Windows of Opportunities

The Glazed Area and its Impact on the Energy Balance of Buildings

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Abstract

The impact of window area on the energy balance of a building was investigated by simulations in DEROB-LTH. The glazed area was varied in three types of buildings with different types of glazing and for several climates.

One low energy house was compared to a less insulated house but identical in size and layout. Three different types of glazing were used; uncoated double glazing, double glazing with one low-e coated pane and triple glazing with two low-e coated panes. Climates with variations in solar radiation, mean temperature, altitude and latitude were chosen.

The results show that if energy efficient window alternatives are chosen the flexibility of choosing the glazed area and orientation is higher. Choosing a larger area facing south resulted in a higher heating demand for uncoated double glazing in the standard house. An increased area also resulted in an increased peak load for heating for all the simulated cases. Choosing the energy efficient glazing type gave a decrease in heating demand for increased south facing glazed area in the standard house. In the low energy house the difference in heating demand between different areas was smaller than for the standard house.

An office module with two types of switchable glazing and one solar control glazing unit was used in three different climates; Stockholm, Brussels and Rome. Larger window areas increase the cooling demand but if glazing types with lower solar transmittance are used, the difference in cooling demand between different window areas decreases. An extremely large window area, however, increases the peak load both for cooling and for heating and should therefore be avoided. Energy can be saved by using switchable windows instead of solar control or in particular standard glazing.

Keywords: building simulations, DEROB-LTH, glazing, window size, energy efficiency, glazed area

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Till alla er som betyder så mycket!
This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfill specific needs.

The research groups that participate in the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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1. Introduction

This thesis deals with how the glazed area influences the energy balance of a building, depending on which type of glazing is used, in which type of building the glazing is placed, where in the world the building is situated and how the building is oriented.

1.1 Aim and limitations of this thesis

A great deal of the energy used in buildings is lost through the windows, and therefore it is important to improve our knowledge of the processes involved. By discussing the function of windows and how the glazed area influences the energy balance of a building, I hope to be able to inspire the development towards a more energy efficient way of constructing buildings. In this work the impact of the size and orientation of the windows in different types of buildings has been investigated. Building simulations in DEROB-LTH, a dynamical software tool for energy models, have been performed and the results are presented in Chapter 6.

The simulations were made on a low energy terraced house, a standard terraced house and an office module for European and North American climates. The glazed area of the windows was varied while the frame area was kept constant for most of the cases. Increasing the frame area would lead to a higher heating energy demand, but would not influence the trends in the simulated results. Other properties of the frame are also important but the analysis of these were left out.

No analysis was made on the ventilation system or the internal gains from the occupants. These factors have a great impact on the energy balance, but since this is a comparative study, a higher ventilation or a more intensive energy use by the occupants would lead to an increase in the calculated numerical values on the whole.

Windows are important not only to get a nice view but also to let light into the building and create a comfortable indoor environment. Performing daylighting simulations could find the optimized size for a comfortable light situation in the house, which may not be the same as the one found from an energy perspective [1]. No daylighting calculations were performed in this thesis, but are discussed briefly together with the results.
A higher thermal mass of a building leads to a higher usage of the solar gains. That is, a larger window area in a building with high thermal mass allows the heat to be stored in the construction materials and used later, instead of leading to overheating problems. No variations of thermal mass were investigated.

This work was focused on the energy balance of a terraced house and of an office module. Neither economical aspects were taken into consideration, nor were the systems for the central heating and air conditioning.

1.2 Outline of the thesis

In Chapter 1, I briefly introduce the concepts and the aim of the thesis. The content of the appended papers is briefly summarized. Chapter 2 gives the background of windows and the building as an energy system. It also presents some of the earlier work done on how the glazed area influences the energy balance of a building. After this you are hopefully eager to learn more about window physics in Chapter 3 and energy simulations in Chapter 4.

The modeled cases are presented in Chapter 5. One low energy terraced house, one standard terraced house and an office module were studied. The properties of the used climates are also presented. Chapter 6 presents and discusses the results on how a variation of glazing area influences the energy balance of a building. From the results, general conclusions are drawn in Chapter 7, together with some suggestions for future work. Finally a Swedish summary is given in Chapter 8.

1.3 Content of the appended papers

Paper I discusses how the glazed area facing south influences the energy balance of a low energy house in Göteborg, Sweden. Simulations were also performed for different orientations of the house. The results show that since the energy demand for heating is low in this type of building the solar gains coming through the windows is only needed during the coldest periods when the sun seldom shines. A larger glazed area facing south therefore increases the heating demand because of the higher losses that cannot be compensated for by higher solar gains. Orienting the larger window area in other directions only increases the heating demand slightly, which implies that a more evenly distributed window area is preferred.

With less insulation the heating season is longer. This means that the solar gains are needed during a longer period of the year and therefore a larger glazed area facing south should be of more interest in this type of building.
Paper II shows that orienting the houses differently will have a larger impact on a less insulated house. Less energy efficient glazing also leads to higher energy losses if the window area is increased.

An office building has higher internal gains and often larger window areas to provide daylighting. This often leads to overheating problems when the extra heat is not useful, which is taken care of by air conditioning and shading devices. Another way of decreasing the energy demand for cooling can be the emerging technique of switchable windows. This is investigated in Paper III, where electrochromic and gasochromic glazing are compared to uncoated and solar control coated glazing of different sizes. Also in this case the energy efficient types of windows lead to a higher flexibility when choosing the building orientation and window area.

Paper IV is a way of generalizing the previous results to other cold to moderate climates. Simulations for the two types of terraced houses with two different types of glazing were performed for eleven locations mostly in Europe and North America. An increased glazed area resulted in an increased peak load for heating for all the simulated cases. In climates with higher solar radiation, a larger low-e coated glazing area is profitable for the annual energy demand for heating for most of the cases, but for uncoated double glazing a larger glazed area facing south leads to a higher heating demand for any climate.

A comparison of the used simulation tool, DEROB-LTH, with two other simulation tools; IDA and ESP-r was made in Paper V. The comparison was made for the low energy terraced house modeled in this thesis, but with some small changes to adjust the three models to each other. The annual predicted energy demand from the three software showed good agreement and it was shown that the deviations from the parametric study were larger than the deviations between the compared programs.
2. Background

During the last years we have become more aware of the need to save energy by using more energy efficient equipment, but the need for energy will still increase in the nearest future. Today two billion out of about six billion people have no access to electricity in their homes [2]. It is urgent to improve this, and it can only be achieved by energy efficient thinking and by inventing new ways of extracting energy from renewable sources. A lot of research on renewable energy sources is carried out, but none of them seems to cover the energy need for the future on its own, and it will cost a lot to change our thinking and actions to become more energy efficient. In the long run, however, it will probably be even more costly not to do so. Pollution and the increased greenhouse effect might cause diseases, flooding or other unforeseen effects. Even though the opinions go apart on this subject we cannot afford to carry on doing nothing. Adjusting the society to be more environmentally friendly and more energy efficient will bring many positive opportunities and even lead to higher comfort and economical savings.

Since we cannot be sure of finding an unlimited energy source, we have to start saving. But, human beings as we are, we cannot start saving without finding something that motivates us. Some of us will be motivated by believing we are kind to the environment but others want to see more immediate results. To improve our willingness to contribute to a sustainable world, further incentives are therefore necessary. Some of these come from national organizations in the form of information to improve our knowledge, or legislation about how to handle the energy system. Other incentives can be closer to the individuals, such as comfort and the individuals’ possibilities due to economy and availability of energy efficient products in the country. A better economy is something that will influence both the individuals and the society in the long run.

In the industrial countries, especially in the north, a major part of the total energy need is used in buildings. In 2003, the energy use for buildings in Sweden contributed to 38% of the total energy use [3]. Increasing energy efficiency in this area would decrease the energy need in total, which motivates us to build better buildings from an energy point of view. And it is possible! Examples of low energy houses show that they can use less than a third of the energy used in average new buildings in Sweden [4].
Choosing a window with a low heat leakage will minimize the draught from
the frame and panes. This means it is possible to lower the indoor temperature,
and sometimes the radiator, normally situated below the window trying to
prevent this draught, can be excluded. Lowering the indoor temperature by one
degree would save about 5% of the energy need for the building [5]. Energy
efficient windows do not only save energy, but they also give the user higher
comfort and a better economy.

It is also important to think of the energy demand for cooling when building
new buildings. Frank claims that if the climate change results in an increased
mean annual air temperature of 4.4 °C in the period 2050-2100 compared to
the 1961-1990 climatological normals, this would increase the cooling energy
demands for an office building by 223-1050%. The study points out a short-
ening of the heating season by 53 days in Swiss climate, which of course also
decreases the heating energy demand, but not to the same degree as for the
increase of the cooling demand.[6]

2.1 The building as an energy system

A building could be a summer cottage in the forest, a large office complex in
the middle of the stressful city as well as everything between. Looking at the
energy aspects of these different systems would give considerably different
outcomes, but there are common factors. Before doing energy calculations it
is a good idea to be aware of these to get the most out of the results. This is
considered in more detail in Chapter 4, but first a more general description of
the energy system is given.

As can be seen in Fig. 2.1 a lot of factors influence the performance of a
building. The most obvious function of a building is that it should give shelter
and provide safety. But it should also supply electricity for light and electrical
appliances, take care of heating and cooling, give us fresh air by ventilation
and satisfy our water needs. Aesthetics and design are other important factors
that influence most of the aspects in the figure. Even the surrounding trees and
houses influence the energy need of a building by shading, and the climate has
to be taken into account when calculating the annual energy need.

The energy balance of a building is a description of the incoming energy
which should balance the outgoing energy losses. If the heat going out of the
building exceeds the amount of energy coming into the building the indoor
temperature will decrease. This balance is not only strongly influenced by the
chosen heating system and the way in which the building is constructed, but
also by the other aspects in Fig. 2.1. Performing a calculation on the energy
need of a building is therefore complicated. To simplify the process, several
building simulation tools are put at our disposal. More about building simula-
Figure 2.1: The building as an energy system. Different aspects need to be taken into account when studying the energy need of a building. Included in the system is not only the techniques inside the building but also the environment around it and the actions taken by the occupants.

As have been indicated earlier, windows are an important part of a building’s energy system. They transmit solar radiation and cause thermal losses. The heat leakage rate for a window is about ten times higher than for a wall, which might suggest that small windows should be optimal. Because of the improvement in making windows more energy efficient, however, the solar energy that can be collected through the windows can under certain conditions help to gain energy. Depending on in which type of building the energy efficient windows are placed, they have different characteristics. There are mainly two different types of buildings: commercial and residential. The former is often cooled during a large part of the year, while the energy balance of the latter ones is focused on heating depending on where in the world they are situated.

2.1.1 Commercial buildings

A commercial building could be an office complex, a shop or a factory. These are all different and in this work only the office complex will be studied in detail. An office is occupied in the weeks mostly and only during daytime. Electrical equipment such as computers and photocopiers are included in the energy system, warming up the building. Even in colder climates many com-
mmercial buildings are cooled by air conditioning during a large part of the year. Air conditioning systems give a comfortable indoor temperature for the staff working in the office, but they may also make us forget about saving energy by preventing the heat to enter the building already at the design stage. The amount of energy used for the cooling process can be reduced and sometimes even eliminated by using solar control windows and shading devices preventing the sun to overheat the building. Sometimes these buildings are cooled and heated at the same time, which is sadly inefficient. Especially important energy aspects of a commercial building are therefore the windows, shading devices, air conditioning systems and of course the people working in the building.

2.1.2 Residential buildings

Residential buildings can be divided into many different subgroups. The main groups are detached and semi-detached houses, terraced houses and apartment blocks. In a residential building, at least in a temperate climate, the heating demand is higher than the cooling demand, and solar energy can contribute if the windows are suitable, i.e. letting solar energy in, while minimizing heat leakage. We spend most of our life time in these kinds of buildings and it is therefore necessary to make them comfortable and healthy. The most important energy components in these buildings are the users, the heating and ventilation system, and the building envelope insulation including the windows. Assuming a house will be used for at least fifty years, 85% of the total energy use, typically comes from the occupancy phase [7]. It is therefore extremely important to build houses that need as little energy as possible throughout their life time.

By looking at the building as an energy system at the early design stage of a project there are many opportunities to design the building in an energy efficient way. Insulating well and avoiding thermal bridges will save energy for the next fifty years or more. An efficient ventilation system with exhaust heat recovery and excellent windows can make it possible to exclude a separate heating system. One example of a low energy building is described in Chapter 5 where also the other modeled buildings are presented.

2.2 Windows

There is a large number of different window types on the market and many aspects need to be taken into account when choosing windows for a building. Some of them are shown in Fig. 2.2 such as how much light they transmit, if they should block heat radiation or not, if they are aesthetic and if they should
be fire resistant. In this thesis the energy efficiency of the windows is in focus and the other aspects have been put in second place. This, however, does not necessarily mean they are less important.

2.2.1 Glass and windows in history

A supercooled liquid is a popular description of glass, a material that is molecularly amorphous, like a liquid, but actually is a solid. It is made out of molten silica, a special kind of sand, that is carefully cooled without crystallizing. Glass has a known history of 4,000 years, but it took about 2,000 years to get the idea of using it for windows [8].

In the 1830s a new manufacturing technique appeared, which made it possible to manufacture larger areas, 1.0 x 1.3 meters (earlier the maximum was 0.75 x 0.5 meters), and also a more uniform thickness of the glass [9]. This made it possible to enlarge the openings in the facades and rendered it possible to build, for instance, Crystal Palace in London in 1851. Since then architects have been dreaming of larger glass facades to create a close contact between the inside and the outside of the buildings.

At the beginning of the 20th century several drawn flat sheet processes started breaking ground which could provide for even larger glass areas. Today this kind of technique is still used in a developed form.

In 1959 Pilkington introduced the float glass technique which revolutionized the production of flat glass [10]. Now sizes up to 3210 x 6000 mm were
possible to manufacture. More than 90% of the fabricated glass today is made by the float process [9]. This process is described more in section 2.2.2.

Coatings are deposited on glass to give the glass different optical, electrical, chemical and mechanical properties [11]. In 1817 the first antireflection layer was discovered more or less by accident. This was the first kind of coating on transparent glass for technical applications. In the 1970s we started to think more about our energy consumption and at the beginning of the 1980s a number of different coatings appeared on the market. Hopefully coated energy efficient glazing will become standard in the near future.

2.2.2 Glass manufacturing

Float glass manufacturing is a fascinating process. Sand and recycled glass are molten together in a big furnace at a temperature of 1600°C. The molten glass floats onto a bed of molten tin and forms a ribbon while it cools down to 1000°C. Tin has a higher density than glass which means that the glass floats on the tin bed. Since glass has a higher melting point, it helps to keep the tin bed liquid. Later the glass cools down in a tunnel to 620-250°C after which it is cut into manageable lengths. It is also possible to deposit energy efficient coatings at this stage when the glass ribbon is still warm. This is done by Chemical Vapor Deposition, CVD, which means that the deposited material is bonded to the glass in a chemical way and gives a hard coating. Another technique used is magnetron sputtering, where the coating material is deposited onto the glass in a vacuum process, which gives a soft coating.

