor temperature during a day. Injection of surplus heat during the time t_i and, after a storage period t_s, heat recovery during a night period t_r.

The recovered heat e_r (J/m^2) reduces the heating demand during the night by this amount e_r. The paper focuses on the thermal response for any unit area of an interior wall of any material. The analyses are based on the response to a unit indoor temperature step. The corresponding accumulated heat $e(t)$ in the wall is a key tool of analysis.

The exact solution, $e(t)$, for a homogeneous indoor wall with a surface boundary layer is presented using Laplace transforms (for short times) and Fourier series (for longer times). The heat recovery factor is here defined as the recovered heat divided by the heat capacity of the unit wall area:

$$f = \frac{e_\mathrm{r}}{C}, \qquad C = \rho\, c L; \qquad f = \frac{\bar{T}_+ \cdot e_\mathrm{r}}{\bar{T}_+ \cdot C}. \tag{9}$$

The factor f gives the recovered heat as a fraction of the maximum heat that can be stored in the wall. It is independent of the magnitude of the temperature step $\bar{T}_+$, since this magnitude occurs both in the nominator and denominator.

The recovered heat is given by

$$e_\mathrm{r} = e(t_s + t_\mathrm{i}) + e(t_s + t_\mathrm{r}) - e(t_s) - e(t_s + t_\mathrm{i} + t_\mathrm{r}) \tag{10}$$

The formula is obtained from a superposition of two temperature steps as explained in Paper IV.

The simplest possible approximation of the thermal behavior of the wall is to represent it by a lumped mass. The temperature within the wall is represented by a value at a single node. It is shown in the paper that the best choice is to put the node at the distance $L/3$ from the wall surface (the total thickness of the symmetric wall is $2L$). The following simple formula for $e(t)$ is obtained in the lumped-mass approximation:

$$e_{\mathrm{m}}(t) = C \cdot \left(1 - e^{-k \cdot t}\right), \qquad k = \frac{a}{L \cdot \left(d + L/3\right)}. \tag{11}$$

The parameter d (m) is a measure of the surface resistance. A layer of the wall material with the thickness d has the same resistance as the surface boundary layer: $1/\alpha = d/\lambda$. The lumped-mass approximation with its important time constant $1/k$ is shown to be remarkably good in the present applications.

A handy formula for e_{mr} is obtained in the lumped-mass approximation from the above formulas for e_{r} and $e_{\mathrm{m}}(t)$:

$$e_{\mathrm{mr}} = C \cdot \left(e^{-k \cdot t_{\mathrm{s}}} + e^{-k \cdot (t_{\mathrm{s}} + t_{\mathrm{i}} + t_{\mathrm{r}})} - e^{-k \cdot (t_{\mathrm{s}} + t_{\mathrm{i}})} - e^{-k \cdot (t_{\mathrm{s}} + t_{\mathrm{r}})}\right). \tag{12}$$

The heat recovery factor $f = e_{\mathrm{mr}}/C$ becomes in the lumped-mass approximation:

$$f(k; t_{\mathrm{i}}, t_{\mathrm{s}}, t_{\mathrm{r}}) = e^{-k \cdot t_{\mathrm{s}}} \cdot \left(1 - e^{-k \cdot t_{\mathrm{i}}}\right) \cdot \left(1 - e^{-k \cdot t_{\mathrm{r}}}\right). \tag{13}$$

The heat recovery factor involves the product of three exponential factors. The formula shows in a very clear way the influence of t_{i}, t_{s} and t_{r}.

The above heat recovery factor f attains a maximum at a certain k for constant times t_{i}, t_{s} and t_{r}. This maximum, which depends on these times or on $\tau_{\mathrm{i}} = t_{\mathrm{i}}/t_{\mathrm{av}}$ and $\tau_{\mathrm{r}} = t_{\mathrm{r}}/t_{\mathrm{av}}$, with $t_{\mathrm{av}} = t_{\mathrm{s}} + (t_{\mathrm{i}} + t_{\mathrm{r}})/2$, provides a handy upper limit for the amount of heat that can be buffered and then recovered for any choice of the three times. See Figure 11. The value of k at which the maximum is attained is also a function of τ_{i} and τ_{r}. Typical values for the times t_{i}, t_{s}, and t_{r}, are 4, 8, 4 hours, respectively: $f(1/3, 1/3) = 0.063$. Only at most 6.3 % may be recovered whatever the parameters of the wall are.

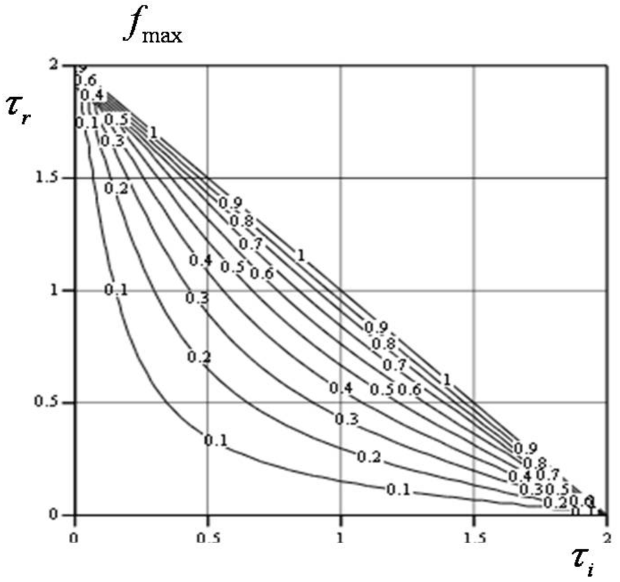

Figure 11. The maximum heat recovery $f_{\max}(\tau_{\mathrm{i}}, \tau_{\mathrm{r}})$.

Example 2:
An office is mechanically cooled during all weekdays due to high internal gains. The indoor temperature is kept constant 20 ºC. In order to reduce the cooling demand, free cooling, by high ventilation rates during the weekends are used. This can reduce the cooling demand from Monday to Friday. During the weekends the temperature is kept at constant 17 ºC. Data for this case is presented in Chapter 9.1 in Paper IV and Table 9.4 in Paper IV shows the reduced cooling demand day by day during the week, as a consequence of the weekend lowered indoor temperature. The total stored cooling energy at the end of the weekend was 23.832 kWh. Almost all of the stored cooling energy, 99.9 %, was recovered during the first day.

3.7 Simplified models for predicting the interaction between the indoor temperature and the thermal mass of a building

A ventilated space is described with the help of thermal circuits in Figure 3 in Paper I. The circuits describe the thermal properties of the space when it is subjected to periodic temperature changes. The indoor temperature amplitude can be derived from the heat balance equation of the ventilated space (Publication VII / Ståhl 2000):

$$T_i^A = \left(T_e^A + \frac{Q^A}{K_{wv}} \right) \cdot \beta_i \left({}^{d}\!/_{d_p}, {}^{D}\!/_{d_p}, {}^{d_2}\!/_{d_p}, \ldots \right) + T_e^A \cdot \beta_e \left({}^{d}\!/_{d_p}, {}^{D}\!/_{d_p}, {}^{d_2}\!/_{d_p}, \ldots \right) \qquad (14)$$

where $T_{\mathrm{e}}^{\mathrm{A}}$ (C°) is the outdoor temperature amplitude and Q^A (W) the internal heat emission amplitude. The combined conductance for windows and ventilation, K_{wv} (W/K), is given by:

$$K_{wv} = U_w \cdot A_w + n \cdot V \cdot \rho_a \cdot c_a \qquad (15)$$

where A_w (m²) is the total surface area of the windows and U_w (W/m²·K) their U-value.

The damping factor β_e for the external driving force is much smaller than β_i, which is why its influence on the indoor temperature normally can be ignored (Publication VII / Ståhl 2000). Although the damping factors β_e and β_i do depend on more parameters than here discussed, if the insulation thickness and the surface resistance is know, the damping factors are functions of the three dimensionless parameters d/d_p, D/d_p och d_2/d_p. The parameter d_2 (m) describes the structure's thermal conductivity and area in relation to the inflow of heat via windows and ventilation:

$$d_2 = \frac{\lambda \cdot A}{K_{wv}} \tag{16}$$

Equation (9) in Paper I shows an approximation where the insulation is considered an adiabatic layer. The internal dampening factor of this approximation is denoted β_i^a and is shown in Figure 12 for some common building materials. The exposed area is 410 m² and the surface resistance R_{si} is 0.13 m²·K/W. The window area A_w is 26.2 m^2, the air exchange rate n is 0.5 h^{-1}, and the volume of the building V is 407 m^2.

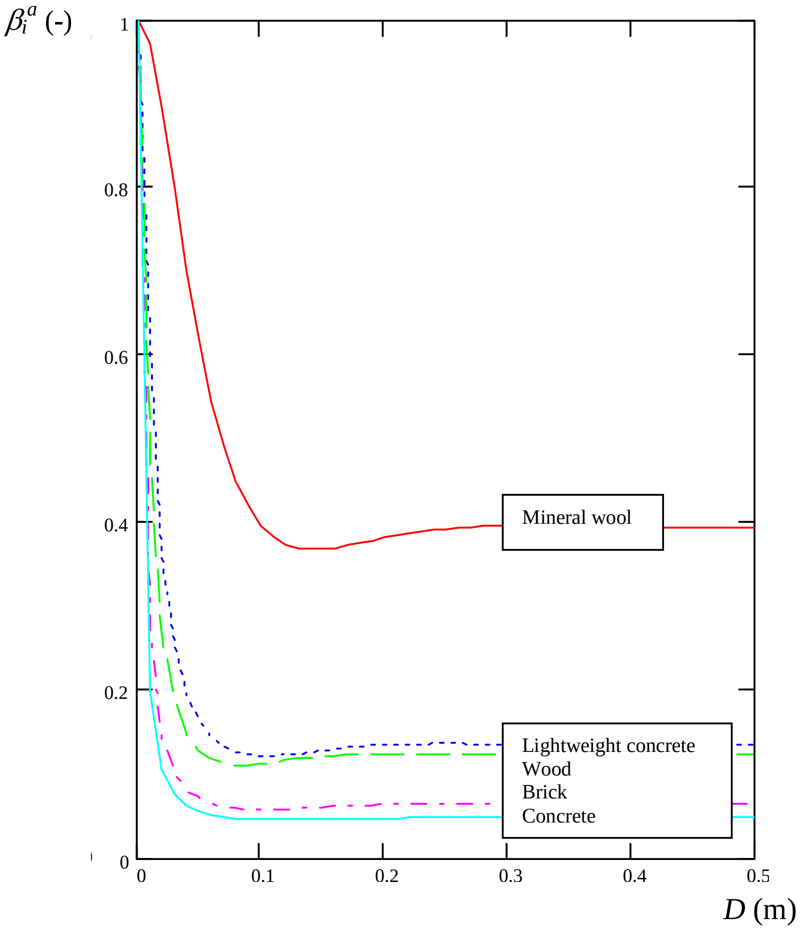

Figure 12. The temperature damping factor β_i^a as a function of the thickness of the innermost layer of the building structure.

