Climate and Energy Use in Glazed Spaces

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1996

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Report TABK--96/1009

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Building Science

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This report relates to Research Grant No 930118-2 and 930930-7 from the Swedish Council for Building Research to the Department of Building Science, Lund University, Lund Institute of Technology, Lund, Sweden.

Keywords

atrium buildings; glazed spaces; climate; solar energy; energy requirement; heating; cooling; thermal comfort; calculations; field measurements; design tool.

Swedish translated and English edited by L J Gruber BSc(Eng) MICE MIStructE
Layout: Hans Follin,LTH, Lund
Cover front: The Palm House in Kew Gardens outside London.
back: Arcade in London.

Printed by Wallin & Dalholm Boktryckeri AB, Lund, Sweden, 1996

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ISSN 1103-4467
ISRN LUTADL/TABK--1009--SE

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Abstract

Glazed spaces ranging from small glazed verandas to large atrium buildings have become a common feature in architecture. A glazed space is greatly affected by aspects of the outside climate such as insolation and temperature. In the design of such spaces, more sophisticated design tools are therefore required in order to estimate the climate inside the glazed space and the energy requirements for heating and cooling than in the design of ordinary buildings.

One object has been to elucidate the relationship between building design and the climate, thermal comfort and energy requirements in different types of glazed spaces. Another object has been to study the effect of the glazed space on energy requirements in adjacent buildings. It has also been the object to develop a simple calculation method for the assessment of temperatures and energy requirements in glazed spaces.

The research work has mainly comprised case studies of existing buildings with glazed spaces and energy balance calculations using both the developed steady-state method and a dynamic building energy simulation program. Parameters such as the geometry of the building, type of glazing, orientation, thermal inertia, airtightness, ventilation system and sunshades have been studied. These parameters are of different importance for each specific type of glazed space. In addition, the significance of each of these parameters varies for different types of glazed spaces.

The developed calculation method estimates the minimum and mean temperature in glazed spaces and the energy requirements for heating and cooling. The effect of the glazed space on the energy requirements of the surrounding buildings can also be estimated. It is intended that the method should be applied during the preliminary design stage so that the effect which the design of the building will have on climate and energy requirement may be determined. The method may provide an insight into how glazed spaces behave with regard to climate and energy.

Contents

List of symbols

A	area (m²)
a	absorptivity (-)
$C(0)$	tracer gas concentration at time 0 (ppm)
$C(t)$	tracer gas concentration at time t (ppm)
c_h	actual cloud base height (km)
c_{h0}	reference cloud base height (8.2 km)
c_n	fractional area of the sky covered by clouds (-)
c_p	heat capacity of air (Wh/kg°C)
DR	draught rating, i.e. the percentage of people dissatisfied due to draught (%)
d	distance from the wall (m)
E_{cool}	energy requirement for cooling the glazed space (MWh)
E_{heat}	energy requirement for heating the glazed space (MWh)
E^t_{to}	fabric losses between the buildings and the glazed space (MWh)
$E^t_{to,red}$	reduction in fabric losses between the buildings and the glazed space (MWh)
E^v_b	total ventilation losses of the adjacent buildings (MWh)
E^v_g	total ventilation losses of the glazed space (MWh)
G	ratio between specific losses and specific gains of the glazed space (-)
h	number of hours
h_D	hour of the day
$I_{D,m}$	direct solar radiation of perpendicular incidence, measured (W/m²)

$I_{D,c}$	direct solar radiation of perpendicular incidence, calculated for clear days (W/m²)
M	heat storage capacity (Wh/°C)
n	number of air changes per hour (1/h)
n_g	number of air changes per hour in the glazed space (1/h)
n_i	number of air changes per hour in adjacent buildings (1/h)
P_{abs}	mean power of absorbed solar radiation (W)
P_{cool}	power requirement for cooling the glazed space (W)
P_{heat}	power requirement for heating the glazed space (W)
P_{sun}	transmitted solar radiation, mean over time (W)
$P_{tot,gl}$	total incident short wave radiation on the outside of the sunspace (W)
$P_{trans,gl}$	total short wave radiation transmitted into the sunspace (W)
$P_{net,gl}$	the part of $P_{trans,gl}$ that remains in the sunspace (%)
P_{tot}	total incident short wave radiation on the outside of the windows of the room (W)
P_{trans}	total short wave radiation transmitted into the room (W)
P_{net}	the part of P_{trans} that remains in the room (%)
p_{atm}	atmospheric pressure (mbar)
PMV	predicted mean vote. Index that predicts the mean value of the votes of a large group of persons on a 7-point thermal sensation scale. (ISO 7730)
PPD	predicted percentage of dissatisfied. Index that predicts the percentage of people likely to feel uncomfortably warm or cold. (ISO 7730)
Q^t_{from}	fabric losses of the glazed space (W)
Q^v_{from}	ventilation losses of the glazed space (W)
Q_{from}	the sum of fabric losses and ventilation losses of the glazed space (W)
Q^t_{to}	transmission gain in the glazed space (W)
Q^v_{to}	ventilation gain in the glazed space (W)
Q_{to}	total gain in the glazed space (W)