Earlier the glass surface had to be polished after it had been cut, but since the float process gives a smooth surface of the glass this is no longer necessary. The thickness can be controlled by the speed with which the glass is drawn from the bath and it can vary between 1 and 25 mm [10]. The float process is difficult to start up and therefore goes on around the clock and it is only stopped once every seventh year for maintenance.

2.2.3 Energy efficient windows

There are mainly two ways of saving energy by using the right window for the right purpose. Either you could save energy by using low emissivity glass (low-e) which reduces thermal losses, or you could use a solar control glass to prevent solar heat from getting into the building. Air conditioning installations are getting more common in the world but by using solar control windows the energy required to use this equipment can be reduced. Both these kinds of windows should have a high transmittance for visual light without losing the two mentioned energy efficient properties. This is possible by constructing optically selective glass, designed in a way so that it lets part of the radiation
through and reflects another part, see also Chapter 3. Since the solar radiation can be divided into visual light and heat radiation (often referred to as near infrared) this is an important property of a window.

How do optically selective windows actually work? A simplified explanation is that the glass is coated by a thin layer, normally silver or tin oxide, which reflects infrared heat radiation, but lets the visual light through. This is actually true for both types of windows, just the composition differs. In the low-e case the reflecting metal side is placed closer to the room, and for solar control it is placed closer to the outside. This is explained in more detail in Chapter 3.

It is also possible to block the sun by using different kinds of tinted glazing. These reduce the transmittance of visible and/or some of the heat radiation, but have no low emissivity properties. A modern example of energy efficient windows for the future is the smart window. It has variable optical properties which can be controlled depending on available daylight and what lighting conditions the user wants.

2.3 Earlier studies on window area and energy need of a building

Windows are so common that we tend not to notice them, and still we react as soon as we get into a room without windows. We need daylight to feel well and perform better [12] and the windows also help us to save energy by decreasing the need for artificial light. But what kind of research do we need on windows? Someone asked me once,

"But is there anything more to know about windows? We have had them for so long, haven’t we gone through all the research already?"

There is probably a good reason for asking this question. The windows of today are much better than the windows we had 50 years ago in many aspects. But although in many countries double and triple glazed units are finding their markets, the most common window in the world is still the single pane construction. At the beginning of the 1980s the research on coated glass expanded. This led to a big improvement for the architects who like to use large glass areas to let more light in and get an aesthetic facade. Unfortunately, it is not always a good idea to open up large areas to the outside, as we will see later in this work. Besides the exposed view to the inside of the building that is created, the energy losses in the winter and the overheating problems in the summer increase considerably. Already in 1966 Pleijel wrote that it is impossible to use the solar energy only by increasing the window area [13]. This
would only lead to overheating during the periods when the sun shines the most. Many studies on the window size have been undertaken and some of them are presented briefly here.

A literature study was made by McKennon about building energy needs and window area mostly relevant to UK type of climates. The study was made in 1985 and points out a great variance in optimum size for windows. The final conclusion is, however, that if the windows are designed in an integrated manner having the energy potentials in mind all the time, the freedom of choosing is great.[14]

Increasing the window area could lead to an increase in useful solar heat gains under the condition that the all of the extra heat is needed. The amount of useful solar energy is a function of the ratio between transmitted total solar energy and the total heat loss from the building. Using double glazing in England, Yohanis and Norton found that a higher thermal mass, i.e. a higher time constant, gives smaller differences between different orientations. This is because a higher thermal mass has the possibility of storing the heat until the evening when it is needed. Irrespective of time constant the smallest difference compared to the south, is for the east orientation, and the highest difference is for the north orientation. A final conclusion of the work is that orientation should always be considered together with thermal mass.[15]

2.3.1 Residential buildings

Bansal et. al. have investigated the glazing area for three Indian climates; composite, cold and cloudy, and cold and sunny. Recommended glazing areas for an insulated house were 10% of the floor area for the composite climate, 20% for the cold and cloudy climate, and 30% for the cold and sunny climate.[16] This should mean that a larger glass area could compensate for the higher total U-value of the building.

In a Turkish study made by Inanici and Demirbilek the window ratio was varied from 25 to 90% of the facade for different type of climates. The results for the apartment units with no roof or ground contact show that for a north facing window the total energy load decreases with an increased window area. One reason for this, the authors claim, is that the overall U-value was kept constant for all the window sizes, which means that the U-value of the insulation was decreased when the glazed area was increased. When increasing the south facing window area the total energy load decreased for cool climates and increased for the warm climates. The optimum size in hot climates was 25% of the facade area, which was the smallest area investigated.[17]

According to Simonson, reducing the window area from 16.4% to 15% of the gross heated floor area of a well insulated single family house in Helsinki decreases the energy use very little [18]. The reason for the low impact
should be, except for the modest increase, the low U-value of the windows (1.2 $W/m^2K$) and that most of the window area faced south.

Andersson et al. used a residential building with a double pane glazed area of 15% of the floor area, with a larger area on one of the long facade and a smaller area on the other long side. The study was carried out for 25 climates in the United States. One conclusions of the study is that the orientation can significantly influence the energy use in a moderately well-insulated house. East and west orientation result in a higher total load (heating plus cooling) than for the north and south orientations. The difference is greater for the hot climates than in the northern U.S. If the shading is increased the difference between various orientations diminishes, which agrees with the conclusions by Johnson et al.[19, 20]

In Singapore’s hot and humid climate the cooling can be reduced by 9-12% by changing the orientation from east-west to north-south of a high-rise residential building.[21]

Gueymard claims that the orientation becomes more important in a sunny and warm climate and proposes that the window type well can be chosen differently for different orientations. The way of doing this is to select a window with high solar control factor on a south facade and a window with a low U-value on the north facade in a sunny and warm climate. Gueymard summarizes that the effect of orientation can be significant for the differential energy savings both for cooling and heating.[22]

When Enz and Hastings studied a low energy house in Switzerland, the orientation was shown to be a less critical parameter. The window to facade area fraction of the studied houses was between 15 and 40% and a deviation of up to 45° from south can be compensated by other design features.[23]

### 2.3.2 Commercial buildings

Choosing the size of the windows is not only a matter of energy, but also about standards [24], architecture and purpose. Window management can be taken care of in different ways. It is possible to classify them into seasonal and daily management [25]. The seasonal management requires only infrequent effort on the part of the user, which means that the savings are more likely to be realized than with daily management. Examples of seasonal management, often made during the planning stage, are type of glazing, surrounding trees and overhangs. The daily management can entail the rollers, venetian blinds and drapes, which leads to a great potential of energy savings if they are properly used. The energy required for cooling and the energy required for heating can mostly not be valued the same. Different type of buildings and different climates will influence if cooling or heating is most important to minimize. Another important factor is the system that is used for the cooling or heating.
In most of the studies for a commercial building both types of energy have been included.

In a Swedish report the saving potential is at least 259 GWh if replacing the windows in office buildings built between 1970-1999 [26]. Another study shows that the saving potential for incorporating double glazing with low-e glass in EU(15) is 94.4 TWh or almost 4000 MEuro per year [27]. Going from single glazing instead of double glazing would mean to double the saving potential. When choosing windows we also need to know how to size and orient them energy efficiently.

The recommendations for energy efficiency and daylighting do not always agree, which means it can be hard for the architects to choose which window area would be most appropriate [1].

Using a method which should lead to facades giving low energy use, good visual and thermal comfort, Erichsen and Horgen A/S came to the conclusion that limiting U-value and area of the window is necessary to develop low energy buildings in Norway. A sufficient area is needed to establish a good visual comfort, however, and the recommended minimum window to floor area fraction was 12% (light transmittance of the glazing was 75%). This would mean a daylight factor of 2%, which is recommended by Norwegian standard. Choosing a too large area will make it harder to minimize the heating demand even if windows with a low U-value are used.[28]

Ghisi and Tinker have studied the window area on the north facade in Florianópolis, Brazil and come to the conclusion that the ideal window area for a smaller room is between 14-17% of the facade area from an energy point of view. For a larger room the optimum area lies between 31-40% but the flat curves of this case indicates that a deviation from this area should not influence the energy use of the room significantly.[29, 1]

Bülow-Hübe has investigated how six different glazed areas 0, 10, 20, 30, 40 and 50% GWAR (glazing to wall area ratio) influence both the energy balance and the lighting conditions in an office-module situated in Lund, Sweden. The conclusion was that the glazed area had a relatively large effect on the cooling demand and much smaller effect on the heating demand. With uncoated triple pane glazing with a total U-value of 1.97 W/m²K the annual cooling demand increased by 15 kW/m² if the GWAR was changed from 30% to 50%. The annual heating demand increased by 5 kW/m² for the same area change.[30]

Nielsen and Svendsen present an optimization method based on minimization of the life cycle cost constrained by performance requirement. They have chosen a modern office with high internal gains and discusses that this together with a high transmittance of the windows to achieve a high daylight level may often lead to the solar energy gain being unwanted. Three orientations were chosen for optimization; north, south and west. For all three orientations op-
timal window fraction was at the lowest limit, which was 40% of the facade area. For the north window low-e coated glazing was chosen and for the office room facing south and west, a solar control coating was chosen.[31]

Singh and Bansal found that for a building with a U-value higher than 0.6 \(W/m^2K\) the energy required for lighting is much less than the energy needed for heating and cooling. Studying both energy for lighting and cooling/heating, the window area was optimized for five types of climates in India; hot and dry, warm and humid, composite, moderate, cold and cloudy, cold and sunny. Generally for the cold climates the optimum window area was larger than for the other types of climate and varied between 20-40% depending on type of window and the number of solar hours. Using a double glazed low-e window instead of a plain double glazed combination decreases the difference for different orientations and lower the total energy usage.[32]

Contradictory to Singh and Bansal, Bodart shows that an increase in the ratio of window area to floor area from 16% to 32% can reduce the lighting consumption by 12% or 36% for a glazing with the visual transmittance of 20% or 81%, respectively. This was done for a Belgian climate and nine glazing types of various visible transmittance were analyzed. The different locations for which the two studies were made give different lighting needs.[33] It can be noted that the Indian climate gives higher needs for lighting during the summer depending on how the building construction allow daylighting into the building, while the Belgian building needs more lighting during the winter when less solar radiation is available. Daylight, however, is important to how we feel and how efficient we are at work as well, so an optimization of window size should not depend only on energy for heating and cooling.

A detailed study was made by Johnson et. al. to find out how fenestration affects various aspects of energy performance. Among other factors they looked at how window area and orientation influence the energy balance, including daylighting for two types of climate; hot and cold climate in USA. The effective aperture was defined as the product of floor-to-ceiling window-to-wall ratio (WWR) and the visible transmittance. For both types of climates the electrical consumption for lighting first drops off sharply and then levels out approaching a minimum as the effective aperture increases. This is due to interaction between the building’s occupancy schedule and the daily and seasonal pattern of daylight availability.[20] When this study was made the electrical lighting was not as efficient as today, which means that the maximum estimated electrical savings should be more modest today and therefore displaced towards a smaller effective aperture. Still an effective use of daylight can produce large reductions in electric lighting energy consumption. Other types of glazing have emerged on the market since then and this has to be investigated further, but the effective aperture might still be a good parameter to use.
Heat storage and shading devices are important when designing buildings with passive use of energy. Gratia studied, with the same office building as used in this thesis, the concept of building energy efficiently in Belgium. The best orientation of the building is north-south with the larger window area facing north if no shading devices are used. If shading devices are used on the south-oriented building the cooling load is reduced by 45%. Using reflecting glazing reduces the cooling loads by 34% but at the same time the heating loads are increased by 17%.[34]

Using shading devices and other types of window management mitigates the differences between daylight availability on the north and south facades. A small aperture and no shading devices give larger differences for different orientations. Having a larger effective aperture saturates the daylight levels on all orientations.[20]

In Bülow's Ph D thesis the orientation of an office module was found to be of more importance when looking at the heating demand than when looking at the cooling demand in Lund. The difference on the annual heating demand could be up to 20 kWh/m² for uncoated triple pane glazing. The result for the annual cooling demand was slightly more than 10 kWh/m².[30]

The optimal orientation of a building was found to be north-south by several studies. Aboulnaga has looked at some buildings in the Gulf region, most of them with large glass facades and found that not only the orientation matters, but also the incoming solar intensity and glazed area of the building.[35]

The position of the window influences the daylighting distribution and therefore the electricity used for lighting. The higher the window is placed the better the inner parts of the room are illuminated and the deeper the naturally lit zone is.[34]. Horizontal windows are more energy efficient than vertical in warm climates[36], but also to be preferred when looking at how the office workers wish to have the shape of their windows[37]. The window area should not drop below 20-25% of the area of the window wall to achieve a high satisfaction by the people in the room[38].

The studies referred to above show that the lowest energy demand is given for different window areas depending on outer conditions such as building insulation, glazing type, orientation and climate. Many of the studies were made for uncoated windows and less insulated buildings indicating that a larger window area facing south would give a lower energy demand. What happens as the U-values of the glazing and building are improved? The result of this thesis tries to give an answer to this question.
3. Window physics

What are the properties of solar radiation? What happens as the solar radiation hits the glazing in our windows? How can windows be designed to save energy? We use windows in our buildings primarily for visual contact between inside and outside and as a daylight source. Of course there are a number of other reasons and aspects to take into account when choosing windows, see Fig. 2.2 in Chapter 2. They should match the architecture of the building, they should be operable or be permanently closed or they should prevent noise from the outside close to a busy road.

Selecting an energy efficient window does not only mean choosing a suitable coated glazing combined with a low U-value frame, but it is also important how large the window area is, which direction it faces and what shading devices are used. A large glass area will cause energy losses during colder periods (nights and winter time) but also gain more solar energy during sunny periods than a well insulated wall. If the house has a low heat capacitance, however, the harvesting of solar energy might cause overheating. This can sometimes be prevented by good shading devices, although they obstruct the view to the outside.

To be able to compare different glazing combinations in a window it is necessary to know the basic terms that describe their properties. In this chapter some typical parameters describing windows from energy aspects are introduced. We will learn about the solar radiation and how it interacts with the window panes. Since some of the energy flow through the window is thermal, it is necessary to introduce some thermodynamic equations. Understanding the basic physical concepts is necessary in order to design and construct energy efficient windows.