Example 3:
Table 2 shows the amplitude of the indoor temperature T_i^A for a ventilated space using different material in the building interior structure and using two approximations of the dampening factor β_i. The window area A_w is 26.2 m² and its U-value U_w is 1.9 W/m²·K. The air exchange rate n is 0.5 h^{-1}, the volume of the building 407 m³, and the volumetric heat capacity $\rho_a \cdot c_a$ is set to be 1200 J/m³·K. The internal heat gain amplitude Q_g^A is set to 1740 W and the outdoor temperature T_e^A to 3° C. The inner layer of the structure, D, is 0.15 m. Other data are the same as those in Example 1.

Table 2. Values used for the dimensionless parameters determining β_i for different structures in Example 3 and the results of using the two approximate solutions for β_i expressed by the amplitude of the indoor temperature.

Material	d/d_p (-)	D/d_p (-)	d_2/d_p (-)	β_i^s (-)	β_i^a (-)	T_i^A (°C)
Concrete	1.41	0.96	37.82	-	0.046	0.885
		∞		0.05	-	0.815
Brick	0.71	1.36	18.91	-	0.061	1.154
		∞		0.065	-	1.08
Wood	0.24	2.00	6.51	-	0.121	2.191
		∞		0.123	-	2.16
Lightweight concrete	0.21	1.63	5.67	-	0.129	2.416
		∞		0.136	-	2.29
Mineral wool	0.047	1.357	1.261	-	0.369	7.03
		∞		0.395	-	6.559

The factors β_i^s and β_i^a are calculated using Equations (8) and (9) in Paper I or taken from a β-diagram for each material and dependent on the quotients d/d_p, D/d_p och d_2/d_p. β_i^s denotes an approximation where the thickness of the interior structure D is considered semi-infinite. The amplitude of the indoor temperature T_i^A for both approximations can be calculated using Equation 14. As before, β_e is ignored.

In this example, a structure using concrete or brick is to be preferred as the indoor temperature amplitude is the lowest when these materials are used. The example also shows a construction with mineral wool exposed to the building's interior; this is not normal procedure as the wool is commonly covered by plasterboard or similar which dampens the indoor temperature variations.

4 NUMERICAL SIMULATIONS – CASE STUDIES

This section presents three case studies where the heating and cooling demands of one or several buildings have been simulated. The first case study (Paper II) focuses on the choice of material, and its thickness, for the structure of the building, and on the comfort interval and internal heat gains of the building and their influence on the heating and cooling demands during one 24 hours period. The second case study (Paper III) focuses upon the choice of ventilation strategy and its influence upon heating demands. The third case study (Paper VI) presents the simulated heating and cooling demands during 1 year in four different types of buildings: a terrace house, a school, a block of flats, and an office building. Each building type is presented in two versions, one with a heavy structure of good heat storage capacity and another with a lighter structure and poorer heat storage capacity.

4.1 Influence on the heating and cooling demand by choice of thermal mass and comfort interval

In this study, the International Building Physics Toolbx IBPT (Sasic Kalagasidis 2004) is used to calculate the heating and cooling demands of a building. Figure 13 shows schematically the simulated building unit as part of a larger building.

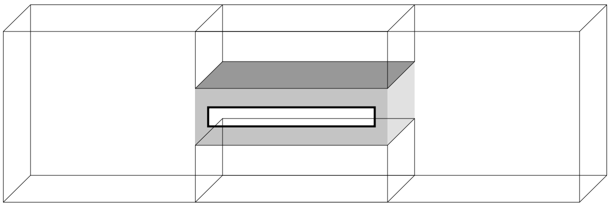

Figure 13. The position of the simulated unit within the larger multi-storey building.

The simulated volume could be a part of an office building or a large apartment in block of flats. In the simulations, the shell of the unit consists of one exterior wall, one window and one interior wall representing interior partitions (i.e. floor and ceiling in this model) and the party walls to the apartments on either side. The exterior wall consists of two layers: an outer, insulating, layer and an inner one. The interior partitions are constructed from the same material as the inner layer of the exterior wall, but – thanks to symmetry – the thickness is halved and the wall (or floor) is covered with an adiabatic layer with zero heat flow. The properties and thickness of the material of the inner layer (of both the exterior and the adiabatic walls) vary according to Table 3 and 4 in Paper II. The thickness of the insulation on the exterior wall varies so that a constant U-value for the wall (0.162 W/m^{2}K) is maintained in all cases. The U-value of the window is 1.9 W/m^{2}K. Table 2 in Paper II lists surface areas and thermal data for the climate shell for the simulated building. The floor area of the building unit is 150 m^2.

The ventilation rate is constant during the 24 hour of the day at 0.5 h^{-1} for each basic case, although some cases have been added where the ventilation rate is 0.25 and 1.0 h^{-1}, respectively. Total internal gain is given by ($Q_i + Q_s = Q_g$):

$$Q_g = Q_0 \cdot (1 + \sin(2 \cdot \pi \cdot (t - t_{delay})/t_p)) \tag{17}$$

where Q_0 = 0, 479, 857, 1740, 2244 and 2370 W. The internal gain is shown in Figure 14.

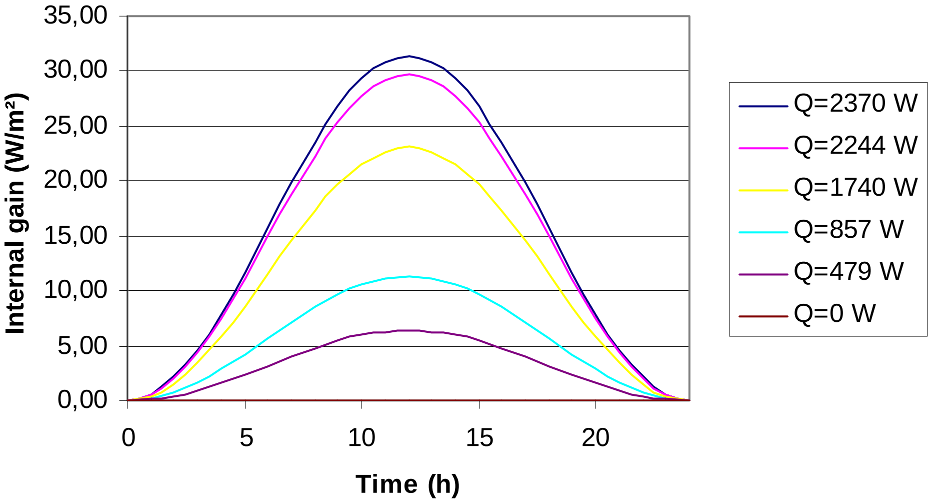

Figure 14. The internal gain during one day.

Three comfort intervals for the indoor temperature T_i have been used: 21 - 23 °C, 20 – 24 °C and 18 – 26 °C. To keep the temperature within acceptable range both heating and cooling might be required. The heat generated by the simulated Heater/Cooler is always sufficient to keep the temperature within the comfort interval.

The outdoor temperature during one 24-hour period is taken from a reference year in Copenhagen, Figure 15. Mean outdoor temperature is 8.2°C for one day, the 15th of May.

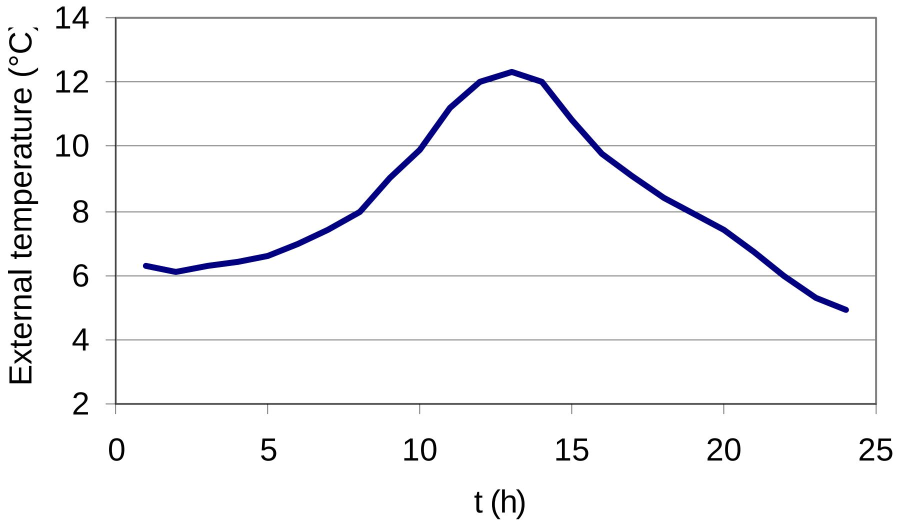

Figure 15. The outdoor temperature during the 15th of May from a reference year for Copenhagen.

The basis of the parameter study is 13 basic cases with different internal heat gain and comfort interval, see Table 7 Paper II. This has been complemented with 3 plus 3 cases where the ventilation rate n is 0.25 and 1.0 h^{-1}, respectively. As well as with 2 further cases with 7 types of building materials using two different comfort intervals. The result of this part of the cases study is shown in chapter 5.1.

4.2 Influence on the heating demand by choice of ventilation strategy

In this case study, too, the International Building Physics Toolbx IBPT is used to calculate heating and cooling demand of a building. Area, volume, surface resistance, and radiation exchange are the same as for the IBPT model in section 4.1. The unit consists of one external wall, one window, and one adiabatic wall.

What is different in this case is that the body of the building consists of one of three specific materials; i.e. granite, wood and mineral wool. These represent materials with high, medium, and low heat storage capabilities. However, as before, the thickness of the interior layer of the building varies in seven steps, see Table 2 in Paper III.

In all cases, as Q_0 = 1740 W, the internal heat gain is given by Equation (17). The gain has been chosen in order to achieve an average free running temperature of temperature of 22°C; this lies in the middle of the comfort interval $20 \leq T_i \leq 24$°C. Climate data are the same as in the previous model (Section 4.1).

In this study, 9 different ventilation strategies have been used: in the first strategy, the ventilation rate is constant at 0.5 h^{-1}; in the remainder, the ventilation rate varies during the 24-hour period, with an average of 0.5 h^{-1}. The ventilation rate increases during the day in four cases, and in the night for the remaining 4; the lowest rate for these 8 cases is 0.2 h^{-1}. The chosen ventilation strategies include both increased ventilation during the day to meet the internal gains and increased ventilation during the night to pre-cool the interior structure. Figures 16 and 17 show the different ventilation strategies.