Q_{trans}	transmitted solar radiation for the glass combination in question (W/m²)
$Q_{trans,clear}$	transmitted solar radiation for the clear glass combination with the same number of panes as the glass combination in question (W/m²)
R	long wave sky radiation (wave length > 4 μm) (W/m²)
S	solar collection property of the glazed space (-)
T_g	temperature in the glazed space (°C)
$T_{g,heated}$	required temperature in the glazed space (°C)
T_i	temperature in adjacent buildings (°C)
T_o	outside temperature (°C), (K)
T_{sky}	sky temperature (K), (°C)
T_{dp}	dew point temperature (°C)
T_{local}	local air temperature (°C)
$T_{\perp}$	transmission for the glass combination in question, for perpendicular incidence (-)
$T_{\perp,clear}$	transmission for the clear glass combination for perpendicular incidence (-)
TU	local turbulence intensity, defined as the ratio of the standard deviation of the local air velocity to the local mean air velocity (%)
t	time which has elapsed between the two values of tracer gas concentration (h)
U	heat transfer coefficient (W/m²°C)
V_g	volume of glazed space (m³)
V_i	total volume of adjacent buildings (m³)
v	local mean air velocity (m/s)
v_{max}	maximum air velocity (m/s)

Greek symbols

ε_{sky}	sky emissivity (-)
ε_0	clear sky emissivity (-)

ε_c	hemispherical cloud emissivity (=1)
η	energy efficiency of the heat exchanger (-)
ρ	density of air (kg/m^3)
σ	$5.6696 \cdot 10^{-8}$ (W/m^2K^4) (Stefan-Boltzmann Constant)
τ	time constant (h)

Acknowledgements

I wish to thank the property owners and managers who made buildings available for measurements and provided the necessary information. They all adopted a positive and helpful attitude to my wishes which may at times have been rather demanding.

I also wish to thank all colleagues at the Department of Building Science who have helped me in my work. I especially want to thank my supervisor, Professor Bertil Fredlund who has been patient for such a long time.

I am also grateful to research fellows in other countries who have given me so much joy in my work. Dedicated research colleagues are essential for my happiness.

Last but not least, I wish to thank the Swedish Council for Building Research which has financed the research work. I also wish to thank the Central Office of Historic Monuments in Norway which financed a part of the study on the abbey church ruins at Hamar, Norway.

Hopefully this is the end of the beginning, not the beginning of the end.

Lund, November 1996

Maria Wall

1 Introduction

This chapter describes the background to the research work. After a brief historical review, the aims and limitations are set out. Previous research in this field is discussed and related to the thesis.

1.1 Background

During the 1980s, glazed spaces became a common feature in new buildings, both in Sweden and in other countries. There were many ideas and great enthusiasm. Both small glazed spaces such as verandas and balconies, and larger ones covering whole courtyards, streets and squares, were built. Existing buildings were also converted; balconies were provided with glazing and the spaces between buildings were covered with a glazed roof in order to provide climatic protection. In the 1990s also the use of lots of glass in buildings has continued to be popular.

Office buildings often have a glazed courtyard which is used as a circulation space, cafeteria, restaurant, reception, etc. There are also many examples of hotels where the reception, breakfast room and restaurants are located in the atrium. In commerce, it is hoped that glazed arcades and galleries will increase the number of customers.

In the residential sector also, glazed courtyards and arcades are used, apart from circulation, to enhance social contact and social intercourse between the residents. During large parts of the year, it is so cold in Northern Europe that we do not like being outdoors to speak with a neighbour. The idea is that the glazed space will function as a room which will be perceived as intermediate between indoors and outdoors. It is warmer than outdoors, and in addition there is no rain, snow or wind. In this way, we will spend more time outside the dwelling and make contacts with our surroundings. As far as glazed verandas and balconies are concerned, there is sometimes the idea that plants and vegetables can be grown for household needs.

Those who design the glazed space have their own ideas and visions about how the glazed space will function and the temperature level which will be provided. The users also make demands. They have formed an impression of what a glazed space can be used for, and, among other things, stipulate the temperature level which must be maintained.

In addition, those who design the glazed space want this to be aesthetically pleasing and comfortable to use. If they do not know how the design of the building can affect the climate and energy needs in the glazed space and the surrounding buildings, the design adopted at an early stage may have the result that the climate in the glazed space will be unacceptable. There will then be a temptation to provide both heating during the winter and active cooling in the summer inside the space. The intention to save energy cannot be realised, and total energy use may even be higher than if no glazing had been installed.