3.1 Solar spectrum

The sun transforms about five million tonnes of hydrogen to energy every second. Some of this energy reaches the earth in the form of electromagnetic radiation, giving us both heat and light. Everything around us like the walls and the furniture in a house absorb and emit radiation. It is important to be familiar with the properties of this radiation to understand the concept of energy efficient windows.
All bodies absorb and emit electromagnetic radiation. A body which totally absorbs the radiation falling on it is defined as a *black body*. The blackbody radiation for a body of temperature $T$, can be described through Planck’s radiation law [39]:

$$I_{e\lambda} \, d\lambda = \frac{2\pi h c^2}{\lambda^5} \cdot \frac{d\lambda}{e^{hc/\lambda kT} - 1}$$  \hspace{1cm} (3.1)

The left hand side of this equation represents the power per surface unit area, which is radiated in the interval $\lambda \pm d\lambda$ (W/m$^2$), i.e. the radiated energy is divided into different wavelengths, $\lambda$. On the right hand side we have Planck’s constant, $h = 6.626 \cdot 10^{-24}$ Js and Boltzmann’s constant, $k = 1.381 \cdot 10^{-23}$ J/K and finally the speed of light, $c = 2.998 \cdot 10^8$ m/s. Now we know the emitted power per square meter and per wavelength interval ($d\lambda$) and if we integrate this function over the whole wavelength spectrum the power radiated per unit area of the body is obtained. This relation was found experimentally by Josef Stefan and theoretically by Ludvig Boltzmann and is therefore called the Stefan-Boltzmann law [39]:

$$I_e = \sigma T^4$$  \hspace{1cm} (3.2)

Here the Stefan-Boltzmann constant is given by $\sigma = 5.67 \cdot 10^{-8}$ W/m$^2$K$^4$. If we instead take the derivative of Planck’s equation and equal this to zero we find the wavelength for which the maximum intensity is reached, Wien’s displacement law:

$$\lambda_{\text{max}} T = 2.898 \cdot 10^{-3} \text{mK}$$  \hspace{1cm} (3.3)

This means the higher the temperature, the shorter the wavelength is that corresponds to the maximum radiation.

A good example of a black body is the sun and Fig. 3.1 shows its radiation reaching the surface of the earth. The black body radiation from the sun travels a long distance and the intensity is reduced by the square of the distance. As the radiation passes the earth’s atmosphere it is attenuated due to absorption by gas molecules.

The blackbody radiation for a body at room temperature is drawn to the right in Fig. 3.1. This radiation comes from everything around us; for example a Spanish book, hot chocolate and human beings.

The electromagnetic radiation interval of interest is often divided into four wavelength intervals [40]:

1. $280 \text{ nm} < \lambda < 380 \text{ nm}$: The ultraviolet radiation (UV) carries about 5-10% of the solar energy and is harmful to humans, plants and textiles.
Figure 3.1: The solar spectrum. The solar radiation reaching the earth is shown to the left in the figure. To the right the blackbody radiation curves corresponding to bodies of three different temperatures can be seen.

2. \(380\,\text{nm} < \lambda < 780\,\text{nm}\): The visual light (VIS) has about 50\% of the solar energy and contains the light we can see with our eyes.

3. \(780\,\text{nm} < \lambda < 2500\,\text{nm}\): The near infrared (NIR) has the remaining part of the solar energy, about 40-45\%.

4. \(\lambda > 2500\,\text{nm}\): Nothing of the infrared radiation (IR) from the sun reaches the earth, but as said earlier every body radiates IR all the time, which means that we are surrounded by this radiation.

The different wavelength dependent properties have some good implications as we will see later. This makes it possible to design glazing, which let through part of the solar spectrum and block other parts. In this way windows can be manufactured that provide light without gaining too much heat or, for another type of window, loosing too much heat.

The solar radiation is often divided into diffuse and direct radiation, where the diffuse radiation is a combination of reflected radiation from the surroundings and atmospherically scattered radiation.

3.2 Reflectance, transmittance and absorptance

As electromagnetic radiation falls onto a glass pane in a window some of the light is reflected, some goes right through, is transmitted, and some is
absorbed in the glass. This is illustrated in Fig. 3.2. The absorbed radiation is transformed to heat and the glass emits radiation due to the temperature increase in the pane.

As the total incoming energy cannot be destroyed but only transformed we have:

\[ A(\lambda) + R(\lambda) + T(\lambda) = 1 \] (3.4)

where \( A \) is the absorptance, \( R \) the reflectance and \( T \) the transmittance, defined as the corresponding fractions of the incident radiation. These are spectral values, i.e. \( A, R \) and \( T \) depend on the wavelength, \( \lambda \). As mentioned earlier, all materials constantly emit radiation. When an object is in thermal equilibrium, i.e. has a constant temperature, the absorptance and the emittance are balanced:

\[ A(\lambda) = \varepsilon(\lambda) \] (3.5)

Can we say anything about in which directions the light is reflected or transmitted? When light reaches a glass pane it actually chooses the fastest way according to Fermat’s principle [41]. Using this, it is straightforward to find that the reflectance angle has to be equal to the incidence angle, and after some more trigonometry, Snell’s law can be derived:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \] (3.6)

where \( n_1 \) and \( n_2 \) are the refractive indices of the first and second material. \( \theta_1 \) and \( \theta_2 \) are the incidence angle and the angle of refraction, respectively.

This is true for the direct, or specular, reflectance of light. Some of the light,

![Figure 3.2](image.png)

*Figure 3.2:* Light transmitted (\( T \)), reflected (\( R \)) and absorbed (\( A \)) by a glass pane. The absorbed light is transformed to heat and later emitted to the inside and the outside as blackbody radiation.
Figure 3.3: The reflectance and transmittance of a glass pane. The light is reflected and transmitted at every boundary layer between air and glass, which leads to multiple reflections that must be added to find the total transmittance and reflectance of the glass pane. The incoming light has the intensity $I = 1$, $R$ is reflected light and $T$ is transmitted light in the first and the second surface, 1 and 2. $R'_1$ stands for the reflectance in the boundary layer 1 between glass and air, as the light is on its way back from boundary layer 2.

though, will be scattered in other directions if the surface of the pane is rough.

How much of the light will be transmitted and how much will be reflected? Looking at the pane illustrated in Fig. 3.3, it is possible to calculate the fractions of transmitted, $T$, and reflected, $R$, radiation. Supposing the absorption is $\alpha$ in the pane and $d$ is the thickness of the pane, the transmittance through the pane will be reduced by $e^{-\alpha d}$ as it reaches surface 2. Due to lack of space, this term is only shown twice in the marked rectangles in the figure. The terms show the amount transmitted light in the points between air and glass pointed out by the arrows. Starting with the total intensity, $I$, falling on the window, we can see that one part, $R_1$, is reflected back in surface 1 and the rest, $T_1$, passes through. The fractions $T_1$ and $R_1$, depend on the optical properties of the glass. Adding up the different reflected terms gives a geometrical series with the exact solution:

$$R = R_1 + T_1^2 R_2 e^{-2\alpha d} \cdot (1 + R'_1 R_2 e^{-2\alpha d} + (R'_1 R_2 e^{-2\alpha d})^2 + \ldots) = R_1 + \frac{T_1^2 R_2 e^{-2\alpha d}}{1 - R'_1 R_2 e^{-2\alpha d}}$$

(3.7)
In the same way we obtain the transmittance:

\[ T = \frac{T_1 T_2 e^{-\alpha d}}{1 - R_1' R_2 e^{-2\alpha d}} \]  

(3.8)

Equations 3.7 and 3.8 can be used for calculating the transmittance and reflectance for a window system of two panes. In this case the different surfaces will correspond to the two panes, 1 and 2 in Fig. 3.3 separated by the air gap, which has an absorption that can be neglected. The transmittance and reflectance values correspond then becomes:

\[ R = R_1 + \frac{T_1^2 R_2}{1 - R_1' R_2} R_1 + \frac{T_1^2 R_2 e^{-2\alpha d}}{1 - R_1' R_2 e^{-2\alpha d}} \]  

(3.9)

and

\[ T = \frac{T_1 T_2}{1 - R_1' R_2} \]  

(3.10)

\( R_1' \) in this case, stand for the reflectance of the “back” surface of pane 1 and can differ from the light reflected by the front surface if one surface is coated.

3.3 Angular dependence

As the earth rotates around its axis it seems as if the sun crosses the sky from east to west every day. This gives a variable incidence angle by which the solar radiation enters the window. When performing measurements on the glass, however, the spectral properties are often measured from only one angle, close to zero. In Fig. 3.4 it is possible to see how the transmittance varies with the angle of incidence. This curve is different for different types of glazing and different window combinations. The transmittance is higher for lower incidence angles and decreases for higher angles.

Fig. 3.5 shows the direct annual radiation versus angle of incidence for a south facing window in two different European cities [42]. Most of the energy flow is found at angles between 50-60 degrees for both Stockholm and Madrid. This is clear since at these angles the sun is high on the sky, i.e. the radiation has a shorter way through the atmosphere, and the intensity is at the highest level during the day. But the incidence angle through the window is high as the solar radiation comes from the sides onto the window too. This happens for example in the morning and the evening for a south facing window. From this kind of diagram it is possible to identify a mean incidence angle for Stockholm, which is 55 degrees [43].

As mentioned above the measured value, which is used in calculations, is usually taken at normal incidence, i.e. the incidence angle is zero. Going back

22
Figure 3.4: The transmittance versus incidence angle. The transmittance decreases for larger incidence angles. The definition of incidence angle is shown below the curve.

Figure 3.5: The direct annual radiation falls on a vertical, south facing window in two European cities, Madrid and Stockholm versus incidence angle [42]. The maximum energy flow is found at angles between 50-60 degrees.

to Fig. 3.4 we can see that the value at an incidence angle of 55 degrees is 7% lower. This means that the energy coming through the window is overestimated using the near normal values of transmittance in the energy calculations.
3.4 Spectral averages

When describing a window we normally use the optical properties, \( R, T \) and \( A \), defined above. Since these are all wavelength dependent a large amount of data are required to describe the whole situation. In practice, however, it is the average values over a wavelength interval which are of interest. These values are obtained by integration over a spectral interval resulting in one single value for every needed property. There are three commonly used values for glass weighted over three different kinds of spectra; the solar, the visual and the thermal spectral ranges. For example the solar transmittance can be found from the equation:

\[
T_{\text{sol}} = \frac{\int_{\lambda_1}^{\lambda_2} T(\lambda)\Phi(\lambda)\,d\lambda}{\int_{\lambda_1}^{\lambda_2} \Phi(\lambda)\,d\lambda}
\]  

(3.11)

where \( \lambda_1 \) and \( \lambda_2 \) correspond to the lower and upper wavelength of the integrating spectrum that is used. For the solar spectrum these are 300 and 2500 nm. The same equation can be used for \( T_{\text{vis}} \) and \( T_{\text{therm}} \) by changing the wavelength interval and the spectrum used as weighting function, \( \Phi(\lambda) \). For the solar transmittance \( \Phi \) is taken from ISO 9845 [44] for the visual the spectrum \( \Phi \) is a product of the solar spectrum and the sensitivity curve for the eye, for the infrared properties the blackbody radiation spectrum is used. Replacing \( T \) in equation 3.11 by the other glass properties; \( R, A \) or \( \varepsilon \) gives the spectral averaged values for these parameters.

3.5 Total solar energy transmittance - TSET

Another integrated property of the windows is the Total Solar Energy Transmittance, \( T_{\text{SET}} \). This is often denoted the g-value and represents the total amount of energy which enters the room. It consists of the sum of direct solar transmittance according to equation 3.11 and the part of the solar radiation first absorbed in the panes and then reemitted towards the inside of the building. Another term used for the same property is Solar Heat Gain Coefficient, \( \text{SHGC} \). The calculation of \( T_{\text{SET}} \) is given in the standards ISO 9050 [45] and EN 410 [40].

3.6 Thermal properties

A window would loose up to ten times more energy than a wall, if solar radiation is not taken into account. Looking at a whole year, and taking into account
that the sun contributes to heating the building, a window can, however, be a positive contribution to the energy balance.

The heat transfer through a window takes place in three ways:

- **Radiation** is the thermal radiation exchange between surfaces and surroundings. The main part of the heat losses from the glazed fraction of a traditional window is by radiation. This can be prevented by a coating on the glass, which is described in more detail in the next section.
- **Convection** is when heat is transported away from the surface by air movements, like circulation or wind. The convection can be prevented by different measures for instance by placing an inert gas between the panes in the window.
- **Conduction** is when heat is transferred by the thermal motion of atoms and molecules.

### 3.6.1 Radiation losses

A warm body radiates infrared radiation towards a colder body. This is the reason why we experience draught from the windows when it is cold outside. To obstruct this draught, radiators are placed below the windows. Since radiation losses are the main contribution to heat leakage through the glazed fraction of a window this is were we want to do the first reduction. Coatings on the glass panes can prevent most of the radiation losses. By applying a thin layer of silver or tin oxide on the surface of the glass, most of the infrared radiation is reflected instead of absorbed in the glass.

Especially during a night with a clear sky the radiation losses are high. This is because the window radiates infrared radiation towards space, which is much colder than the surrounding air. If the window is placed horizontally more of the surface will “see” the sky and the losses increase. An example of this phenomenon is a car parked halfway under a roof. The windows below the roof will have no frost formation, while the ones outside the roof facing the clear sky will have ice on them. This could happen even if the air temperature is above zero.

### 3.6.2 Convection and conduction

Heat is transferred not only by radiation, but also by convection or conduction. Conduction is when the energy, in the form of heat, goes through a material by the electrons and phonons in a material. A good conductor is for example a metal while an insulator such as plastic conducts heat very poorly. The wind blowing outside the window will sweep the heat away from the glass surface by convection. Air movements will always be present in the air around us, which means convection will not only take place in strong wind, although it
has a stronger impact then, but also on the inside and between the panes in the window.

3.6.3 U-value

By combining these three heat transfer properties, radiation, convection and conduction, it is possible to obtain the U-value for a window. This is a measure of the thermal leakage through the window per square meter and degree temperature difference between the inside and the outside of the window \([W/m^2\degree C]\). For a window it can be calculated by:

\[
\frac{1}{U} = \frac{1}{h_e} + \frac{1}{h_i} + \frac{1}{h_t}
\]  (3.12)

Here the internal and external heat transfer coefficients, \(h_i\) and \(h_e\), give the rate of heat transfer between the inside and outside surfaces and the surrounding air. \(h_t\) is the heat conductance of the air gap.

A window consists of the different panes and the frame to keep them together. The frame and edge-seal could be constructed in different materials such as plastic, wood and aluminum or the combination: aluminum covered wood. Better insulating materials are introduced on the market, for example fibreglass, but still the uncertain service life time of these materials slows down the introduction on the market. Since the glazing has been greatly improved during the last decades the next step is to develop the edge-seal and frame technology. The thermal conduction through the window also depends on the shape of the frame and how the window is built into the wall. There are two different U-values classifying windows; the glazing U-value and the total U-value of the window. Since the thermal properties of the different zones of a window differ, the total U-value is weighted over these:

\[
U_{tot} = \frac{U_{frame}A_{frame} + U_{edge}A_{edge} + U_{glass}A_{glass}}{A_{tot}}
\]  (3.13)

It is of course important to compare the same type of U-values, which can sometimes be difficult since the definition is not always clear in product catalogues.