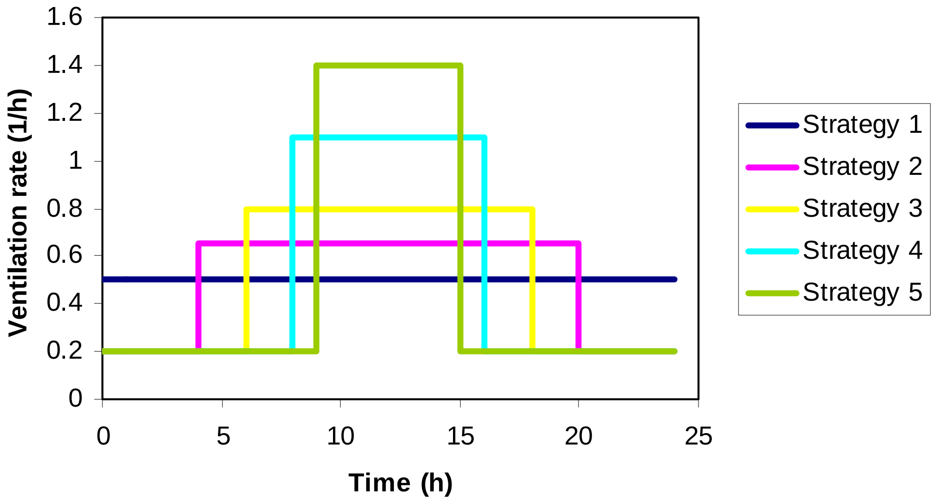

Figure 16. Ventilation strategies 1 to 5.

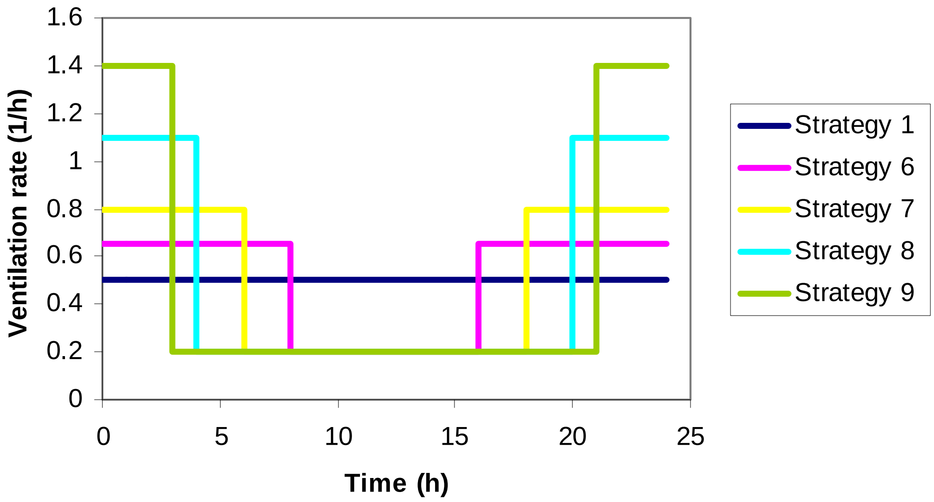

Figure 17. Ventilation strategies 1, and 6 to 9.

The result of this part of the cases study is shown in chapter 5.2.

4.3 Heating and cooling demand of a building during one year – Occupation phase

In this case study, the heating and cooling demand of four different types of building during one year is calculated with the help of the energy calculation program Derob-LTH. This program allows a more detailed description of the building components, and also that the building can be divided into several volumes or units. Climate data used by the simulations were recorded in Lund in 1988. The study is summarised in Paper VI and discussed in more detail by Ståhl (2000).

The four building types that have been simulated are: a terrace house, a block of flats, a school and an office building. In each case, two versions of the building type have been simulated. The first version has a thermally heavy structure and the second a thermally light one. The climate shell has the same U-value for both versions. The internal heat gains and ventilation strategies have been adjusted so they reflect the function of each building type. In each case, simulations with a 30 percent poorer and a 30 percent better U-value of the building envelope has been done (excepting the windows which all have the same U-value.)

The terrace house has two storeys with a total area of 148.5 m^2. The U-value of the building is 0.261 W/m^{2}K. The ventilation rate remains constant at 0.5 h^{-1} for the whole 24-hour period. The internal heat gain is equivalent to 2 adults and 2 children, including appliances. The internal gain varies during the 24-hour period, but its average value is 2.89 W/m^2 during weekdays and 3.82 W/m^2 during the weekend.

The simulated block of flats is of 4 storeys, each containing 2 flats of 75.4 m^2. The U-value of the building is 0.327 W/m^{2}K, and the ventilation rate remains constant at 0.5 h^{-1}. The internal gain equates to 1 adult and 1 child per flat, it varies, but the average value is 2.85 W/m^2 during weekdays and 3.76 W/m^2 during the weekend.

A simulated classroom, placed in the southeast corner of a four classroom one-storey building, represents the school. The classroom is 60.2 m^2 and the U-value is 0.217 W/m^2K. During the day the ventilation rate is 2.9 h^{-1} and the internal gain 32.9 $W/m^{2,}$ at other hours the gain is zero and the ventilation rate 0.1 h^{-1}.

The office has 4 storeys, each of 150.8 m^2. The U-value is 0.327 W/m^2K. During daytime the ventilation rate is 0.7 h^{-1} - and it remains at this value during daylight hours of the weekend as well - and the internal load is 27.2 W/m^2.

Each building type comes in two versions: one with a heavy and one with a light structure. The heavy structure consists of a concrete floor structure in ceiling and floors, concrete outside walls and a concrete basement slab (except for the terrace house where the outside wall is made of brick), for further details see Ståhl (2000). The light versions consists of a timber frame covered in plasterboards on the interior and mineral wool insulation; the floor between the two storeys is covered by plasterboard on the underside and by chipboard on the top; in all light structures the basement slab is made of concrete.

5 RESULTS AND ANALYSES OF CASE STUDIES

This chapter shows the most important results from the case studies presented in chapter 4.

5.1 Influence on the heating and cooling demand by choice of thermal mass and comfort interval

Figure 18 shows the heating demand of the simulated building as a function of the thickness of the structure divided by its periodic penetration depth. The internal gain is given by Equation 17 when Q_0 = 857 W and the comfort interval is 20 – 24°C. The average free running indoor temperature is 14.9 °C when the internal gain is 857 W.

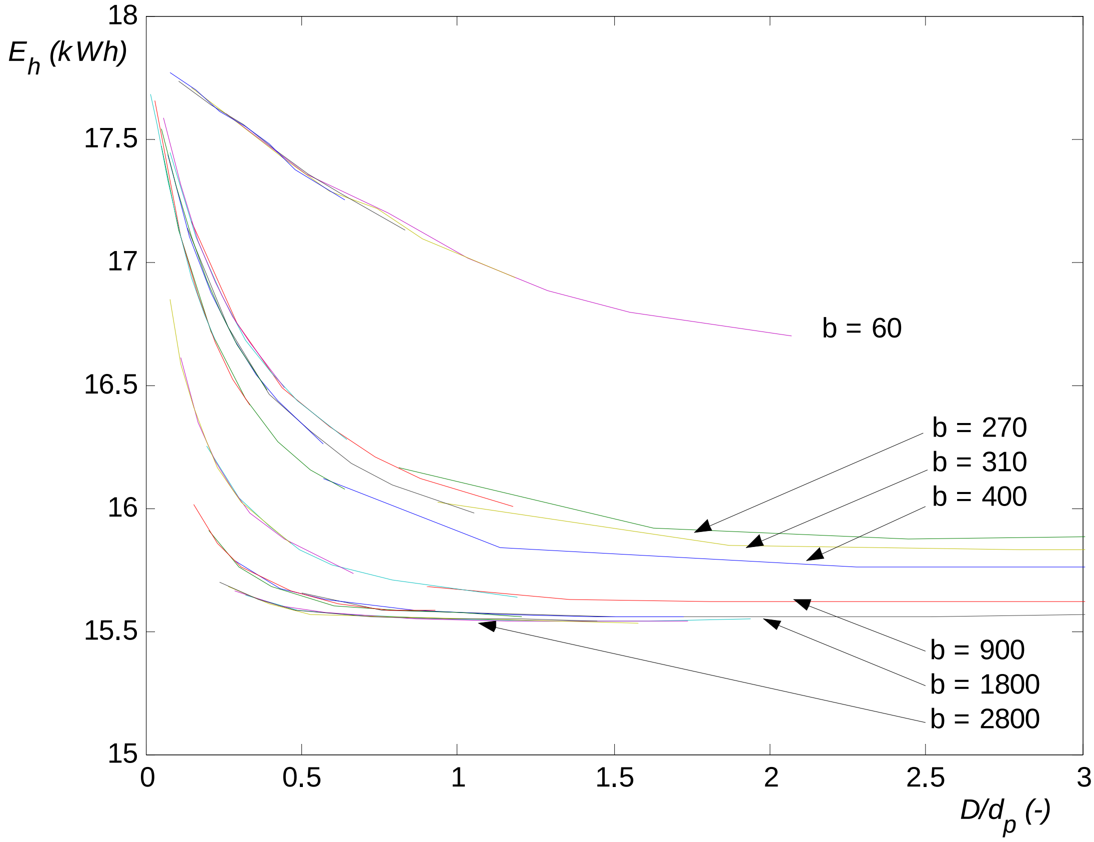

Figure 18. The heating demand E_h (kWh) of the simulated building as a function of the interior structure thickness D divided by the periodic penetration depth d_p when the average internal gain is 857 W and the comfort interval is 20 - 24 °C.

Figure 18 shows seven “clusters” of curves with different thermal effusivity b $(W \cdot \sqrt{s/m^2} \cdot K)$. Each cluster contains four curves with the same thermal effusivity but where the heat conductivity and the heat capacity per unit volume vary according to Table 3 in Paper II. The graph shows that the energy demand of the simulated building remains approximately the same where the thermal effusivity is the same irrespective of heat conductivity and capacity per unit volume. The graph also shows that the heating demand decreases with increased thermal effusivity. The demand decreases with increasing thickness of the structure, although it levels out when the thickness approaches the periodic penetration depth of the material.

Figure 19 - 22 shows the heating demand of the simulated building when the average internal gains are 479, 827, 1740 and 2244 W; as before the comfort interval is 20 – 24°C.

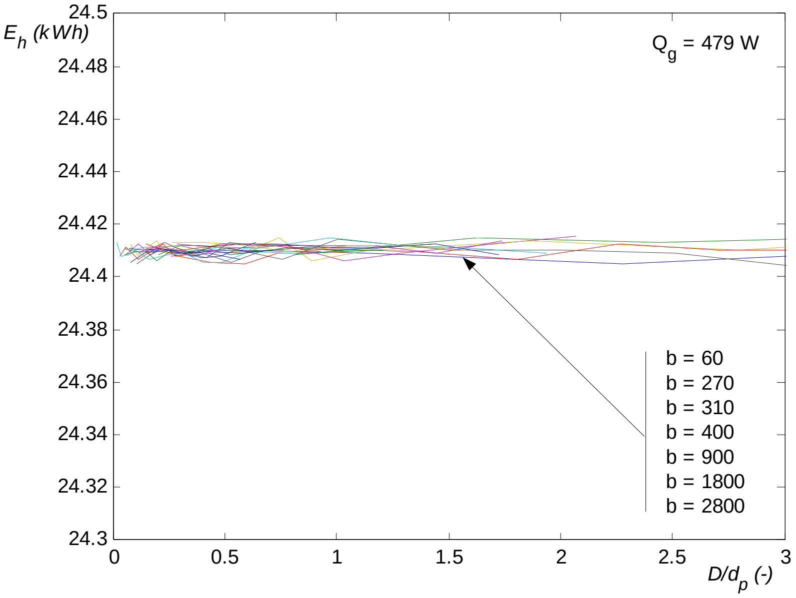

Figure 19. The heating demand E_h (kWh) of the simulated building as a function of the interior structure thickness D divided by the periodic penetration depth d_p when the average internal gain is 479 W and the comfort interval is 20 - 24 °C.