3.7 Optical selectivity

The solar spectrum and the blackbody spectrum are separated on the wavelength axis, see Fig. 3.1, which can be used to manufacture optically selective glazing. By depositing a coating the glazing is given different properties in different wavelength intervals. A transparent heat mirror has high transmittance
in the visual and sometimes near infrared spectrum but low transmittance in the thermal spectrum. By using different coated panes, solar control and low emissivity windows are designed. There are two different kinds of coatings; soft and hard coating. The soft coating is sensitive to environmental degradation and must be used in an insulated glass unit to be protected against rain and pollutants, while the hard coating has a surface as strong as the glass itself and can be used without restrictions.

3.8 Daylighting

Energy efficient windows enhance the possibilities of using larger window areas giving more daylight to our indoor environment. This can also imply more problems with glare which means large differences in luminance levels. It is therefore important to try to design windows that give evenly distributed lighting conditions in the room. In this way the building occupants can take advantage of the good health aspects that come with a cleverly daylighted surrounding. Exactly how daylight influences us is hard to tell, but it is clear that we prefer daylit environments and two summaries of different studies on this subject can be found in [46] and [47]. In [46] some examples of methods for calculations are also discussed. Often the daylight factor, DF, is mentioned as a measure on the daylight situation in a room. DF is defined as the ratio of the internal illuminance to the external illuminance. It is depending on the type of window, position of window, shape of window and room depth. If the daylight factor is high the artificial lighting often can be reduced and electricity use can be decreased. But increasing the glazed area too much gives a high risk of overheating. This risk can of course, be reduced by using shading devices, but then the daylight factor is decreased.

3.9 Low-e and solar control coatings

For normal float glass, energy is mainly lost by radiation while for a frame, conduction is the main mechanism to reduce. Of course it is important not to forget the overall picture when choosing windows. It is no point in putting new windows into a ramshackle building for the same reason as we do not put a cover on top of a leaking bucket.

We start by reducing the main loss, the one by radiation. Comparing the different parts of the window with a system of resistors as in Fig. 3.6 gives a clue where to place the coatings to save energy. Starting with the low-e case, i.e. stopping the heat radiation from the inside as close to the room as possible, the coating should be on the inner pane. But on which side? In the
Figure 3.6: Heat transfer through a window. Drawing the parallels between a window and a series of parallel connected resistor pairs, indicates where it is most important to prevent heat leakage.

In the figure, $R_{1,\text{con}}$ stands for the convection and conduction resistance and $R_{1,\text{rad}}$ is the radiation part, preventing the heat to go from the air in the room to the glass. The black point in the connection would correspond to the resistance in the glass, which can be neglected in this case. The next parallel coupled resistances, $R_{12,\text{con}}$ and $R_{12,\text{rad}}$, are the ones between the glass surface, the air gap and the next surface. We now want to increase one of the radiation resistances by applying a coating on the inner pane. $R_{1,\text{con}}$ is fixed and fairly low, meaning if we increase $R_{1,\text{rad}}$ the heat will anyway take the way through $R_{1,\text{con}}$ instead. Over the other resistance pair the situation is different. $R_{12,\text{con}}$ is higher and will increase even more if in addition to increasing $R_{12,\text{rad}}$ the air gap is filled up with a gas, which prevents the air movement. In addition to this, the coating is better protected from oxidation and moisture, which is an advantage. In the same way the placement of the solar control coating can be decided, and both combinations are shown in Fig. 3.7. A common way of numbering the different surfaces of the panes, 1 for the outer surface, 2 for the next and so on, is also shown in the figure. There are actually two schools of how to do this - the other starts from the inside - but the one pictured in Fig. 3.7 is used in the following chapters. Looking at a triple glazed unit, TGU, putting the coating on the middle pane should always be avoided, since this could trap
the heat in between the panes and cause thermal stress and even breakage of the insulated glass unit, IGU.

Depending on in which climate the building is situated and in which type of building the window should be placed, either solar control or low-e windows can be the most appropriate. A building which needs to be both heated and cooled, which is often the case, might need different types of window in different directions. This is not commonly done today, probably because of the costs, lack of knowledge and the trouble of ordering different types of windows, but might be a good investment to investigate in the future. A lot of cooling energy can be avoided choosing the right shading devices together with the window [47].

### 3.10 Switchable windows

Switchable windows combine shading and comfortable light transmittance in a new way for future buildings. They have the advantage of being able to regulate the inlet of light by varying the transmittance. There are different types of regulation methods. For example gas, electric current, light and heat can make the glass combination shift optical properties.

In 1998 the first commercial electrochromic window was introduced [48]. The electrochromic windows are regulated by an electric current and consist of several different layers. When an electric voltage of 1-2 V is applied,
lithium or hydrogen ions are transported between the active layers in a similar way as in a rechargeable battery. The charged state is then dark and the uncharged state is fully transparent. The visible transmittance, today, varies between 0.50-0.70 in the bleached state and 0.02-0.25 in the colored state [49]. The g-value varies between 0.10 to 0.50. These numbers will of course be improved in the future.

For an overview of electrochromic tungsten oxide films see Granqvist [50]. The article also discusses processes for improving the switching process to become faster, which is one of the challenges this type of industry struggles with. Although the market still worries about the life time and the cost of these products, a bright future of switchable glazing is anticipated. Sottile reports from an interview study with US architects that expect that by 2009, 13.5% of all new exterior and interior windows, doors and skylights will include switchable glazing [51]. Factors that will influence this progress are the price, the ability to control light to avoid glare and product warranties. Lee and DiBartolomeo report from a full-scale field test of large area electrochromic devices, that electrochromic windows can improve the conditions for computer use in offices with the dynamic illumination control they provide [52].

For Gasochromic windows (GC) diluted hydrogen is added to a coated surface to color the glazing and thereby lowering the transmittance [53]. By adding oxygen the coated surface bleaches and the transmittance increases. To obtain a steady state the insulated glass unit is isolated from further changes in gas content. The hydrogen gas can be produced by an electrolyser that is integrated in the facade. For gasochromic windows the visible transmittance varies between 0.10 and 0.59 and the g-value is 0.12-0.46 [49].

Many building simulation tools so far only have the possibility of using static windows, which means that switchable windows are difficult to simulate correctly. An interesting discussion is about how to control these windows in reality; the user’s wishes and the energy issues do not always coincide. A deeper discussion about this follows in Chapter 4.

The switchable windows can be a good alternative for future large glass facades in big office blocks as well as in residential buildings in warm climates with overheating problems. This is especially the case if the quality of these windows is improved and the cost of producing them decreases. By using switchable windows it should be possible to lower the energy need for cooling and at the same time keep the view to the outside.
4. Energy simulations

This chapter gives an introduction to the possibilities and restrictions of energy simulations for buildings. First a short description of how the simulation tools work, which parameters that are important and what methods are used for the calculations. Then follows a deeper analysis of DEROB-LTH, the energy simulation tool for buildings used in this thesis.

4.1 Simulation tools

There are a number of different tools available to estimate how a building will function. Uncomplicated software tools in MS Windows environment as well as more advanced simulation programs are necessary to fulfill our different needs. The more user friendly programs with simpler mathematical methods are suitable for someone who wants to predict the energy need at the beginning of a project, while a more advanced tool can be useful in a later stage of the project and for research purposes. It is difficult, not to say impossible, to get an exact result from a building simulation [54]. It is therefore not unusual that the predicted values at the beginning of a building project do not agree with the measured values at the end [55].

Carrying out energy simulations means to a great extent finding out the influence of incoming solar irradiance and how much of the incoming energy can be used, especially for calculations on windows. Some of the window properties were described earlier under Chapter 3, however, many other factors are relevant to take into account when making energy simulations. Size of the building, orientation, situation, climate and building materials such as for example wall insulation and window frames are important examples. Some of these factors are easier to define than others. The material properties are often well known but it is much harder to predict the climate of the next twenty years even without considering an increasing greenhouse effect. And even if we should know how much the sun is shining, it is hard to predict exactly how much the solar radiation will contribute to the heating of the simulated system due to, for instance, shading effects. Depending on which factors the simulation tool takes into account, the tools can be divided into two main groups: static and dynamic models. Static models are more simplified, while dynamic models are more detailed and allow conditions to vary over time. Both of these
are built up by several equations describing the energy system of a building.

4.2 Building components

Many aspects have to be taken into account when constructing a building, see Fig. 2.1. There are also different types of buildings, such as residential and commercial buildings of different kind. In these buildings, different purposes should be fulfilled e.g. sleeping, cooking and various types of working. It should also match the surrounding architecture where it is situated and last for a long time.

When performing an energy simulation in a project it is important to remember that it is only approximate numbers you get out of the simulation. When evaluating the results, it is an output formed by the input you choose. If, for example, the climate data are incomplete or the air tightness of the building is overestimated the simulated data will differ from reality. How you use the building according to regulation of heating system or wished indoor temperature is also important to take into account when comparing the simulated results with the actual energy demand. Choosing the parameters carefully will give good opportunities to get useful information from the simulation. This is facilitated by standardization.

From an energy perspective of a building there are mainly four types of heating sources that are balanced by four types of losses [56]:

- + Heating system
- + Domestic hot water
- + Internal gains (persons, electric appliances etc)
- + Solar radiation

- - Transmission losses
- - Air leakage/infiltration
- - Ventilation losses (controlled)
- - Waste water losses

The heating system should provide heat to reach the desired indoor temperature in the building. The required energy amount needed is called heating demand. This can be satisfied by a wood stove, district heating or a solar thermal collector together with the radiators and water pipes.

The domestic hot water system could be combined with the heating system or be independent. In the energy simulations performed in this thesis, only the total heating demand has been calculated independently of type of heating system.

Internal gains which come from electrical appliances such as freezers, fridges, computers and electric lighting contribute to the heating of the
building as well as increase the cooling load during the warm summer period. Here the user plays an important role not only acting as an extra radiator of about 70-140 W but also by choosing how often and when to use the washing machine or PC. It is really hard to estimate how big this contribution is. For simulations of a hypothetical planned building a usage pattern based on a large number of interviewed people can be used, or the parameters have to be estimated in another way.

The climate is often represented by measured data or produced from measured data by averaging methods. Solar radiation is one of the properties, which contributes to the heating of the building. A building is supposed to stand for at least fifty years and as we do not really know how the climate will be in the future, we can only make a good guess and select the different components of the building for what we believe will be reasonable. At least we know that the energy we do not need today, we do not have to pay for in the future either.

The envelope of the building should be well insulated and tight to minimize transmission losses and air leakage, respectively. Depending on the thermal mass for different materials in the wall construction, the heat capacity is different. Heavy constructions, for instance concrete, can store more heat than a light construction, such as wood. This can be experienced in a cool church during warm summer days, as the thick walls take some time to warm up. A light building on the other hand is easy to warm up but also easy to cool. The heat capacity influences the choice of heating system. A heavy building is able to store heat for some time, e.g. from day to night, and can therefore manage with a heating system of less peak power [57]. The cooling system also needs less capacity in a heavy construction. To simulate the heat storage capacity of a building a dynamic tool is necessary.

The U-value of a wall is calculated by adding the different contributions to the heat resistance by:

\[
U = \frac{1}{R_e + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \ldots + \frac{d_i}{\lambda_i} + R_i}
\]  

(4.1)

where \(R_e\) and \(R_i\) correspond to the external and internal thermal resistance of the wall, \(\lambda_i\) and \(d_i\) are the conductance and the thickness of layer \(i\) in the wall, respectively. To get the steady state heat flow through the wall, \(Q\ [\text{W}]\), the area as well as the temperature difference between outside and inside have to be taken into account, so that

\[
Q = U(T_i - T_e)A
\]  

(4.2)

where \(T_i\) and \(T_e\) are the indoor and outdoor temperatures, respectively, and \(A\)
Another component of the building envelope is the window. About 35% of the heat losses go through the windows in a standard house [58]. This makes it possible to save a lot of energy by choosing energy efficient windows. Energy efficient windows, however, are not always the same for every situation. In buildings that need cooling most of the year, a good window is one that does not transmit too much heat, but still transmits visible light, unless the building is an archive for expensive drawings that would be damaged by the light. In colder climates windows that permit the near infrared light as well as the visual light to enter reduce the heating demand of the building.

The cooling demand is the required energy needed to keep the indoor temperature below a certain temperature. This temperature can be reached by opening the windows, using shading devices or an air conditioning system. Sometimes opening the windows are enough and for other situations extra energy is needed to restrict the indoor temperature.

An energy efficient ventilation system with a heat exchanger can reduce the heat losses noticeably. The air change rate is a measure of how often the air in the volume is exchanged. If the ventilation system is managed well there will be no problem with polluted or damp air. Some of the air will take other ways out of the building due to insufficient air tightness. These losses are known as the air leakage or infiltration.

Depending on how much water the tenants use and the temperature difference between incoming and outgoing water the waste water losses can be calculated. Some of the heat from the water is used for heating the building on its way out, but this is only useful during the heating season. Sometimes an accumulator tank is used as storage in the heating system or for domestic hot water and if this tank is placed inside the house the heat losses contribute to the heating of the house.

4.3 Standards for energy calculations

The reason for making an energy calculation of a building or part of a building, for example a window, is to be able to estimate the energy performance of the building. Having the results, makes it possible to compare them with other calculations made by someone else for validation purposes. It is then extremely important to know that the calculations have been performed in a similar way. For this reason special standards have been, and still are, developed all over the world. The main standardization groups we consult in Sweden and the rest of Europe are The International Organization for Standardization, ISO and Comité Européen Normalisation, CEN (earlier EN). Several methods for calculations on windows, ventilation, solar radiation are described in their docu-
ments. Some of the standards describe how the properties of the components should be measured. Standards are good both for the customers as well as for the industry. The customers get a validation of the data given for a product and the industry get access to structured methods for how to produce the data for product specifications. In different parts of the world different standards are used and they often give slightly different results.

4.4 Static models

At an early stage of a project it is more important to see the orders of magnitude than to do an exact calculation. A simple way is to calculate by hand or formulate the simplified equations as a simple computer program. In the model it is possible to vary certain parameters and see how they influence the indoor climate. The reason for keeping it simple at the beginning is that often not all the parameters are known. Architects and planners need to begin by a simple estimation.

Important parameters to check in the beginning of a project are the orientation, the design of walls, windows and ventilation. Having the data of these parameters it is also possible to do a first estimation of the heating demand. In a steady state calculation the heat capacity of the envelope and furniture is neglected and only static numbers are used, which will not vary over time.

There are a number of static models [59, 60]. Two examples are mentioned here, which concentrate on windows in different ways: WinSel and WIS.

4.4.1 WinSel

WinSel is based on a static model and programmed in Visual Basic [61]. The purpose is to be a simple tool for selection of windows. By using solar energy transmittance (g-value), thermal leakage (U-value) and the type of coating for the glazing as input, an energy balance calculation can be made for comparing the chosen window combination with a base case. The program uses hourly climate data of direct and diffuse radiation and the balance temperature as input data. The balance temperature is the outdoor temperature below which the building must be actively heated. Both heating and cooling demands are calculated. Outputs are presented in the form of saved energy for the simulated window compared to the base case and the energy balance can be shown. A simple cost estimate function is also included. A Matlab version of the program also exits which have more possibilities such as getting the results on a monthly basis or using more specific input data.
4.4.2 WIS

WIS, advanced Window Information System, is a simulation tool developed to assist building designers and component developers treating window systems [62]. The main structure of the tool was developed at TNO Building and Construction Research in Holland. The tool works under MS Windows operating system and combines different built-in choices for a wide range of applications. The user can choose to build up a window from scratch by selecting components from the pane, gas and frame data base. Venetian blinds and some environmental data are other factors included in the program. It is also possible to choose between different calculation routines, environment conditions and design the output format. The U-value, g-value and light transmittance are calculated and can later on be used in WinSel or a building simulation tool for energy estimations.

4.5 Dynamic models

Dynamic models take variations over time into account. The heat storage capacity of the building materials is also included. Often an hour-by-hour calculation is made where the house stores heat from the sun during the day to keep the inside warm in the night. There are a number of different methods used to calculate the heat flow through the envelope taking this into account e.g. finite difference methods, response factor method and the Fourier-method, which all are based on one-dimensional heat flows [56].

An important parameter, which vary over time is the climate. Treating the solar radiation in a proper way is especially important when performing calculations on windows. The incident angle for solar radiation varies over time and year which influences how much energy enters the window. For buildings with large glass facades it is important to treat diffuse and direct solar radiation separately [63]. In many models the solar radiation enters the window and is directly absorbed by the walls in the room. In a real building, part of the light is reflected by the walls and part is absorbed. If there are large glass facades, some of the light will actually be reflected out of the building again and therefore not contribute to the energy gain. Longwave sky radiation will also have a larger impact on large glazed areas than for normal sizes of the windows. One simplification that can be made for buildings with normal windows is to let the solar radiation coming in through a window be treated as diffuse and evenly distributed to the different surfaces of the room.

To study the air movements Computational Fluid Dynamics, CFD, can be used [64]. They are more complex and need more time than other energy balance programs. As the computer technique has developed and still is making great progress these calculations are a lot easier to use today. In this study
though, no CFD calculations have been made.

Dynamic models of different aims and different calculation methods exist both as research tools and commercial tools [59, 60]. Some examples are ESP-r, IDA and DEROB-LTH which is described in Paper V. The energy simulation tool used in this work, DEROB-LTH, is described in the next section.

4.6 DEROB-LTH - Dynamic Energy Response Of Buildings

DEROB-LTH (Dynamic Energy Response Of Buildings) is a tool to perform energy simulations on buildings [65]. The program was first developed at the University of Texas but has later been further developed at LTH (Lund Technical University). It consists of 8 routines that are run in sequence. This may in some cases increase the computational efficiency. If, for instance, the climate file is changed, the geometry for the building does not have to be recalculated.

The first two modules calculate the geometry of the input data, volumes, shapes and areas of the surfaces. The third module calculates the illumination factors for solar radiation and infrared radiation. The fourth calculates the heat transfer properties for walls, floors and roofs and the fifth the hour by hour distribution of solar radiation. The amount of energy needed for cooling and heating is calculated in module six. The two last modules take care of thermal and visual comfort analysis and provide the output in the form of plots and tables.

By using the solar gains, body heat and internal gains, it is possible to calculate the space heating and cooling demand that is necessary to supply in order to achieve the desired indoor temperature, see Fig. 4.1. The output is presented in hourly values for each volume.

4.6.1 Thermal model

Heat transfer in a building is mostly a transfer in three dimensions. In building simulations, however, the heat transfer is often reduced to be one-dimensional to avoid too long calculation times. The one-dimensional heat conduction in solids is given by the Fourier equation:

$$\frac{\partial T(x,t)}{\partial t} = a \frac{\partial^2 T(x,t)}{\partial x^2}$$  \hspace{1cm} (4.3)

$$a = \frac{\lambda}{c\rho}$$  \hspace{1cm} (4.4)
where \( a \) is the thermal diffusivity. This equation for heat conduction in walls is in the simulation solved by using the Crank-Nicholson difference method [65]. This method has the disadvantage that all temperatures must be solved simultaneously but it is, on the other hand, stable for all time steps [66]. This is done by the Gauss-Seidel method using a time step of one hour. The different components are connected into nodes where the energy balance can be summed. The different nodes form a matrix from the equation system which can be solved for each hour.

The heat transfer through the wall can be calculated by taking the different material properties into account and dividing the wall into suitable nodes. Conductivity, specific heat and density of the wall, floor and roof materials must be given by the user.

A thermal model with one temperature node in each pane is used to calculate the unlinear heat transfer in the windows. The heat resistance in the glass is neglected, which is acceptable when two or more panes are used in the model. For more details about this see [66].

The different components are connected into nodes where the energy balance can be calculated for each node. The different nodes form an equation system which can be solved for each hour.
4.6.2 Ventilation and infiltration

A schedule for infiltration rates over the day can be defined to regulate how much air that is supposed to flow from the inside to the outside. The program calculates how much energy the air mass would correspond to and uses that as energy losses in the energy balance. The infiltration rates can be varied over time.

Another way of transporting air, hence energy, between the volumes is the forced ventilation function. This function makes it possible to define how air flows between the different volumes and the outdoor air. The forced ventilation is not possible to regulate over time, but is held constant throughout the simulation.

4.6.3 Radiation distribution

Solar radiation coming into a zone is absorbed, transmitted and reflected depending on the receiving surface. The amount reflected radiation to other internal surfaces are calculated using view factors.

The solar radiation is divided into a diffuse and a direct part, which are treated separately. The incidence angle of the radiation is taken into account and so are the internal reflections between the panes. The solar radiation may also be transmitted between two rooms of the building, which is good for simulations on buildings with large window areas, like atriums, or with internal glazing. All radiation that is reflected in an opaque surface is treated as diffuse after the reflection.

The sky radiation and the surrounding ground radiation are included in the model. Surrounding buildings and shading elements on the house are possible to include in the model. The inner surfaces are also connected to other thermal nodes by IR radiation from other wall surfaces and by convection to the indoor air.

4.6.4 Comfort parameters

A comfort module is included in the program where the output is given in predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices. By using this an estimation of the indoor climate can be done. Since not only the indoor temperature influences how the user will react to its surrounding other factors such as clothing, air velocity and the position in the room. More details on this can be found in the appendix of [65].
4.6.5 Output

The output is presented as hourly values for each volume. Mean temperatures for each volume over a whole year make it possible to check when there is a risk for overheating or when the available heat is not enough. Heating and cooling load each hour makes it possible to find the peak power of the building for cooling and heating demand. Inner surface temperatures as well as incoming solar radiation, transmitted solar radiation and absorbed solar radiation can be obtained for each volume. Comfort indices can be calculated for one volume at a time.

4.6.6 Limitations

Since only the total energy demand has been calculated independently of the type of heating system, the efficiency of the energy source influences how much the bought energy becomes.

The angle dependence of the optical properties are calculated with the Fresnel relations and Snell’s law. This model is correct for uncoated panes, but is less accurate for coated panes. A special model for coated panes is planned to be included in the next program version.

There is often a temperature difference between the air close to the ceiling and the air close to the floor. This is normally neglected in a building simulation and the different surfaces of a room is often assumed to be isothermal, which is case in DEROB-LTH.

No heating system is included in the model, but only a limitation of maximum heating and cooling load can be specified.
5. Studied cases

Three different types of buildings were investigated. One multistory office block, and two terraced houses that only differed in thermal insulation, air infiltration and heat recovery on the exhaust air. The conditions are different in a residential house and an office in many ways. In an office, for example, electrical equipment causes a higher internal gain, which often extends the cooling season. Appropriate lighting conditions are also more important in the office.

5.1 Low energy terraced house

In 2001, twenty low energy terraced houses were built outside Göteborg, with careful thoughts of not making them look different from standard houses [67]. An evaluation of the houses made by the Swedish National Testing and Research Institute can be found in [68].

A model of a mid house was constructed consisting of five volumes as shown in Fig. 5.1. The total floor area was 120 m², and the original window area was about 16% of this, which is more than what was recommended in the Swedish building regulations for sufficient indoor lighting conditions [69]. The south window area was much larger than the area facing north in the original case.

The building envelope was set up by defining the properties of the different elements in the walls, floor and roof. The windows were composed by the corresponding properties of the panes and gas layers in the triple glazed units in the same way, and the frames were added as wall sections.

The defined simulation parameters are given in the following sections.

5.1.1 Construction

The building construction was more air tight and with thicker insulated than traditional houses in Sweden. In Table 5.1 the different U-values of the construction elements are specified. The intermediate walls are the ones separating the apartments. They were defined as adiabatic walls since no heat was assumed to be transferred through them. Inside the house there were several internal walls that were not adiabatic.
Figure 5.1: Model of the mid low energy terraced house. The house was divided into five volumes, two in the ground floor and three in the second floor together with the loft. The wall facing south consisted to a large extent of windows. The arrows show the air flow generated by the mechanical ventilation system in the house. To compensate for heat recovery the air flows were reduced by 83%, which should correspond to the efficiency of the exhaust heat recovery. Numbers in parenthesis show the measured values of the flow rate.

Table 5.1: The used U-values of the construction elements in the low energy terraced house.

<table>
<thead>
<tr>
<th>Construction Element</th>
<th>U-value [W/m².K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor (excluding ground)</td>
<td>0.12</td>
</tr>
<tr>
<td>External wall</td>
<td>0.09</td>
</tr>
<tr>
<td>Roof</td>
<td>0.07</td>
</tr>
<tr>
<td>Intermediate wall (between units)</td>
<td>adiabatic, R=1/U∞</td>
</tr>
<tr>
<td>Beam joist</td>
<td>0.65</td>
</tr>
<tr>
<td>Window frame</td>
<td>1.20</td>
</tr>
<tr>
<td>Door</td>
<td>0.80</td>
</tr>
</tbody>
</table>

5.1.2 Windows

A combination of triple (2 low-e) glazing was used. The combination represents very energy efficient glazing and consists of one fixed (triple F) and one operable (triple O) configuration, see Table 5.2. This combination is the same glazing used in the low energy house built outside Göteborg that worked as prototype for our model. The reason for using two different triple configurations is that the constructions are different for the fixed and operable windows.
Table 5.2: The four different glazing types used in the simulations. The uncoated double glazing was used only in the standard terraced house. In Paper II simulations for a standard house with a double combination with one low-e coating were performed. The two similar types of triple combinations with two low-e glazing were used in the same simulation, one fixed (triple F) and one operable (triple O), placed on different positions in the facade. Pane 1 is the outer pane adjacent to the outside of the building, Pane 2 or 3 is closest to the inside, see Table 5.3.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>Pane 1</th>
<th>Space</th>
<th>Pane 2</th>
<th>Space</th>
<th>Pane 3</th>
<th>U-value [W/m², K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>double</td>
<td>clear</td>
<td>air</td>
<td>clear</td>
<td>-</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td>(uncoated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>double</td>
<td>clear</td>
<td>Ar</td>
<td>low-e</td>
<td>-</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td>(1 low-e)</td>
<td></td>
<td>(soft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>triple F</td>
<td>low-e</td>
<td>Kr</td>
<td>clear</td>
<td>Kr</td>
<td>low-e</td>
<td>0.54</td>
</tr>
<tr>
<td>(2 low-e)</td>
<td>(soft)</td>
<td>(soft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>triple O</td>
<td>low-e</td>
<td>air</td>
<td>clear</td>
<td>Ar</td>
<td>low-e</td>
<td>0.74</td>
</tr>
<tr>
<td>(2 low-e)</td>
<td>(hard)</td>
<td>(soft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

and that only one operable window per room was considered necessary. Both combinations consist of three 4 mm thick panes.

In the fixed window the middle pane of the IGU is ordinary clear float glass, while the outer and inner panes have a thin silver low-e layer facing the middle pane, surfaces (2) and (5) in Fig. 3.7. The two gaps between the panes are filled with 90% krypton.

The operable combination consists of one single outer pane and one double IGU. The IGU is filled with 90% argon, while there is air in the ventilated space between the IGU and the outer pane. The pane in the IGU facing the room has a thin silver layer on its outer surface (2), as in the fixed combination, and the outer pane has a hard coating of tin oxide on its inner surface (5).

In DEROB-LTH the different windows were identified by the solar transmittance, reflectance and thermal emissivity of the panes in combination with the gas filling properties. The specified values of the different panes are listed in Table 5.3.

In Table 5.4 the variation of glazed area facing south is shown. The original window area was 16% of the floor area. The glazing to wall area ratio of the
Table 5.3: The optical data of the glazing. The solar transmittance, reflectance and thermal emissivity of the panes in the glazing combinations used in the simulations.

<table>
<thead>
<tr>
<th></th>
<th>$T_{sol}$</th>
<th>$R_{sol}$</th>
<th>$\varepsilon_{coated}$</th>
<th>$\varepsilon_{uncoated}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>clear</td>
<td>0.83</td>
<td>0.07</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>low-e (soft)</td>
<td>0.58</td>
<td>0.28</td>
<td>0.04</td>
<td>0.84</td>
</tr>
<tr>
<td>low-e (hard)</td>
<td>0.71</td>
<td>0.12</td>
<td>0.16</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 5.4: Variation of glazed area facing south. Glazing to wall area fraction, GWAR, is shown for the various glazed areas investigated, where the glazed area facing south was divided by the total area facing south of 25.4 m$^2$.

<table>
<thead>
<tr>
<th>GWAR</th>
<th>Glazed area (south) (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.86</td>
<td>21.8</td>
</tr>
<tr>
<td>0.42</td>
<td>10.6</td>
</tr>
<tr>
<td>0.33</td>
<td>8.4</td>
</tr>
<tr>
<td>0.21</td>
<td>5.4</td>
</tr>
<tr>
<td>0 (no south windows)</td>
<td>0</td>
</tr>
<tr>
<td>No windows (south+north)</td>
<td>0</td>
</tr>
</tbody>
</table>

The south facade was defined as:

$$GWAR = \frac{A_g}{A_{sf}}$$  \hspace{1cm} (5.1)

where $A_g$ is the glazed area and $A_{sf}$ is the area of the south facade. Six different cases were investigated; GWAR=0.86, 0.42, 0.33, 0.21, 0 and no windows (south+north). The original GWAR was 0.42. Only the glazed area was varied. The frame area was kept constant at 3.6 m$^2$, which corresponds to the original case.