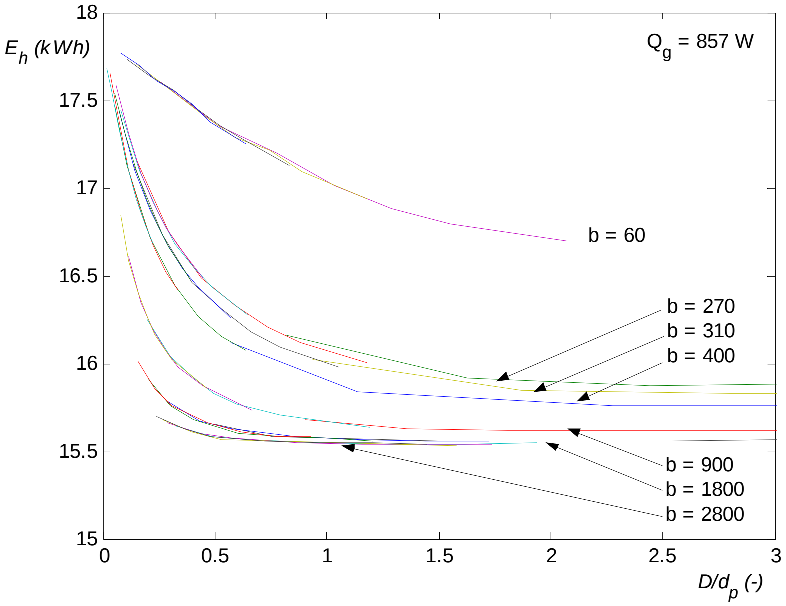

Figure 20. The heating demand E_h (kWh) of the simulated building as a function of the interior structure thickness D divided by the periodic penetration depth d_p when the average internal gain is 857 W and the comfort interval is 20 - 24 °C.

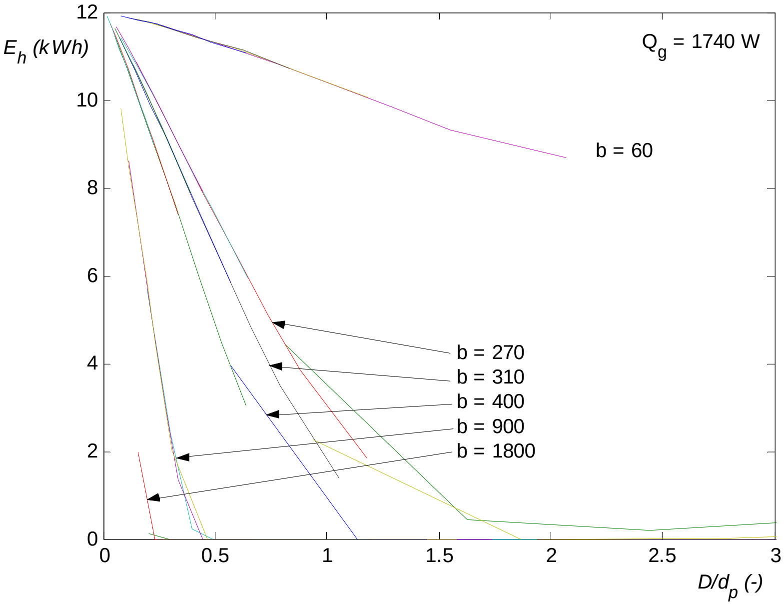

Figure 21. The heating demand E_h (kWh) of the simulated building as a function of the interior structure thickness D divided by the periodic penetration depth d_p when the average internal gain is 1740 W and the comfort interval is 20 - 24 °C.

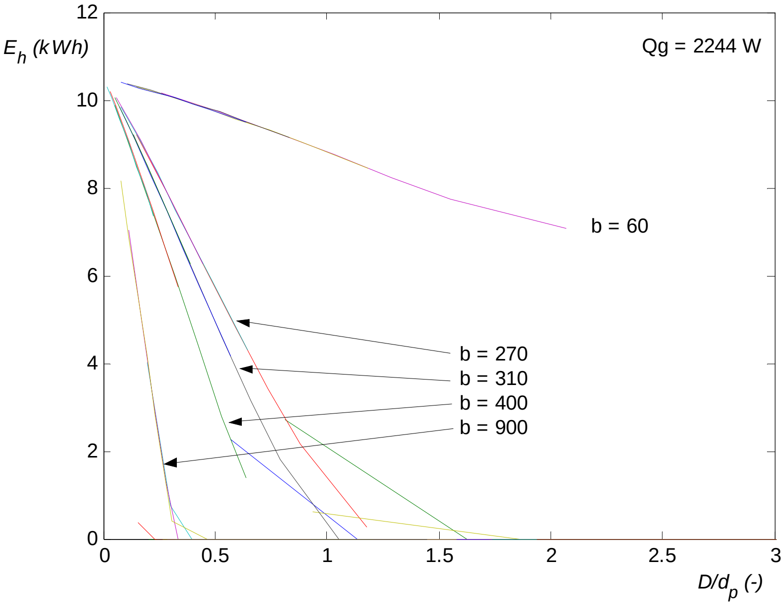

Figure 22. The heating demand E_h (kWh) of the simulated building as a function of the interior structure thickness D divided by the periodic penetration depth d_p when the average internal gain is 2244 W and the comfort interval is 20 - 24 °C.

The heating demand decreases as the internal heat gain increases. When the internal gain is low (479 W) the heating demand is the same irrespective of what material the inner layer of the structure is made of. However, when the internal gain increases, the thermal effusivity and the thickness of the inner layer of the structure become increasingly important for the energy demand. High thermal effusivity means lower energy demand if the internal gain is high. Figure 23 and 24 shows the cooling demands in two cases.

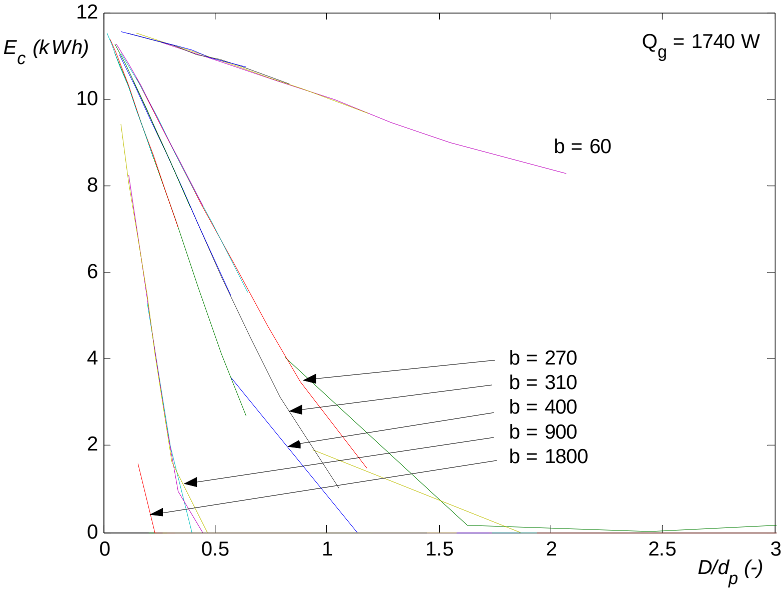

Figure 23. The cooling demand E_c of the simulated building as a function of the interior structure thickness D divided by the periodic penetration depth d_p when the average internal gain is 1740 W and the comfort interval is 20 - 24 °C.

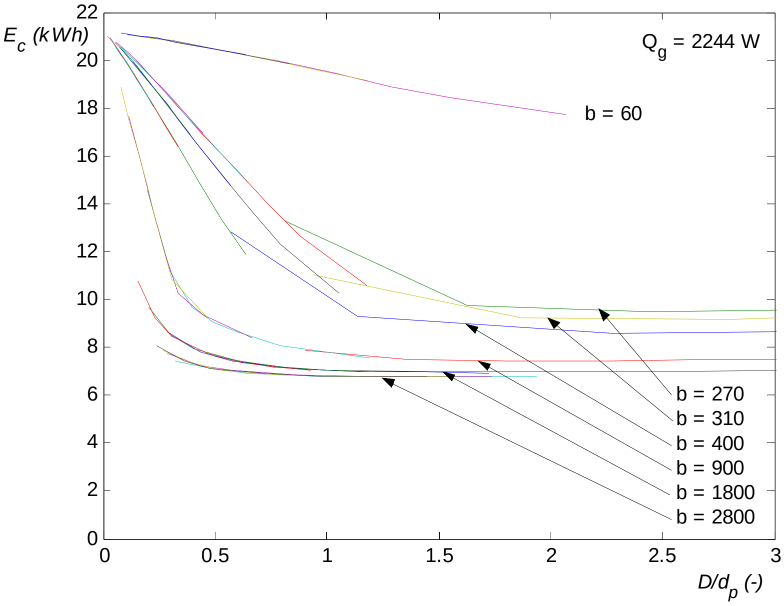

Figure 24. The cooling demand E_c of the simulated building as a function of the interior structure thickness D divided by the periodic penetration depth d_p when the average internal gain is 2244 W and the comfort interval is 20 - 24 °C.

The cooling demand is the same as the heating demand when the internal gain is 1740 W because the mean temperature is then 22°C – exactly in the middle of the comfort interval. When the internal gain is increased to 2244 W, the cooling demand increases sharply compared to the modest change in the heating demand.

The width of the comfort interval can be of importance to the amount of heat that can be stored in a building's structure. Figure 25 shows how much of the internal gains that is utilized in the structure of the simulated model as a function of the width of the comfort interval. The utilization factor η (-) shows to what extent the internal heat gains can be used to decrease the heating of the space:

$$\eta = \frac{\overline{Q}_T + \overline{Q}_V - \overline{Q}_h}{\overline{Q}_g} \tag{18}$$

The heat losses and gains in Equation 18 refer to daily average values. When the utilization factor is 1 all of the internal heat gain can be used to heat the building; when the utilization factor is 0 none of the internal heat gain can be. The utilization factor is further described in Paper II.

The transmission losses Q_T (W) and the ventilation losses Q_V (W) in the numerical simulations are derived by:

$$\overline{Q}_T = K_T \cdot \left(\overline{T}_x - \overline{T}_e\right) \tag{19}$$

$$\overline{Q}_V = n \cdot V \cdot \rho_a \cdot c_{pa} \cdot \left(\overline{T}_a - \overline{T}_e\right) \tag{20}$$

The thermal conductance of the building envelope is denoted by K_T (W/K) (windows included). The average indoor air temperature is denoted by $\overline{T}_a$ (°C) and the average resultant interior temperature is denoted by $\overline{T}_x$ (°C) (de Wit et.al. 1988).