5.1.3 Shading

The houses are built with an extended roof, which prevents the solar radiation from entering the south facing windows during the summer when the solar altitude is high, but lets it through during spring and autumn when the sun is lower. This shading is included in the simulation model, but no other external shading, such as trees or other surrounding buildings has been included.
5.1.4 Heating, ventilation, air conditioning and internal gain

It was suggested that the house should keep a minimum indoor temperature of 23°C and a maximum indoor temperature of 26°C. Normally 20°C is considered as a standard indoor temperature, but the decision to increase the lower temperature set point to 23°C for heating was due to the actual temperatures in the houses during the evaluation of the project [70]. The set point for cooling is defined as the temperature when the occupants are supposed to open windows and use shading devices.

Table 5.5: Schedule for internal gains from electrical equipment, persons and lighting.

<table>
<thead>
<tr>
<th>Hour</th>
<th>Volume 1</th>
<th>Volume 2</th>
<th>Volume 3</th>
<th>Volume 4</th>
<th>Volume 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Living room</td>
<td>Kitchen</td>
<td>Two bedrooms</td>
<td>Hall</td>
<td>Bedroom</td>
</tr>
<tr>
<td>Winter</td>
<td>1 to 6</td>
<td>66</td>
<td>189</td>
<td>124</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>7 to 8</td>
<td>66</td>
<td>298</td>
<td>106</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>9 to 16</td>
<td>66</td>
<td>189</td>
<td>52</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>17 to 22</td>
<td>146</td>
<td>269</td>
<td>110</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>23 to 24</td>
<td>66</td>
<td>189</td>
<td>124</td>
<td>0</td>
</tr>
<tr>
<td>Summer</td>
<td>1 to 6</td>
<td>66</td>
<td>189</td>
<td>124</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>7 to 8</td>
<td>66</td>
<td>298</td>
<td>106</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>9 to 16</td>
<td>66</td>
<td>189</td>
<td>52</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>17 to 22</td>
<td>106</td>
<td>229</td>
<td>110</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>23 to 24</td>
<td>66</td>
<td>189</td>
<td>124</td>
<td>0</td>
</tr>
</tbody>
</table>

The internal gains are summarized in Table 5.5. The year was divided into two periods, summer (June-August) and winter (September-May), with internal gains of 11.9 kWh/day and 12.7 kWh/day respectively. Tenants were assumed to be more at home during weekends and the winter evenings than in the weekdays and summer evenings. In all simulations, a family of four persons, two adults and two children, were supposed to live in the house. The adults contributed with more body heat than the children. This family configuration may differ from the average configuration in reality, but it does not influence the outcome of this study because the main idea was to compare the energy balance of different cases where these numbers were kept constant.
One adult is assumed to contribute by 70 W and according to an occupancy schedule the available internal gains have been added to the table. For more information about how the tenants influence the energy balance see [71].

The ventilation flow was distributed according to the measurements done in [72] and is shown in Fig. 5.1. The exhaust heat recovery was 83% and an infiltration rate of 0.035 air changes per hour was used.

In practice, additional heat is supplied by an electric heater in the ventilation system, but other energy sources could also be used. Note that the terraced houses are not equipped with an active cooling system. The cooling of the houses is instead facilitated by ventilation through a roof window which, when opened in combination with opening one of the other windows gives rise to a chimney effect. This was not modeled in this work.

5.2 Standard terraced house

The model of the standard terraced house was based on the previous described model of the low energy terraced house, see Fig. 5.2. The standard terraced house meets the minimum requirements of Swedish Building Regulations. The geometry of the two types of houses was the same. Heat recovery efficiency, air infiltration rate and thermal insulation were different and three types of windows were simulated in the standard house. The total floor area was 120 m², and the original window area was about 16% of this. The defined simulation parameters for the standard house are given in the following sections.

Figure 5.2: Basic plan of the investigated mid standard terraced house. The house was divided into five volumes, two in the ground floor and three in the second floor together with the loft. The arrows show the air flow generated by the mechanical ventilation in the standard house.

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5.2.1 Construction

In Table 5.6 the different U-values of the construction elements are specified. The intermediate walls, the walls separating the apartments from each other, were defined as adiabatic, i.e. no heat was assumed to be transferred through them. Internal walls inside the house were not adiabatic. U-values of ground floor, external walls and roof were set to values following the minimum requirements of the Swedish Building Regulations [69].

Table 5.6: The used U-values of the construction elements for the standard terraced house.

<table>
<thead>
<tr>
<th></th>
<th>U-value [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor (excluding ground)</td>
<td>0.21</td>
</tr>
<tr>
<td>External wall</td>
<td>0.30</td>
</tr>
<tr>
<td>Roof</td>
<td>0.28</td>
</tr>
<tr>
<td>Intermediate wall (between units)</td>
<td>adiabatic, $R=1/U=\infty$</td>
</tr>
<tr>
<td>Beam joist</td>
<td>0.65</td>
</tr>
<tr>
<td>Window frame</td>
<td>1.20</td>
</tr>
<tr>
<td>Door</td>
<td>0.80</td>
</tr>
</tbody>
</table>

5.2.2 Windows

Three types of windows were investigated in the standard house; double (uncoated), double (1 low-e) and a combination of a triple (2 low-e) fixed and a triple (2 low-e) operable, see Table 5.2. The latter combination was also used in the low energy house.

In DEROB-LTH the different windows were modeled using the solar transmittance, reflectance and thermal emissivity of the panes and combining these with the gas fillings as in Table 5.2. The specified values of the different panes are listed in Table 5.3. Only the glazed area was varied. The frame area was kept constant at 3.6 m², which corresponds to the one on the original house. The variation of glazed area facing south was made in the same way as for the low energy terraced house above, see Table 5.4.

5.2.3 Shading

The houses are constructed with an extended roof, which prevents the direct solar radiation from entering the south facing windows during the summer, but lets it through during spring and autumn when the sun is lower. This shading
was included in the simulation model, but no other external shading such as
trees and other surrounding buildings were included.

5.2.4 Heating, ventilation, air conditioning and
internal gain

The set points for indoor temperatures were the same as for the low energy
house, $T_{min}=23^\circ C$ and $T_{max}=26^\circ C$.

The infiltration rate was 0.1 air changes per hour and the mechanical vent-
ilation was set to 0.5 air changes per hour with an exhaust heat recovery of
50% according to [69] for the standard house. The distribution of the air flow
can be seen in Fig. 5.2.

Heating or cooling systems were not included in the model. Instead, the ex-
tra amount of auxiliary energy (except internal gains and solar energy) needed
to achieve the set temperatures of $T_{min}$ and $T_{max}$ was calculated. In Sweden a
terraced house would not normally be equipped with an active cooling sys-
tem. The cooling of the house is taken care of by the occupants opening the
windows and by using shading devices. This was not modeled in this investi-
gation.

Assumptions about the heat gains from electric appliances and body heat
inside the house were made in the same way as for the low energy house [73].
The internal gains are summarized in Table 5.5.

5.3 Office

A reference building has been specified as part of IEA Solar Heating and
Cooling Programme - Task 27 and the SWIFT project [74]. The specified data
were used to simulate switchable windows for different conditions. The details
of the simulation model for the office are described in this section.

The reference office space consisted of two office rooms separated by a
central corridor, see Fig. 5.3. In the simulation model three volumes were
defined; the office room facing south, Volume 1; the corridor, Volume 2 and
the office room facing north, Volume 3. Volume 1 and 3 had a volume of 68 $m^3$
and a floor area of 19 $m^2$ each, and the corridor volume was 40 $m^3$ and its floor
area 10.7 $m^2$. Total floor area was 48.7 $m^2$.

The office module was situated in the middle of a large building complex,
which meant that the surrounding parts except for the outer facades were adi-
abatic. That is, only one wall with two glazed openings per office room was
exposed to outdoor boundary conditions. In the base case this was the south-
ern and northern facades of the whole office module seen in Fig. 5.3. The
Figure 5.3: The reference office. The office module consists of two office rooms connected with a corridor having windows facing north and south. It is part of a large office building having all walls adiabatic except for the two facades facing north and south.

east-west orientation was also investigated. The internal doors were considered open to allow air flow between the corridor and the two office rooms.

5.3.1 Construction

In Table 5.7 the different U-values of the construction materials are specified. The walls surrounding the office module were all set to be adiabatic, i.e. no
Table 5.7: The U-value and internal absorptance of the construction elements of the investigated office. The internal walls, doors and glazing are the elements between office rooms and corridor. The boundary walls around the office module were all considered as adiabatic.

<table>
<thead>
<tr>
<th></th>
<th>U-value [$W/m^2 K$]</th>
<th>Internal lining absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate floor</td>
<td>adiabatic, $R=1/U=\infty$</td>
<td>0.80</td>
</tr>
<tr>
<td>Intermediate ceiling</td>
<td>adiabatic, $R=1/U=\infty$</td>
<td>0.15</td>
</tr>
<tr>
<td>Intermediate wall</td>
<td>adiabatic, $R=1/U=\infty$</td>
<td>0.35</td>
</tr>
<tr>
<td>Facade</td>
<td>0.3</td>
<td>0.35</td>
</tr>
<tr>
<td>Window frame</td>
<td>1.8</td>
<td>0.20</td>
</tr>
<tr>
<td>Internal wall</td>
<td>0.42</td>
<td>0.35</td>
</tr>
<tr>
<td>Internal door</td>
<td>2.6</td>
<td>0.60</td>
</tr>
<tr>
<td>Internal glazing</td>
<td>2.9</td>
<td>-</td>
</tr>
</tbody>
</table>

heat was assumed to be transferred through them. All the U-values were taken from the reference office [74].

The colors of the internal lining influences how much of the solar energy that is absorbed, shown in Table 5.7. The absorptance of the external facade was 0.70 and the thermal emissivity of all surfaces was set to 0.87.

5.3.2 Windows

Switchable glazing, see section 3.10, were compared to solar control glazing and a double glazing with one low-e coating. The investigated windows or window states (bleached and colored) are presented in Table 5.8 where the data used for the simulations are defined. Fig. 5.4 shows the two switchable glazing combinations. DEROB-LTH needs the data of each pane to calculate the properties of the combined glazing. These data are presented in Table 5.9. Both states of the switchable windows, bleached and colored, are specified.

As a standard double low-e window, one clear glass pane and one "low-e A" were combined with a gap of 12 mm filled with argon, giving a U-value of $1.3 W/m^2 K$. A solar control window was also simulated. This window was a combination of a solar and a clear glass pane with a 15 mm gap filled with argon. The U-value of this combination was $1.1 W/m^2 K$.

One important reason for having windows is to get daylight inside. To achieve this a suitable window area to floor area fraction, WA/FA, should be chosen. Erichsen & Horgen A/S has recommended a minimum WA/FA of 12% (light transmittance of the glazing is 75%) for a daylight factor of 2%, which is recommended in Norwegian standard [28]. If the light transmitt-
Table 5.8: The investigated different glazing types. Pane 1 is the outer pane adjacent to the outside of the building, Pane 2 or 3 is closest to the inside, see Fig. 5.4. The specifications for the different panes are found in Table 5.9 All gaps between the panes are filled with argon.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>Pane 1</th>
<th>Pane 2</th>
<th>Pane 3</th>
<th>U-value</th>
<th>$T_{vis}$</th>
<th>g-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC (b/c)</td>
<td>1</td>
<td>6</td>
<td>4</td>
<td>0.95</td>
<td>0.60/0.15</td>
<td>0.46/0.15</td>
</tr>
<tr>
<td>EC (b/c)</td>
<td>2</td>
<td>5</td>
<td>-</td>
<td>1.2</td>
<td>0.47/0.10</td>
<td>0.28/0.13</td>
</tr>
<tr>
<td>double low-e</td>
<td>7</td>
<td>4</td>
<td>-</td>
<td>1.3</td>
<td>0.75</td>
<td>0.59</td>
</tr>
<tr>
<td>double solar</td>
<td>3</td>
<td>7</td>
<td>-</td>
<td>1.1</td>
<td>0.68</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 5.9: The specified properties of the panes used in DEROB-LTH for the different glazing combinations.

<table>
<thead>
<tr>
<th>Pane type</th>
<th>$T_{sol}$</th>
<th>$R$</th>
<th>$\varepsilon_{coated}$</th>
<th>$\varepsilon_{uncoated}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. GC bleached/colored</td>
<td>0.72/0.14</td>
<td>0.15/0.11</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>2. EC bleached/colored</td>
<td>0.30/0.06</td>
<td>0.13/0.07</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>3. solar</td>
<td>0.35</td>
<td>0.33</td>
<td>0.02</td>
<td>0.84</td>
</tr>
<tr>
<td>4. low-e A</td>
<td>0.56</td>
<td>0.30</td>
<td>0.04</td>
<td>0.84</td>
</tr>
<tr>
<td>5. low-e B</td>
<td>0.60</td>
<td>0.27</td>
<td>0.04</td>
<td>0.84</td>
</tr>
<tr>
<td>6. clear A</td>
<td>0.82</td>
<td>0.08</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>7. clear B</td>
<td>0.83</td>
<td>0.07</td>
<td>0.84</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 5.10: The different window areas investigated in the study. GA/FA is the fraction between the glazed area and the floor area of the office room.

<table>
<thead>
<tr>
<th>Window area</th>
<th>Frame area ($m^2$)</th>
<th>Glazed area ($m^2$)</th>
<th>GA/FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.84</td>
<td>2.4</td>
<td>0.13</td>
</tr>
<tr>
<td>Medium</td>
<td>1.35</td>
<td>3.8</td>
<td>0.20</td>
</tr>
<tr>
<td>Large</td>
<td>1.86</td>
<td>5.3</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Figure 5.4: The two switchable windows investigated in this thesis. Above the electrochromic, EC, glazing with the outer pane [1] coated with an electrochromic coating on the inside, and the inner pane [2] with a low thermal emissivity, low-e, coating on the outside. Below the gasochromic glazing with the gasochromic coating on the inside of pane number [1], another type of low-e coating on pane number [3] and a clear glass pane in between [2].

...tance is decreased the necessary window area is increased. These numbers are valid for a single person office whereas a "landscape" office needs a smaller WA/FA. Of course this will also vary for different situations of the building, depending on shadings from the surroundings and the sun’s position in the sky. The construction of the window and where it is situated in the wall are other factors that influence the lighting situation. These were not investigated here. Three different window areas were investigated to see how these influence the energy balance of the office, see Table 5.10.
5.3.3 Shading

No shading from the surroundings was taken into account. For high rise buildings where no awnings are installed, the windows are not shaded most of the time. Internal shading devices can be used of course, but at the expense of the view. The model excluded internal shading devices. Ground reflection for incident solar radiation was 20%.