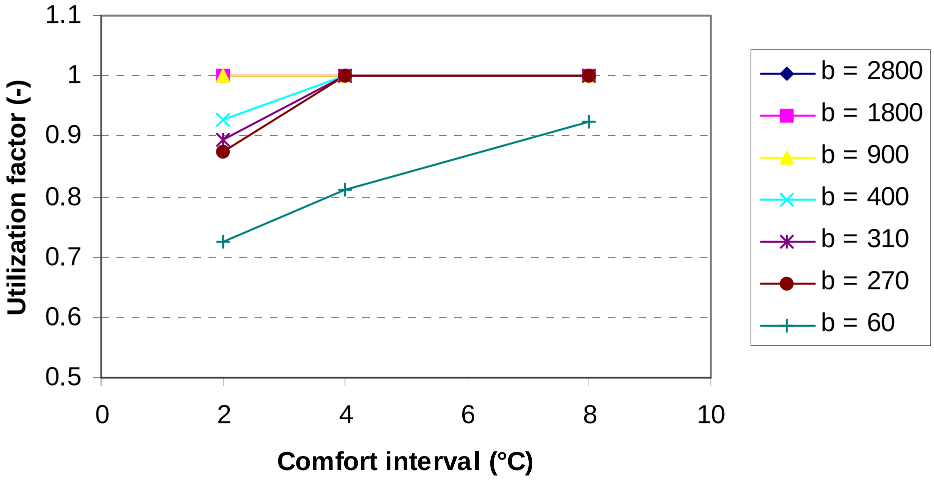

Figure 25. The utilization factor η as a function of the comfort interval when the average internal gain is 1740 W. The comfort interval ΔT is 2, 4 and 8 °C. The intervals are T_i = 21 - 23 °C, 20 – 24 °C and 18 – 26 °C.

If the comfort interval is narrow and the thermal effusivity low, the whole amount of the internal heat gains cannot be stored in the structure.

In this cases study, a few cases with increased and decreased ventilation rate were added. From a heat storage point of view, a decrease in the ventilation rate behaves in many ways as an increase of the internal gain: when the ventilation rate increases, the heat surplus decreases and a smaller share of the heat can be stored in the structure. If the ventilation rate decreases, the amount of surplus heat ventilated out also decreases, and it is more difficult to store the remaining surplus heat in the structure. Thus, the share of the surplus heat that is stored is diminished.

5.2 Influence on the heating demand by choice of ventilation strategy

In this section results from the case study in Section 4.2 are presented. Only heating demand is shown as the cooling demand is almost equal to the heating demand for reasons of symmetry when the average indoor temperature lies in the middle of the comfort interval. Figures 26 and 27 show the heating demand for a structure containing an inner layer of wood and of mineral wool, respectively. The ventilation rate increases during the day. The figures include one case (1) with a constant ventilation rate and four other cases (2-5), where the ventilation rate increases during the day.

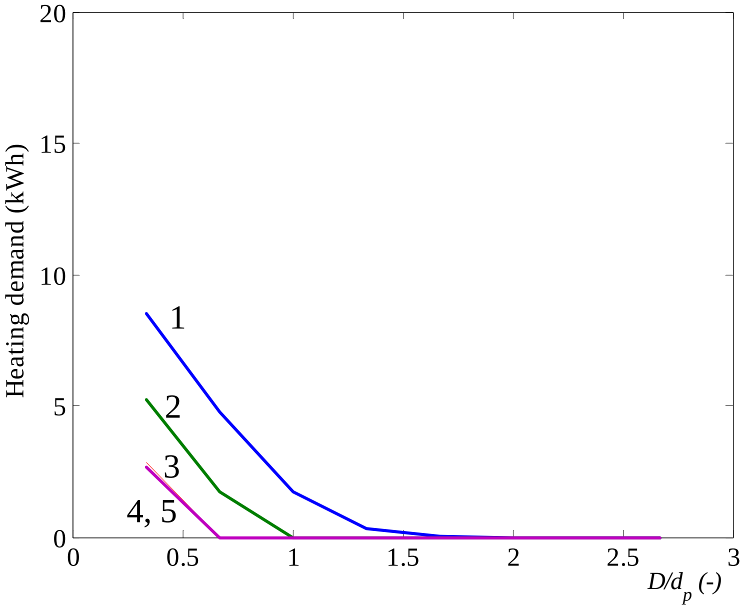

Figure 26. The heating demand for the interior structure made of wood for ventilation strategies 1 to 5.

The ventilation strategies are presented in Figure 16.

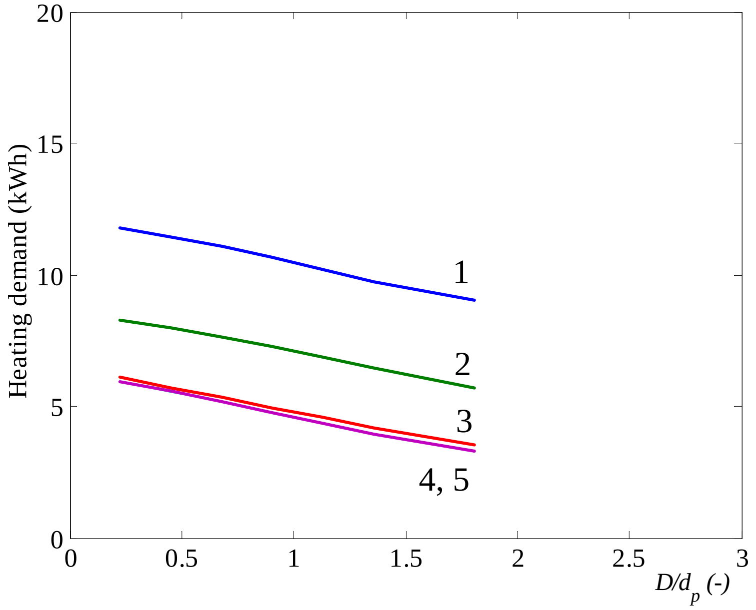

Figure 27. The heating demand for the interior structure made of mineral wool for ventilation strategies 1 to 5.

The structure that contains inner layer of granite does not need any heating since granite is able to store the heat surplus in the cases studied here.

Figures 26 and 27 show that the heating demand for ventilation strategies 3, 4 och 5 are about the same irrespective of whether the structure consists of wood or of mineral wool. In other words, with the heat gains in question, it does not matter whether we choose ventilation strategy 3, 4 or 5: in all three cases the heating demands during a 24 hour period is lessened by 1.9 kWh where the structure is made of wood, and by 5.5 kWh where it is made of mineral wool (these values are applicable where the structure's thickness is the same as the periodic penetration depth for each material). The energy saving can be compared to the average value of the energy losses during a 24 hour period in the model in Section 4.1, this value is 41.8 kWh (average heat loss is 1740 W during 24 hrs, T_e = 8.2°C, T_i = 22°C, n = 0.5 h^{-1}). The losses due to each component are listed in Table 3.

Table 3. Average energy loss during a 24-hour period

Building part	Daily heat loss (kWh)
Outer wall	2.8
Window	16.5
Ventilation	22.5
Total heat loss through the building envelope	41.8

Figures 28 and 29 show the heating demands when the ventilation rate is increased during the night (strategy 6 to 9) for a structure containing an inner layer of wood and of mineral wool, respectively. Again, a basic case with constant ventilation rate is included together with four cases where the ventilation rate increases during the night.

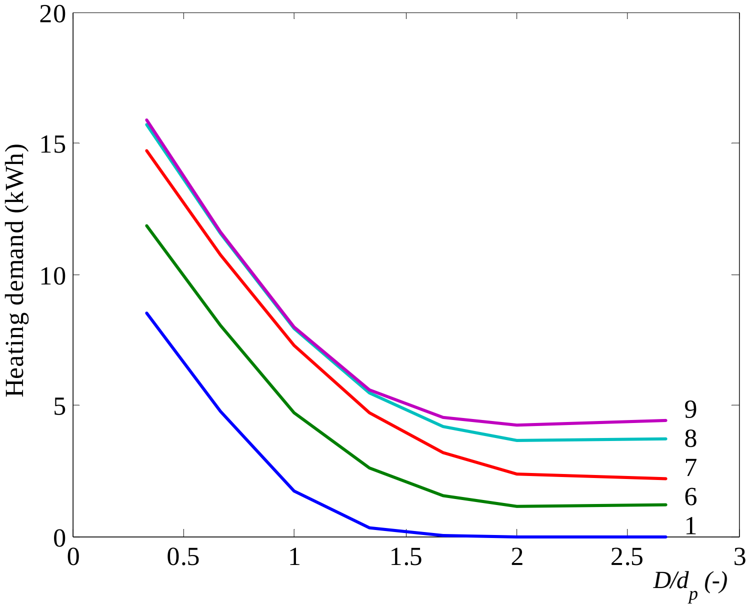

Figure 28. The heating demand for the interior structure made of wood for ventilation strategies 1 and 6 to 9.

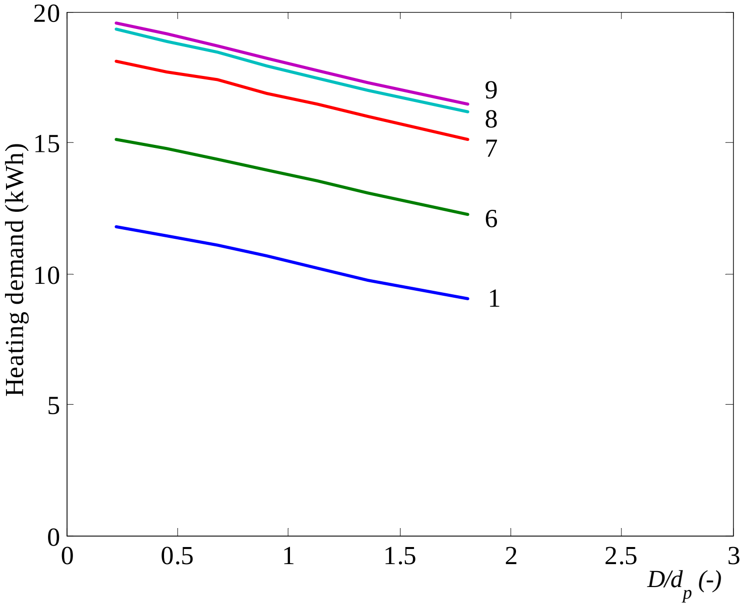

Figure 29. The heating demand for the interior structure made of mineral wool for ventilation strategies 1 and 6 to 9.

As before, if a structure consists of granite there is, in principle, no heating demand under the conditions studied.

As can be seen from the figures, during the night the heating demand increases with the ventilation rate, which is why these strategies are not advantageous for the heat gains in question. Here, too, the heating demand is, in principle, the same for strategies 7, 8 and 9.

5.3 Heating and cooling demand of a building during one year

Figure 30 show the heating and cooling demand for one year of the simulated terrace house and office building, respectively.

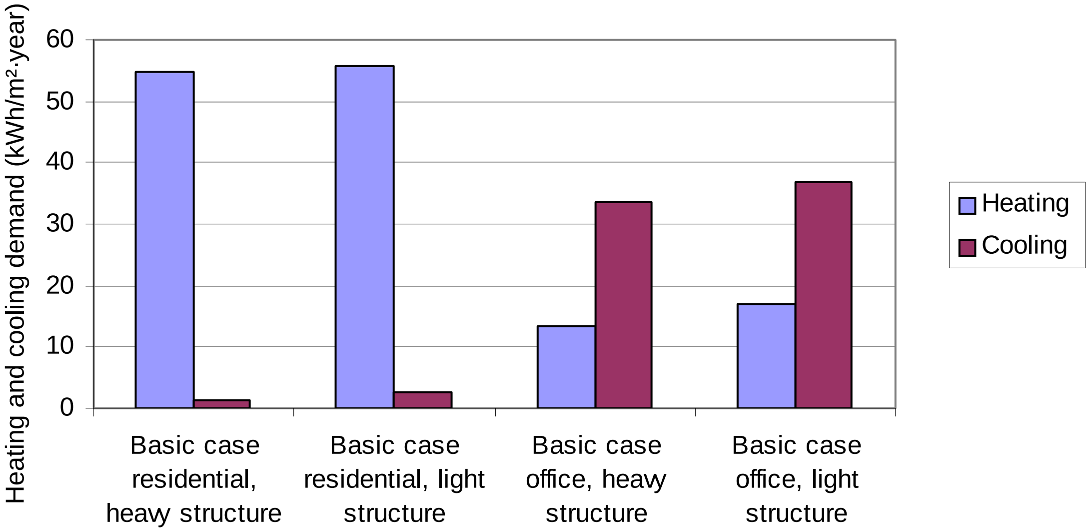

Figure 30. The heating and cooling demand of the terrace house and the office building

The heating and cooling demands are somewhat lower in the buildings with a heavy structure. The difference is one or two percentage points for the terrace house, the block of flats and the school, and 4 percent for the office block. These differences are so small that they fall well within the error margins of the calculation.

Increasing the U-value of the roof, exterior walls, and foundation slab by 30 percent has a much larger effect upon the heating demands than a heavy or light structure, see Figures 31-34.

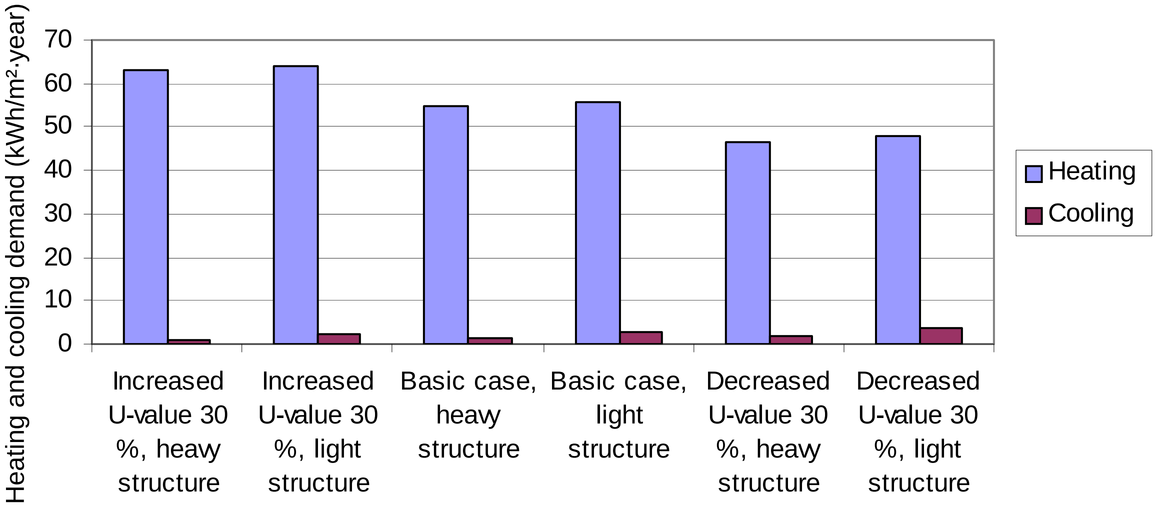

Figure 31. The heating and cooling demand of the terrace house, showing the impact due to changes in the U-value.

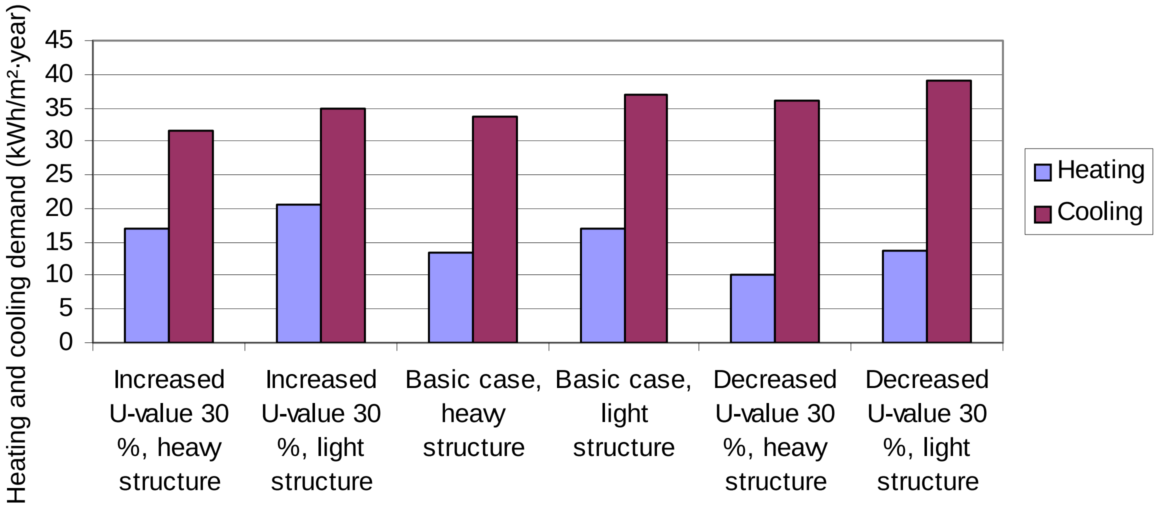

Figure 32. The heating and cooling demand of the office building, showing the impact due to changes in the U-value.

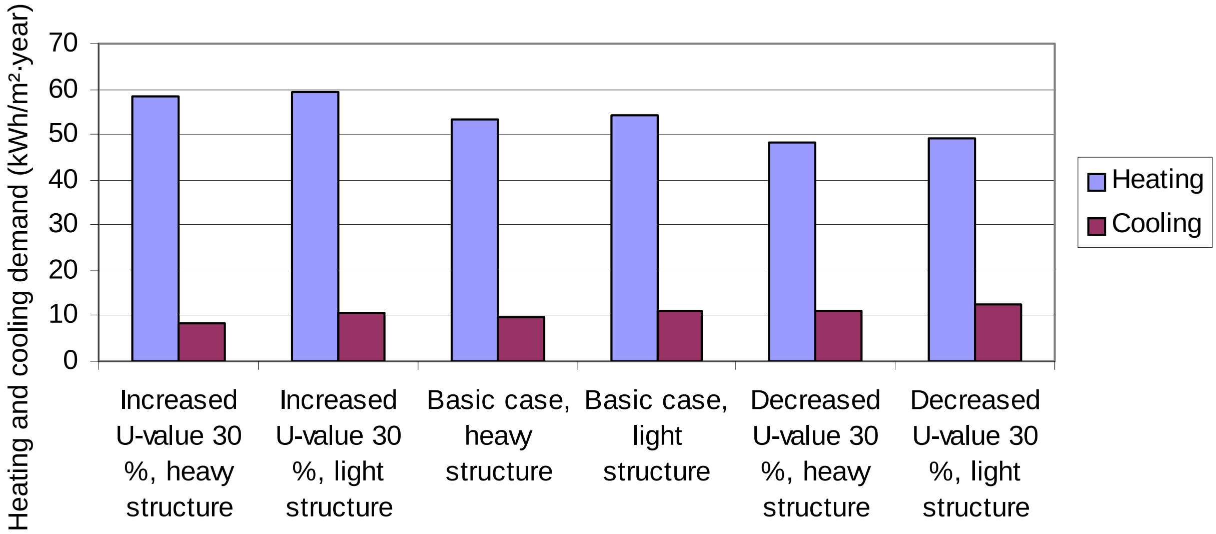

Figure 33. The heating and cooling demand of the block of flats, showing the impact due to changes in the U-value.

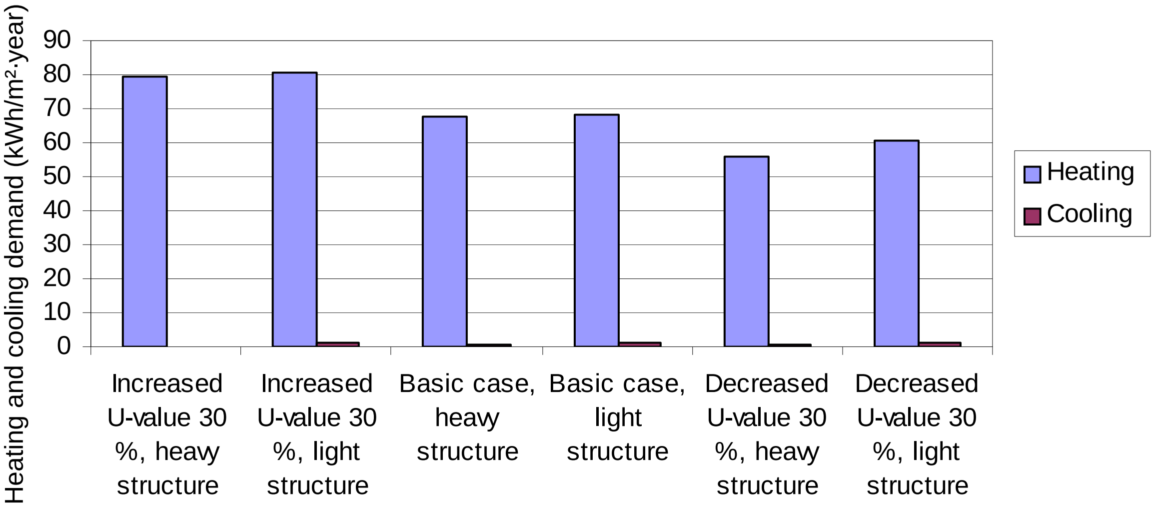

Figure 34. The heating and cooling demand of the school, showing the impact due to changes in the U-value.

The large heating demand of the school is to a large degree due to the large ventilation rate.

A lower U-value will lessen the heating demand but will increase the cooling demand. An increase in the cooling demand of an office building can be problematic as the cooling demand is already very high; in contrast, in the residential buildings (terrace house and block of flats) the cooling demand is low and a change in the U-value has no major impact.

In this case study, the comfort interval is in most cases fixed at 21 – 26 °C, which, to some extent, hinders the utilization of the heat storage potential of the building structure.