5.3.4 Heating, ventilation, air conditioning and internal gain

By using electric equipment in the office heat is gained, which can contribute to the heating. The indoor temperature was set to be between 20°C and 26°C during office hours (8.00 AM-7.00 PM weekdays) and above 16°C at other times (weekends and nighttime).

Table 5.11 shows the internal loads where heat from personnel, electrical equipment and lights are included. One person contributed by 70 W and according to an occupancy schedule, it was assumed that 1.5 persons should occupy the office 85% of the working day based on 8 working hours. It can be noted that, depending on the country, holidays alone give up to 11% reductions in occupancy on an average working day [74].

<table>
<thead>
<tr>
<th>Hour</th>
<th>Volume 1 and 3 (offices) Internal loads[W]</th>
<th>Volume 2 (corridor) Internal loads[W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekdays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 to 7</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>8 to 18</td>
<td>383</td>
<td>10</td>
</tr>
<tr>
<td>19 to 24</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>Weekends</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 to 24</td>
<td>18</td>
<td>0</td>
</tr>
</tbody>
</table>

The mechanical ventilation in one office room was 1.1 air changes per hour during office hours and zero all other times. The natural infiltration was 0.17 air changes per hour all the time. DEROB-LTH only calculates the corresponding energy losses due to the ventilation and not the air flow itself. The corridor has no mechanical ventilation or infiltration losses. To even out the losses from the corridor out to the office rooms a forced ventilation flux of 24 l/s was set between the volumes, from Volume 1 to Volume 2 to Volume 3 and
back to Volume 1. This corresponds to letting the doors be opened all the time. This flux has only a small influence on the total energy demand, but results in a slightly increased heating demand for the south office and a decreased heating demand for the north office. For the same reason, it also reduces the cooling demand in the south office.

5.4 Location and orientation

The aim was to use climates with different solar radiation, temperature pattern and altitude and to see how this matters when choosing the glazed area differently. The climate data was taken from Meteonorm V 5.0 [75] or in some simulations measured data were used. Most of the simulations were made for Swedish and European climates, since this is where our knowledge of the building construction is best. In Paper IV the climates presented in Table 5.12 were used to investigate the impact of the climate more thoroughly. When simulating the office, three different climates were chosen to match the IEA project; cold climate (Stockholm), moderate climate (Brussels) and warm climate (Rome), all taken from Meteonorm. Simulations with the solar radiation set to zero were performed to find out how much of the solar energy that is useful.

Table 5.12: Climate data used in the simulations. Hourly data were taken from Meteonorm V5.0, the annual mean air temperature, global horizontal radiation and total solar radiation on a south vertical surface are presented. The locations marked with an asterisk were chosen as stations in Meteonorm. The others are produced by choosing WMO/OMM.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude [° north]</th>
<th>Alt [m]</th>
<th>Ann mean temp [°C]</th>
<th>Hor sol rad [kWh/m², yr]</th>
<th>Vert sol rad [kWh/m², yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchorage *</td>
<td>61</td>
<td>35</td>
<td>2.2</td>
<td>875</td>
<td>978</td>
</tr>
<tr>
<td>Beijing</td>
<td>40</td>
<td>55</td>
<td>11.8</td>
<td>1342</td>
<td>1155</td>
</tr>
<tr>
<td>Boston *</td>
<td>42</td>
<td>6</td>
<td>10.7</td>
<td>1423</td>
<td>1192</td>
</tr>
<tr>
<td>Denver</td>
<td>40</td>
<td>1656</td>
<td>9.9</td>
<td>1668</td>
<td>1436</td>
</tr>
<tr>
<td>Engelberg *</td>
<td>46</td>
<td>1035</td>
<td>6.1</td>
<td>1195</td>
<td>1079</td>
</tr>
<tr>
<td>Göteborg</td>
<td>57</td>
<td>4</td>
<td>7.8</td>
<td>931</td>
<td>872</td>
</tr>
<tr>
<td>Montreal *</td>
<td>45</td>
<td>133</td>
<td>6.3</td>
<td>1351</td>
<td>1262</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>40</td>
<td>37</td>
<td>11.8</td>
<td>1451</td>
<td>1159</td>
</tr>
<tr>
<td>Quebec</td>
<td>46</td>
<td>70</td>
<td>4.3</td>
<td>1303</td>
<td>1315</td>
</tr>
<tr>
<td>Winnipeg *</td>
<td>50</td>
<td>240</td>
<td>2.5</td>
<td>1394</td>
<td>1512</td>
</tr>
</tbody>
</table>
For the standard house only the window area facing south was varied, but different orientations of the house with a fixed large glazed area were also investigated. For the low energy house some of the variations in glazed area were made for south, west, north and east orientations. The office have windows facing north and south. The glazed area was varied on the two facades simultaneously and simulations for the office module in an east-west orientation were performed to see how this would influence the energy balance.
6. Influence of the glazed area on the energy balance

This chapter presents the results from the simulations and discusses how the glazed area influences the energy balance of a building. We start with a summary in the form of a table trying to briefly discuss how other factors, such as orientation, type of glazing, climate and comfort should influence the choice of window area. The following sections present and discuss the results more in detail.

6.1 Summary of results

Table 6.1 gives a summary of the results in brief. A building is a complex energy system with many factors influencing each other’s consequences on the energy demand. This makes it hard to isolate one factor from the others and to evaluate the impact of one factor on how the window area should be chosen. The table should therefore only be seen as an overview, and a deeper discussion based on specific cases is necessary in order to investigate the influence of the window area on the energy balance of the building.

6.2 Orientation

A large window area is often installed into the south facade of a building to gain solar energy, while the area facing north is smaller. For the low energy terraced house with low-e glazing the heating season is shorter than for the standard house. Since the extra energy for the well insulated house is needed mostly in the winter when less solar radiation is available, especially at high latitudes, the orientation of the large glass facade is of less importance in Göteborg, see Fig. 6.1 (a). For the largest glazed area the difference between having the large area facing south and having it facing north is $5 \text{ kWh/m}^2$ space heating demand. This difference is decreased when the glazed area is decreased. Orienting the houses differently should therefore be possible under these conditions. It should also be possible to distribute the window area more evenly, i.e. decrease the window area facing south and increase the area facing north.
Table 6.1: Summary of the results. The table shows how the glazed area influences the *heating demand* for different conditions; orientation, type of glazing, climate and comfort.

<table>
<thead>
<tr>
<th></th>
<th>Low energy building</th>
<th>Less insulated building</th>
<th>Office</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orientation</strong></td>
<td>Area is of less importance.</td>
<td>Increasing the glazed area facing south decreases the heating demand only if low-e windows are used.</td>
<td>A South-North oriented office building needs less energy both for cooling and heating. If solar control windows are used the orientation is of less importance.</td>
</tr>
<tr>
<td><strong>Glazing</strong></td>
<td>Low-e glazing leads to higher flexibility when choosing window area.</td>
<td>Low-e glazing leads to higher flexibility when choosing window area. Less energy efficient glazing means increased heating demand with increased area also to the south.</td>
<td>If solar control windows or smart windows are used the flexibility of choosing area and orientation is higher.</td>
</tr>
<tr>
<td><strong>Climate</strong></td>
<td>In a sunny climate a large area facing south, east or west decreases or does not influence the heating demand. The cooling demand may increase, however. For higher latitudes a larger area facing south increases the heating demand.</td>
<td>In a sunny climate a larger uncoated glazed area facing south increases the heating demand only slightly. In a less sunny climate the glazed area is of more importance, especially if uncoated glazing is used.</td>
<td>An office in Stockholm needs almost the same cooling energy as an office in Brussels. If large glazed areas are installed, solar control glazing or switchable windows can limit the extra amount heat that enters the windows. In Rome the saving potential is greater.</td>
</tr>
</tbody>
</table>
Figure 6.1: Varied glazed area for different orientations of the low energy house in (a) Göteborg and (b) Denver. The annual heating demand is not influenced noticeably by varying the glazed area facing south from GWAR=0.21 and above. Increasing the area facing the other directions gives a slightly increased heating demand. Neither does an increased area influence the heating demand noticeably above GWAR=0.21 in Denver, except when the varied glazed area faces north. Here the heating demand is slightly increased. Letting the glazed area facing south minimizes the heating demand for both cases.

Looking at the same low energy house located in Denver, shown in Fig. 6.1 (b), the orientation influences the energy balance more. This is because of a larger contribution from the sun even in the winter. The best option is to have the larger glazed area facing south, which reduces the heating demand to almost nothing. Increasing the glazed area facing south, east and west does not influence the heating demand noticeably, while an
increased area facing north will increase the heating demand. Increasing the window area too much may, however, cause overheating problems unless glazing and shading devices are designed properly.

The results in Paper II show the impact of orientation on the annual heating demand for the standard house compared to the low energy house located in Göteborg. Orienting the windows in other directions than south affects the energy balance more if less energy efficient alternatives are chosen. If more energy efficient glazing are chosen in the standard house the energy demand varies less for the different orientations of the house. The case of having a less insulated house than the standard house was not investigated. This case would mean that the heating season would be longer and include the time of the year when more solar radiation is available, which should favour a somewhat larger window area facing south.

Fig. 6.2 illustrates that a north-south oriented office needs less energy both for heating and for cooling than an office module oriented east-west but the difference is not large. Also in this case, the orientation is of less importance if energy efficient windows are chosen. The annual heating and cooling demands were divided by the total floor area of the office module.

Figure 6.2: The annual heating and cooling demands for the office building for two different orientations in Brussels and Stockholm. The positive axis represents heating demand and the negative axis shows cooling demand per floor area and year. Double low-e is a double glazing with low-e coating on the inner pane. GC bleached and GC colored are the gasochromic glazing in the bleached and colored state and EC stands for the electrochromic glazing.
6.3 Type of glazing

During the last two decades a number of new glazing types have been introduced on the market. The U-value of new windows are lower than before and there is a trend of increasing the glazed area, which can be seen in modern architecture. Solar control glazing helps to avoid overheating problems and smart windows may be the next step to make it possible to choose between a high or low transmittance without changing windows. Does the new type of glazing pave the way for an unrestricted window area?

The idea of a low energy house is to minimize heat losses, which implies good insulation of the building envelope. This means that no alternative to energy efficient windows should be given. Therefore a varied glazed area of different types of glazing was not investigated for the low energy house. In [71] different types of glazing were studied for the original area showing that the heating demand decreases, as expected, if energy efficient alternatives are used.

![Temperature vs Heating Load](image)

**Figure 6.3:** Standard terraced house with (a) double (uncoated) glazing and (b) triple glazing with two low-e coated panes on a cloudy winters day (1988-01-31). The dashed line shows the temperature variations during the day.
Figure 6.4: Standard terraced house with (a) double (uncoated) glazing and (b) triple glazing with two low-e coated panes on a sunny winters day (1988-12-01). The dashed line shows the temperature variations during the day.

Installing low-e glazing in a standard house implies that the heating load is only slightly influenced by the glazed area. Comparing Fig. 6.3 (a) with Fig. 6.3 (b) shows that more energy efficient glazing decreases the difference in heat losses during a cold night. The difference is even more obvious when looking at Figs. 6.4 (a)-(b) where a clear sky increases the radiation losses for the uncoated glazing during the night. When clear glass windows are installed in a standard terraced house, the size is therefore of higher importance than if energy efficient glazing is chosen.

In an office building the internal gains are higher than in a residential building. The glazed area tends to be larger to increase the daylighting inside but sometimes also to achieve an attractive architecture of the city. To reach good indoor comfort, both in winter time and in summer time, good windows should be chosen. Otherwise there is a risk for draught from the glazed area in the winter and overheating problems and glare in the summer. Another way of taking care of the indoor climate is to use air conditioning and heating. This
implies a higher energy use in the world and if a good window design could help us minimizing the energy needed it is, of course, better.

\[ R^2 = 0.973 \]
\[ R^2 = 0.997 \]
\[ R^2 = 0.992 \]
\[ R^2 = 0.994 \]
\[ R^2 = 0.997 \]
\[ R^2 = 0.995 \]

\(-30\)
\(-25\)
\(-20\)
\(-15\)
\(-10\)
\(-5\)
\(0\)

\(1\)
\(2\)
\(3\)
\(4\)
\(5\)
\(6\)

Glazed area (m²)

Annual cooling demand (kWh/m²)

EC colored
GC colored
EC bleached
Solar
GC bleached
Double low-e

Figure 6.5: The cooling demand versus glazed area in Brussels. The diagram shows the behavior of the cooling demand when increasing the glazed area of four different types of glazing; Electrochromic (colored/bleached), Gasochromic (colored/bleached), low emissivity and solar control. The area was varied for both the south and north facades at the same time. If the glazed area is increased, the cooling demand increases linearly. The slope of the curves varies with the type of glazing. $R^2$ is the linear regression coefficient calculated according to Excel’s $R^2$-method.

Fig. 6.5 shows how the cooling demand in the office building varies almost linearly with increased glazed area for the different types of glazing in Brussels. All of the curves show a high $R^2$-value (the linear regression coefficient calculated according to Excel’s $R^2$-method), which is also the case for the same building placed in Stockholm and Rome. Choosing a glazing with a lower g-value decreases the importance of window area for the cooling demand. The energy demand for cooling was almost the same for Stockholm, which indicates that a large part of Europe could save a lot of cooling energy by choosing energy efficient windows in the office buildings.

The heating demand in the office building decreases with a decreased window area both in Stockholm and Brussels. The difference between different window areas is higher when the switchable windows are in the colored state than when they are in the bleached state.

6.4 Type of building

Simulations were made for three types of buildings. A low energy terraced house, a standard terraced house and an office. This makes it possible to see
how different insulation strategies increase the flexibility of window area and orientation. Comparing the office with a residential building is interesting in order to see what happens when the internal gains are increased and the purpose of the building changes, but since the purpose for the two buildings differ strongly it is only possible to make a broad comparison.

![Diagram](image.png)

**Figure 6.6:** Different glazing areas for the different cases in Denver. The annual heating demand for different glazing to wall area ratios (GWAR). A GWAR of -0.1 corresponds to having no windows at all and a GWAR of 0 is when there are no windows facing south. The sunny climate makes windows as an energy net gainer.

Figs. 6.6 and 6.7 illustrate how the heating demand varies with glazed area for different types of terraced houses in Denver and Anchorage, respectively. A low energy house shows almost the same heating demand for all the areas. In a standard house with low-e glazing the heating demand is decreased with an increased area. Having uncoated double pane glazing in the standard terraced house gives an increased heating demand with increased area.

A case with the solar radiation set to zero (no sun) for the low energy house, shows how much of the solar energy that contributes to the heating of the house. The solar contribution is larger in Denver than in Anchorage, which was expected because of Denver’s sunnier climate. More about this follows in the next section.