6 PREHEATING OF AIR THROUGH AN EARTH-TUBE SYSTEM

The aim of this work is to determine the temperature and the moisture content in a buried air-inlet system of a terrace house, and also to determine how much heating - and cooling energy that can be extracted from the ground with such a system. This chapter is a summary of Paper V. In (Ståhl 2000) the air inlet system is presented in detail. The methods used are analytical solutions and a case study using a new numerical tool.

6.1 Analytic model of an earth-to-air heat exchanger

A simplified analytic model has been developed. This model consists of two parts. The first part calculates the maximal heat gain through heat transfer between the ground and the air passing through the earth tubes. The second part deals with latent heat gains when moisture evaporates from the ground. This simplified model assumes that the length of the earth-tube is sufficient (infinite) and could be used as a rule of thumb when estimating the amount of energy that is possible to extract from an earth-tube system. The outdoor temperature is described with a sine-function accounting for the average and amplitude of the ambient temperature and is adapted to the Nordic climate. The ground temperature at a certain depth z (m) is also given by a sine-function. The outdoor temperature variation is dampened by the factor $e^{-z/dp}$ at the depth z. The energy E_s (J), that is possible to extract from an earth tube, during a certain period of time neglecting the latent heat due to phase change, is given by:

$$E_s = \int_{t_a}^{t_b} \left(T_{outlet} - T_e\right) \cdot c_{pa} \cdot \dot{M}_a dt \approx \int_{t_a}^{t_b} \left(T_{ground} - T_e\right) \cdot c_{pa} \cdot \dot{M}_a dt \tag{21}$$

Here, T_e denotes the ambient temperature. Latent heat is given by the following approximation:

$$E_l = \int_{t_a}^{t_b} \frac{\dot{M}_a}{\rho_a} \cdot r \cdot \left(v_{inlet} - v_{outlet}\right) dt \approx \frac{\dot{M}_a}{\rho_a} \cdot r \cdot \left(\bar{v}_e - v_s\left(\bar{T}_e\right)\right) \cdot \left(t_b - t_a\right) \tag{22}$$

Here, v_{inlet} and v_{outlet} (kg/m^3) denotes the humidity by volume of the inlet and outlet air, respectively. The start and end of the considered period is denoted by t_a and t_b (s). The moisture content of the inlet air is equal to the average moisture content of the outdoor air for the year $v_{inlet} \approx \bar{v}_e$. The relative humidity of the air at the outlet is considered to be 100 percent. The earth tube is placed at a depth where the ground temperature is considered to be constant throughout the year. The air temperature at the outlet is considered to be equal to the ground temperature, that is the annual average ambient temperature. The moisture content of the outlet air is, therefore, given by $v_{outlet} \approx v_{sat}\left(\bar{T}_{ground}\right) \approx v_{sat}\left(\bar{T}_{outdoor}\right)$. The air density is denoted by ρ_a (kg/m^3) and the latent heat associated with phase change is r (J/kg).

Air that passes through a tube made of concrete and buried in the ground will be humidified due to the high vapour permeability of concrete. By choosing an earth-tube of a vapour impermeable material, for instance PVC, this humidification could be avoided.

6.2 A case study using a numerical model of an earth-to-air heat exchanger

The case study has used a computer program, the numerical model of which is summarised in Paper V and described in more detail by Ståhl (2000). The program calculates the air temperature and relative humidity at the exit of a buried tube and also the energy used to change the temperature (sensible) and to vaporize ground moisture (latent).

In the case study, a single buried pipe with a cross section of 0.04 m^2 is compared with a system of four parallel pipes, each with a cross section of 0.01 m^2. Thus, the air speed is the same in both cases and the airflow of 42 l/s corresponds to a ventilation rate of 0.5 h^{-1} in the building. The tubes are 12, 16 or 20 m long and are buried at a depth of 1, 2 or 3 m. The tubes are made of concrete or PVC, representing materials that are permeable and impermeable to water vapour, respectively.

6.3 Results of cases study

In Figure 35 the outlet air temperature from four parallel earth tubes made of PVC is compared with the outlet air temperature from four parallel, and one single, earth tube made of concrete.

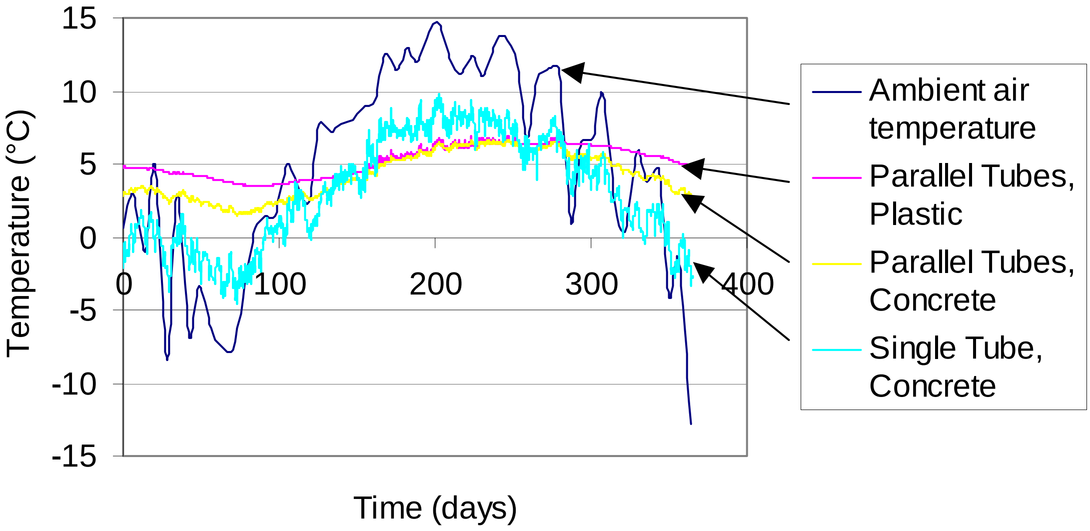

Figure 35. The ambient air temperature and the outlet air temperature from four parallel earth tubes made of PVC or concrete and a single earth tube made of concrete during one year. The earth tubes are 16 meters long and buried at a depth of two meters.

The outlet air from four parallel earth tubes made of PVC is 5±1°C during the entire year which is close to the mean annual ambient temperature 5.17°C for the climatic data used in the simulations.

Figure 36 shows the relative humidity of the outlet air from four parallel, 16 m long earth tubes.

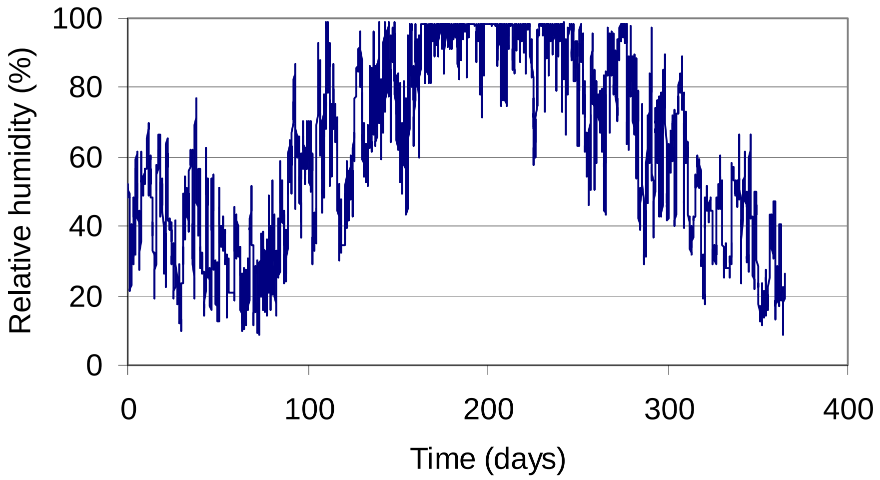

Figure 36. The relative humidity of the outlet air from four parallel, 16 m long earth tubes during one year. The earth tubes are made of PVC and buried at a depth of two m.

During more than half of the year the relative humidity of the outlet air is above 80 percent, favourable conditions for the growth of mould, indeed, during most parts of June, July and August the relative humidity of the outlet air is 100 percent.

The heat extracted during one heating season from four parallel earth tubes made of PVC has been calculated to 1250 kWh/year by the numerical model; heat extraction due to latent heat is not included.

6.4 Conclusion

It is possible to extract approximately 10 kWh/(m^2 usable floor area·year) from an earth-tube system designed for a single-family building. As the heating demand of a single-family building is about 107 kWh/(m^2 usable floor area·year), the investment in an earth-tube system is unlikely to be worthwhile.

The relative humidity of the outlet air of an earth-tube system is high during long periods of the year, which provides favourable conditions for the growth of mould. Therefore the quality of the outlet air from an earth-tube system may be poor.

7 THE EFFECT OF THERMAL MASS ON THE ENERGY USE DURING THE LIFE CYCLE OF A BUILDING

The energy use of a building during its life cycle can be divided into three phases: production, occupation and management, and demolition, see Figure 37. The energy use tends to be largest during the occupation phase: 85 percent for a conventional residential building (Adalberth 2000). This chapter summarises a study of Ståhl (2000) and Paper VI.

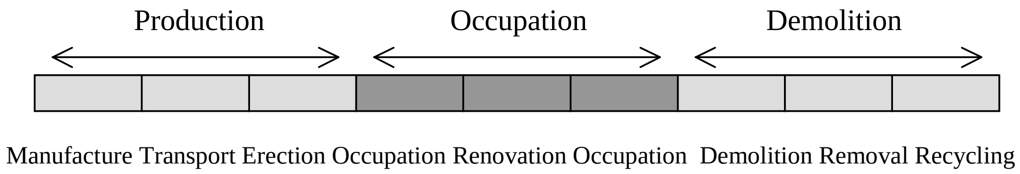

Figure 37. The different phases of the life cycle of a building.

7.1 The energy use during the occupational phase of a building

The heating and cooling demands for different types of buildings were determined in Section 5.3 using Derob-LTH. The amount of energy used to heat hot water and the electricity use in the residential buildings, the school and the office building are based of data from Boverket (1994), Nilsson et al. (1996), and Aronsson (1996). The cooling demand of the buildings has been translated into energy use using of a COP (Coefficient of Performance) of 2.5. The buildings are supposed to last 50 years.

7.2 Evaluating the energy use during the life cycle of a building

The energy used during the production and demolition phases has been determined using methodology developed by Karin Adalberth (2000).

7.3 Results of case study

Figure 38 shows the total energy use during the life cycle of the terrace house and the block of flats.