A comparison of the different types of terraced houses shows that different glazed areas and orientation of the house make less difference for a low energy house than for the standard house. Using energy efficient building technology therefore leads to higher flexibility when designing the building.

Smeds has performed simulations on a well-insulated single family detached house with windows of a U-value of 0.92 $W/m^2K$. A sensitivity analysis was made on variation of the window size for different orientations. For all
the orientations the annual heating demand increased with increasing window area. The increase was lowest for south orientation and was approximately 5 kWh/m² at maximum [76].

For an office building the cooling demand can be a large factor for the energy balance. With higher internal gains the cooling season is longer, but a heating season still exists in colder climates and contributes to the total energy demand. It is therefore important to think both of heating and cooling and choose windows with low U-values and low g-values for this type of climate. Choosing an appropriate, i.e. not too large, window area will help to reduce the maximum cooling load during days with overheating risk. The window area should not be too small, though, since the light coming in through the windows is essential for a healthy working environment. The colored state of the switchable window could reduce the cooling load down to the same level as for a small area of the same window in its bleached state.

6.5 Type of climate

Energy efficient building technique varies for different climates. In a cold climate low U-values are necessary to achieve a comfortable indoor environment and in sunnier climates large glass facades should be avoided or extremely well planned to diminish the risk for overheating. Another way of minimizing the overheating is to have a high thermal mass construction of the building.

Figs. 6.8 (a)-(c) show how a variation of the glazed area facing south
Figure 6.8: The annual heating demand versus the global horizontal solar radiation for the houses in different climates. The locations can be identified in Table 5.12.

Influences the energy balance for climates with different solar radiation. In Fig. 6.8 (a) Göteborg and Anchorage diverge from the other locations if we study what happens when the glazed area is increased in the low energy
house. They have the lowest global solar radiation which is the reason for the different behavior. In all the other investigated climates the heating demand for the low energy house decreases with increasing glazed area. For a standard house with low-e glazing an increased area leads to a decreased heating demand, see Fig. 6.8 (b), and for the standard house with double glazing it is the other way around, Fig. 6.8 (c).

The heating demand was also plotted versus the solar radiation falling onto a south vertical surface and these figures showed the same trend as described above. A figure where the heating demand versus annual mean temperature for the different climates is presented in Paper IV.

Energy efficient glazing makes it possible to increase the glazed area without risking high heating demands during the year. An increased glazed area on the buildings does, however, increase the risk for overheating and may cause thermal comfort problems. It is therefore important to closer study how the cooling loads are influenced by an increased glazed area. This was done only briefly. The cooling energy difference if changing from an area of GWAR=0.33 to GWAR=0.86 is shown in Figs. 6.9 and 6.10 for the simulated climates. The numbers do not show the actual cooling need since the simulations were made with the windows constantly closed and no increased ventilation during the cooling season. The heat exchanger on the ventilation system was not bypassed, which increases the cooling demand. The trends show, however, how the cooling demand would increase more for
Figure 6.10: The annual cooling energy increase if increasing the GWAR from 0.33 to 0.86 versus annual mean temperature.

a climate with high global solar radiation and that the increase is larger for the low energy house than for the standard house. Fig. 6.10 shows that it is not possible to foresee how large the increase in cooling demand would be for a larger glazed area by looking at the annual mean temperature of the climate.

Different window areas were investigated for the office building in three climates. Figs. 6.11 and 6.12 show the results for Stockholm and Brussels. The south and north office are presented separately for a large, middle and a small area, see Table 5.4. The annual heating demand per floor area is shown on the positive y-axis and the negative y-axis represents the cooling demand per floor area.

Looking at the heating demand for the office it can be seen that a lower U-value decreases the influence of the window area. In some cases a larger area could even decrease the heating demand, i.e. when the U-value is low and the window faces south. The cooling demand is always minimized if one of the small window areas are chosen. Here the glazed area is of less importance if the g-value is low.

In Rome, see Fig. 6.13, the heating demand is so small it is not possible to evaluate how the window area influences the space heating demand. The cooling demand, however, can be significantly reduced by choosing a smaller window area, especially if it faces south. A large fraction of the cooling load is for this type of climate caused by high external temperatures, and not only by direct solar radiation, which means it cannot be fully prevented by controlling
Figure 6.11: The energy demands for different window areas in Stockholm. The positive axis represents heating demand and the negative axis shows cooling demand per m² floor area. The first six bars for one type of window show the result for the south office, the next six are for the north office.

Figure 6.12: The energy demands for different window areas in Brussels. The positive axis represents heating demand and the negative axis shows cooling demand per floor area. The first six bars for one type of window show the result for the south office, the next six are for the north office.
Figure 6.13: The energy demands for different window areas in Rome. The positive axis represents heating demand and the negative axis shows cooling demand per floor area. The first six bars for one type of window show the result for the south office, the next six are for the north office.

the solar heat gain.

Brussels and Stockholm have similar cooling demands, which shows that for a large part of Europe it is possible to avoid air conditioning systems by using windows that minimize the cooling load. It also shows that even in a Nordic climate it is essential to install energy efficient windows not only for heating reasons but also to avoid overheating. Rome needs much more energy for comfort cooling but on the other hand almost no heating. When the windows are in their colored states, the difference in cooling demand between the different window areas is less pronounced for all the investigated climates. The south office needs more cooling than the north for each of the climates. It is important to consider the window area facing south for all climates, but especially in climates similar to that in Rome with a long cooling season.

By installing a larger window area the artificial lighting can be reduced and therefore the cooling demand decreases to some extent. On the other hand as the electric lighting becomes more energy efficient the potential for saving by using large window areas will decrease. This was not investigated.
7. Conclusions and outlook

The energy transport through windows is a complex process to describe. Depending on for example outdoor climate, shading surroundings and building orientation the window type and area have to be chosen carefully and every building has its own optimum area. Different glazed areas have been investigated by using a building energy simulation program which makes it possible to keep many parameters fixed in order to find out how one parameter influences the energy balance of a building. If the same study would be made experimentally it would be impossible to keep parameters, such as internal gains and climate fixed. In this chapter some conclusions are presented followed by an outlook for the future.

7.1 Terraced houses

The results show that if energy efficient windows are chosen, the flexibility of choosing the glazed area and building orientation is higher. Choosing a larger area resulted in a higher heating demand for uncoated double glazing in the standard house. Choosing an energy efficient glazing gave a decrease in heating demand for an increased glazed area facing south in the standard house. In the low energy house the difference between different areas was smaller than for the other cases. An evenly distributed glazed area around the house would result in a higher quality in the daylighting conditions for every room. An increased area also resulted in an increased peak load for heating for all the simulated cases. The peak load occurs during cold nights and therefore it is mainly the U-value that influences how large it will be and the g-value is of less importance.

Looking only at the cooling requirement for the low energy house, the optimum would be to reduce the window glass area facing south to zero, but that would be unrealistic. Using shading devices or solar control coated glazing on the windows facing south would be a good way of reducing the cooling demand during the summer as well as on sunny days during spring and fall. It is very easy to air the studied terraced houses, which means that the cooling demand is of less significance than the heating demand. If these houses are built in a warmer climate with more solar radiation, and where air-conditioning might be used, it is important not to choose too large windows in order to
keep the peak load for cooling down. The cooling demand is only marginally influenced by the orientation of the facade with the large window area. One reason for this is the shading from the protruding roof and balcony that prevents the incident solar radiation from entering the house. On a hot summers day, a high cooling load or excessive indoor temperatures can be avoided if a smaller window area facing south is chosen at the design stage.

A comparison of the different types of buildings shows that different window areas and orientation of the house make less difference on the heating demand for the low energy house than for the standard house. Using energy efficient building technology therefore leads to higher flexibility in designing the building.

The glazed area was varied for most of the simulations on the terraced houses. A few simulations, however, were made where the frame area was varied together with the glazed area, and the results do not differ much. The heating demand is increased for the largest case of GWAR=0.86 because the wall area with a lower U-value is replaced by the frame element with higher U-value. For a smaller area than GWAR=0.42 the heating demand is slightly decreased instead. Having a constant frame, however, does not influence the trends and conclusions drawn from the simulations.

The comparison of the differences in heating demand for the different houses should be done in absolute numbers (kWh/m²) since the heating demand is much lower in total for the low energy house. However, for the standard house, especially with uncoated double glazing the increase in heating demand is larger when increasing the glazed area. Since the need for energy is so low in the low energy house, slightly higher internal gains or a less efficient heat exchanger on the ventilation system leads to a significant difference in the heating demand. This can be seen in Paper V, where the parametric study implies that the input data have a greater impact on the energy demand than the choice of building energy simulation software.

Other important factors influencing the choice of window area are the view, the daylighting and the comfort of the room. A larger window area may imply that the interior becomes more exposed to the outside which can be unpleasant for the occupant. Large glazed areas will also lead to a draught from the cold glass surface and excessive indoor temperatures which cause discomfort for the occupants.

7.2 Office buildings

In modern office buildings the window area tends to be larger than what is traditionally common, and fully glazed facades are now frequently used to achieve high daylight levels inside and to obtain an attractive appearance of
the building. This creates a problem of overheating, which can be partly prevented by different kinds of solar shading, but in practice an acceptable indoor environment is reached by air conditioning. This, however, costs us a lot of energy and some of it could be saved by choosing energy efficient windows, such as solar control windows. In the future switchable windows could be used, which have the possibility of varying the transmittance of solar radiation and can in this way minimize the heat coming from the outside through the window during sunny days. In this case the window size is also an interesting issue.

The results show that there is a great energy saving potential if switchable windows are used compared to the double low-e windows. The cooling demand is halved for the climate of Rome and almost diminished for Stockholm and Brussels. The heating demand is only marginally influenced by using the switchable windows.

An appropriate window area could reduce the maximum cooling load during days with an overheating risk. The window area should not be too small though, since the light coming in through the windows is essential for a healthy working environment. The colored state of the switchable window could reduce the cooling load down to the same level as for a small area of the same window in its bleached state. It is important to consider the window area that receives most of the solar radiation during the day for all climates, but especially in climates similar to that in Rome with a long cooling season.

Brussels and Stockholm have similar cooling demands, which shows that in a large part of Europe it is possible to avoid air conditioning systems by using windows that minimize the cooling load. It also shows that even in a Nordic climate it is essential to install energy efficient windows not only for heating reasons but also for avoiding overheating.

Also for this type of building energy efficient glazing leads to a higher flexibility of the building orientation and window area. In this case, however, the energy efficiency is not only having a low U-value, but also to restrict the g-value by using solar control windows or switchable windows.

A large glazed area is often used to achieve high daylight levels in the room. Some claim that the higher heating demand that may be caused by a larger window area can be replaced by a smaller energy need for electric lightings. There is a limit, however, where the effect of daylight savings is saturated, and with more energy efficient electric lighting this may not be as profitable as before.
7.3 Outlook

In the future it would be interesting to study other residential houses with similar windows as studied in this thesis, but with more of these windows facing north than today and less window area facing south to get a better distribution of the light. The same building strategy could also be applied to detached houses, in which case windows could be orientated in all directions.

Using a more complex ventilation model and studying the cooling demand more in detail is also of interest, especially for the climates with low annual mean temperatures and high global solar radiation. This could be compared with the impact of shading devices on the cooling demand. Another question is how the window area influences the energy balance of a house that is strongly shaded by surrounding buildings.

An investigation of the regulation method for switchable windows in the office building would refine the possible energy savings. There is a potential to improve the properties, such as higher transmittance in the bleached state and lower transmittance in the colored state, which can improve the energy savings.

Another parameter that influences our choice of building design is the thermal comfort. This can be investigated both by theoretical models and by interviews with the occupants. Larger window areas may cause larger temperature differences in the room, which leads to larger air movements that leads to discomfort. The indoor comfort situation also depends on how the heat is supplied to the room. Today, the radiators are normally placed below the windows to directly heat the cold air from the glass surface. In the future other options might become more common. Finally, the window area does not only influence the energy demand, but also factors such as the architecture, the view to the inside and to the outside, and the lighting conditions.
8. Summary in Swedish


Denna avhandling handlar om hur man genom att välja fönstertyp och storlek på fönstren kan spara energi varje dag man befinner sig i byggnaden utan att röra ett finger. På köpet får man en god inomhuskomfort utan kallras och med gott dagsljusinsläpp.

8.1 Energieffektiva fönster

Fönstren ger oss dagsljusinsläpp och en möjlighet att se både ut och in i våra hus. De har genom åren setts som en svag länk i byggnadens skal eftersom värmegenomsläppligheten är tio gånger större genom ett fönster än genom en vägg. Med ny teknik har man lyckats förbättra fönstrens isoleringsförmåga, varför det idag är möjligt att öka fönsterytan i en byggnad utan att energiförlusterna ökar. Det är dock fortfarande så att fönstrets isoleringsförmåga är sämre än väggens och en alltför stor glasfasad kan leda till högre energiförbrukning och lägre komfort.

Solstrålningen som når oss på jorden kan delas in i tre olika intervall. Det är den med kortast våglängd som vi kallar för UV-ljus, lite längre våglängd har det synliga ljuset som vi kallar för VIS (visuellt) och längst har den nära infraröda (NIR) strålningen som vi upplever som värme. Energin som vi får från solen ligger huvudsakligen inom VIS med ungefär 50% av den totala energin och NIR med cirka 40-45%. Den infraröda strålning (IR) som alla kroppar (t ex möbler, väggar och människor) strålar ut har ännu längre våglängd än de ovan beskrivna, och det faktum att olika våglängder har olika egenskaper kan utnyttjas när fönsterglas designas.

Genom att belägga fönsterglas med ett tunnt ytskikt, 50-100 atomlager, kan


### 8.2 Spelar storleken roll?

Energibalansen i en byggnad beskriver hur tillförd energi från solen och interna energikällor balanseras mot energiförluster i elektrisk utrustning och byggnadens skal. Om energiförlusterna är större än den tillförda energin leder detta till att temperaturen inomhus sjunker och vice versa.

Hur påverkas energibalansen då en större fönsterarea installeras i en byggnad? I denna avhandling har simuleringar genomförts där fönsterarean har varierats och beroende på klimat, typ av byggnad och fönstrets orientering blir resultaten lite olika.

För ett välisoleras radhus med energiglas i ett tempererat klimat spelar storleken mot söder inte så stor roll sett till värmebehovet över ett år. Detta beror på att värmebehovet inträffar främst under de kalla mörka vinterdagarna då en större glasyta med högre energiförluster inte kan kompenseras av extra solenergi. Huset har lägst energibehov om det orienteras med den stora glasytan mot söder, men att välja en annan orientering påverkar inte värmebehovet radikalt. Det torde därför vara lämpligt att placera
fönstertytan mer jämnt över fasaden så att dagsljusinsläppet ökar i norr och värmetillförseln genom fönstren minskar något i söderrummen under soliga sommardagar.


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