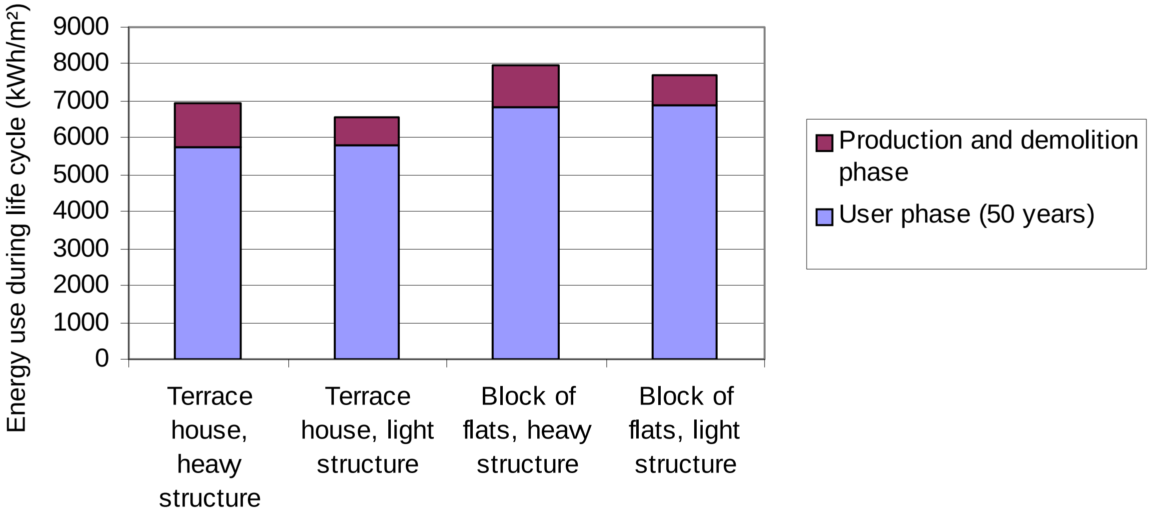

Figure 38. Energy use during the life cycle of the two residential buildings.

Figure 39 shows the total energy use during the life cycle of the school and the office building.

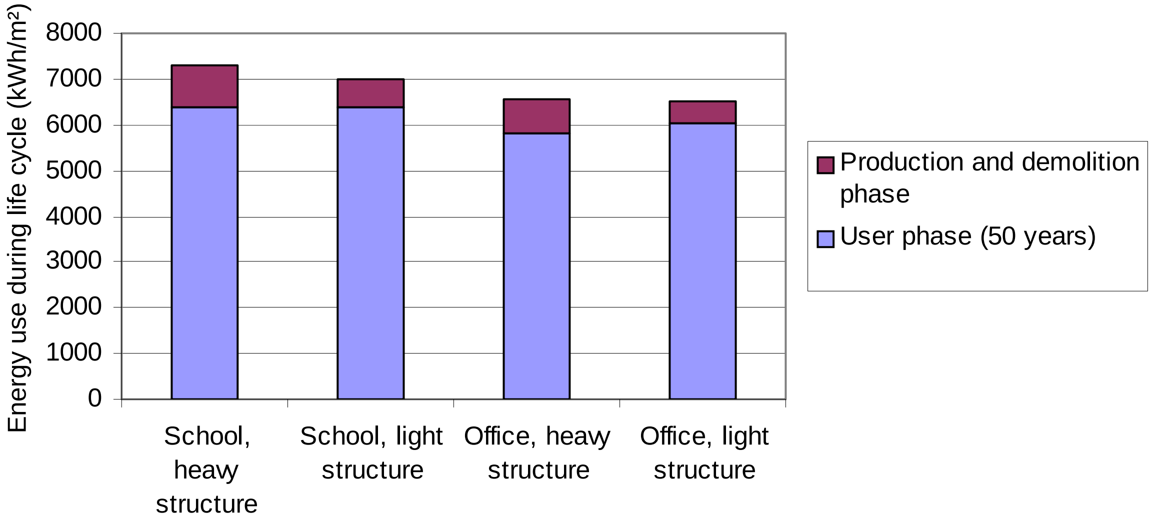

Figure 39. Energy use during the life cycle of the school and the office building.

In all of the above cases the energy use during the occupation phase is slightly higher in the building with a light building structure. However, the buildings with a heavy structure need more energy for production and demolition compared to those with a light structure. Overall, the heavy buildings need somewhat more energy over their whole life cycle compared to buildings with a light structure. The differences are small and well within the error margins of these simulations,

Table 4 lists the energy demands during different phases for the simulated light and heavy basic case of a block of flats.

Table 4. Energy use during the different phases of the life cycle of the block of flats.

Phase	**Heavy structure**	**Light structure**
	Basic case (kWh/m²)	**Basic case (kWh/m²)**
Manufacture	723	693
Transport from manufacturer	30	7
Erection	86	36
Occupation (50 years)	6845	6900
Renovation, manufacture	345	322
Renovation, transport	40	40
Renovation, recycling	-25	-11
Demolition	4	1
Transport of debris	60	45
Recycling of debris	-117	-238
Summation	7991	7795

8 CONCLUSIONS

I. Dynamic analysis of a building unit

Material

The choice of material is of great importance to a building's heat storage capacity, see Figure 12 and the analytical solution in Equation 7. Of all material parameters, the most important is the thermal effusivity and Figure 18 demonstrates the point that a structure with high thermal effusivity facilitates the storage of heat. Figure 18 also shows that different combinations of thermal conductivity and heat capacity are of little importance for the storage of heat if the effusitivy remains the same.

Thickness of interior structure

For periodic heat storage the optimal thickness of a building's structure is close to the periodic penetration depth, and normally nothing is gained by increasing it. This point is made by Figure 9, where the analytical solution shows that periodic heat storage is most favourable when the thickness of the material is close to the periodic penetration depth, and that an increase in thickness does not increase the heat storage capacity. The same points are made by Figure 18 showing the heating demands of a block of flats: the heating demand is steadily decreasing to the point where the structure's thickness is close to the periodic penetration depth; if the thickness is increased, the heating demand falls slightly.

For periodic heat storage most of the heat is stored in the layer closest to the interior of the building. This is illustrated best in Figure 7 (although Figure 6 also demonstrates the point). This is one of the reasons why the heating and cooling demands of the heavy and the light structures are so alike in the third case study; the light construction is clad with plaster- or chipboard giving the inner layer of the structure a fairly good heat storage capacity.

Internal surface resistance

One factor of great importance for heat storage in a building structure is the surface resistance of the material; although this is normally something that one cannot have much influence on without an active use of the thermal mass. Figure 9 shows that only a small part of the heat storage potential is being utilised during periodic heat storage: the top graph shows the potential when there is no surface resistance; if instead, the surface resistance is assumed to be 0.13 $m^2 \cdot K/W$, the factor d/d_p for concrete becomes 1.47 – in which case maybe only 30–40 percent of the heat storage potential can be utilised.

Exposed area of internal structure

The area of the building's structure that is exposed to the interior is of great importance for the heat storage, and the relation between heat storage capacity and area is simple: double the area and the heat storage capacity is also doubled if all other parameters are constant.

Comfort interval

If the internal heat gains are low and the indoor temperature cannot reach the lower limit of the comfort interval without heating, there is no surplus of heat that can be stored in the building structure. Should the internal heat gains increase, either the material must have good heat capacity, or the comfort interval must be sufficiently wide, to allow storage of surplus heat. For maximum use of the heat storage potential of a building structure, the free running indoor temperature should be in the middle of the desired comfort interval and thereby using the structure both as heat and cool storage.

Internal heat gain

It is important that a building's heat storage capacity matches to the internal gains. If the gains are low, it matters little what material the structure is made of (Figure 19), but if the gains are high compared to its storage capacity some of the surplus heat must be ventilated out.

Ventilation strategy

The heating and cooling demand of a building can be lowered through a variation in the ventilation rate during the day to suit the internal gain. In a building with a heavy structure the need for cooling ventilation is less.

II. Preheating of air through an earth-tube system

During one heating season it is possible to extract about 1200 kWh heat from a tube system designed for a single-family building.

By preheating the inlet air of a building using an earth-tube system, the inlet air temperature will remain fairly stable around the mean annual temperature.

High relative humidity during a long continuous summer period of the year produces favourable conditions for growth of mould in the tube.

III. LCA of the energy use of four buildings

There are only small differences in heating and cooling demands of the simulated heavy and light version of each building type. In this study the heavy buildings did require a somewhat larger amount of energy at the production phase, and a somewhat smaller amount during the occupation phase compared to their light counterparts. This study has focused upon the occupation phase because energy use during this phase is by far the largest for most building types. The study of the energy use during the whole life cycle of simulated buildings does show, however, that the energy use during production can be important. A better-insulated building uses less energy during the occupation phase, and therefore the energy use during production becomes relatively more important to the total energy use during the life cycle of the building. Similarly, it is not unusual that a building is used for longer than the 50 years assumed here, and in such cases the energy use during the occupation phases becomes even more important to its total energy use.

9 FUTURE WORK

This work shows that the thermal mass of a building has an impact of the heating and cooling demand of a building. In some cases this impact is significant but in other cases there is almost no impact at all. The case studies of this work are fairly limited and further work could be done in this area. One area for future work could be the effect of thermal mass in extremely well insulated buildings. Today there is an increasing demand for low energy buildings and zero energy buildings. Another area of interest would be the interaction between the thermal mass of a building and the heat distribution system, where the building is a component in a larger system.

10 NOMENCLATURE

A	area (m^2)
a	thermal diffusivity (m^2/s)
b	thermal effusivity $\mathrm{W} \cdot \sqrt{\mathrm{s}}/\mathrm{m}^2 \cdot K$
c	specific heat capacity (J/kg K)
c_{pa}	specific heat capacity of air (J/kg K)
C	heat capacity per unit wall area (J/m^2K)
COP	Coefficient of Performance (-)
D	thickness (m)
d	thickness (m) or the equivalent thickness of the surface resistance (m)
d_p	periodic penetration depth (m)
$e(t)$	accumulated heat flux to the wall for a unit indoor temperature step (J/m^2K)
E	energy (J) (Ws) (kWh)
f	heat recovery factor (-)
k	inverse of the time constant (1/s)
K	thermal conductance (W/ K)
L	thickness (m)
n	ventilation rate (s^{-1})
Q	heat (W) quantity of heat or energy
q	heat flow (W/m^2)
R	thermal resistance (m^2 K/W)
T	temperature (°C or K)
t	time (s)
t_c	characteristic time (s)
U	U-value (W/m^2 K)
V	volume (m^3)
x	length (m)
z	depth (m)
α	surface heat transfer coefficient (W/m^2K)
β	β-factor (-)
γ	gain-loss ratio (-) or γ-factor (-)
λ	thermal conductivity (W/m K)
η	utilisation factor
π	pi (-)
ρ	density (kg/m^3)
σ	σ-factor (-)
Δ	difference

Subscripts

0	
a	air/start time
av	average
b	end time
btg	concrete
c	cooling
$delay$	delay
e	exterior

g	gain
ground	ground
h	heating
i	interior/internal
i	injected
in	in
inlet	inlet
l	loss/latent
m	lumped mass
max	maximum
out	out
outlet	outlet
p	period/periodic
r	heat recovery
s	semi-infinite
s	surface (V_s)
s	solar (solar irradiation, short wave radiation)
s	saturation
s	sensible
se	surface exterior
si	surface interior
storage	storage
T	transmission
v	ventilation
w	window
wall	wall
x	operative interior

superscript

A	amplitude
free	free running
¯	average/mean value
·	per time unit

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