Since, in most cases, building regulations in Sweden and also in other countries do not impose specific requirements on glazed spaces apart from those relating to fire safety, it is possible for the general building regulations to be interpreted differently in different parts of a country. This can create confusion and irritation. The difficulties in judging at an early stage how the glazed space will function from the standpoint of energy and climate do not make the situation any better.

Obviously, many problems can arise. The rain can come in, or the acoustics may be poor, with a long reverberation time. It may be appreciably hotter in summer, and colder in winter, than had been envisaged. These are only some examples of what may happen. A carefully thought-out project where it is really known what requirements are stipulated for the glazed space, and an endeavour is made to meet these, has a far better chance of being successful. *Merely providing a glazed roof for a space does not mean that the climate will automatically become just right.*

It is obvious that there is a need to elucidate the general relationships between building design and climate in a glazed space, and between building design and energy needs in the glazed space in combination with adjoining buildings. It is particularly important to produce knowledge which can be applied at an early stage of design so that well functioning buildings with glazed spaces may be constructed.

Through practical case studies and different types of theoretical studies, work on this thesis has concentrated on increasing general knowledge of glazed spaces. Work on practical design aids has also begun but has not yet been completed.

1.1.1 Development and uses of glazed spaces – brief historical review

As early as the first century after the birth of Christ, there is a description of how the Romans tried to grow cucumbers all round the year (Hix, 1974). The Romans grew cucumbers in large pots with wheels so that they could be easily pushed out into the sun. The pots were covered with a transparent material as protection against the cold outside air and so that sunshine may be utilised more effectively. The transparent material was talc which was cut into thin layers. The *greenhouse effect* was thus noted even then, namely that transmission of short wave solar radiation through glass and closely related materials is high, while the long wave thermal radiation which is emitted, in this case from the pot, is not transmitted so easily but is kept inside.

It was not until the sixteenth century that growing conditions were subjected to a more systematic study. The first botanic gardens were created in Italy and Holland in the middle of the sixteenth century. What were then called greenhouses were only simple brick buildings which were used as a shelter in the winter and could be heated. There was great interest in creating an artificial climate. Botanists and gardeners travelled all over the world to collect exotic plants which naturally had special climatic needs. In order that these plants could survive in the cold climate of northern Europe, the properties of the greenhouses had to be improved. A botanic garden was highly valued and became very popular at this time.

Gradually, *greenhouses* with glass in the windows were built. The windows were oriented towards the south, and to the north there was a thick brick wall without windows. At the beginning of the eighteenth century, sloping glazed roofs were developed in Holland and Switzerland. The duty of the thick wall towards the north was to store heat for the night, and the whole southern facade now consisted of glass in wooden frames, with hinges at the sides or the top. The windows were often open in the summer to keep temperature down while they were kept closed in the winter. Oiled paper on a wooden frame or several layers of cloth were set up in front of the windows as extra insulation in winter. There were also wooden shutters which could be put in front of the windows.

John Claudius Loudon was a gardener and botanist in England at the end of the eighteenth and the first half of the nineteenth century. He advocated the use of glass and iron for greenhouses. This produced slender structures and admitted more light into the greenhouse. Spans could also be larger than for wooden structures.

Loudon developed theories according to which the angle of the glazed surface should be perpendicular to the direction of solar radiation, since in this way transmission of solar radiation was greatest. He did not recommend flat roofs since condensation would in this case drop straight down and damage the plants. Roofs should instead be angled (as in a pitched roof) so that one side was perpendicular to the morning sun and the other to the afternoon sun. Condensation could be drained down into the iron construction which supported the roof. In order to prevent rust, the iron rods could be heated and then covered with paint, coal tar, lead or a tin alloy.

Loudon who died in 1843 had a great influence on the development of greenhouses. He and many others studied the effect of different technical options, for instance the slope of the glass, orientation, window opening, solar control and different types of heating systems. He also had great visions which he set out in his book *Encyclopaedia of Gardening* 1822 (quoted from Hix, 1974):

> Indeed, there is hardly any limit to the extent to which this sort of light roof might not be carried; several acres, even a whole country

> residence where the extent was moderate, might be covered in this way.

He thought specifically of northern countries with harsh climates when he wrote:

> In Northern countries, civilised man could not exist without glass; and if coal is not discovered in these countries, say, in Russia, the most economical mode of procuring a proper temperature will be by at once covering whole towns with immense teguments of glass, and heating by steam or otherwise, the enclosed air common to all the inhabitants.

Development did not proceed quite so fast, but as iron structures began to be used, greenhouses in any case became larger. It was mainly the engineering aspects which were developed. One of the most prominent engineers in this field in England in the 19th century was Richard Turner (Hix, 1974). He designed many glass buildings, but what he became best known for was the Palm House in Kew Gardens on the outskirts of London; see Figure 1.1. The building was designed in 1844-66 in collaboration with the architect Decimus Burton and was wholly constructed of glass and iron. The Palm House is still in existence; it was completely restored in 1984-89.

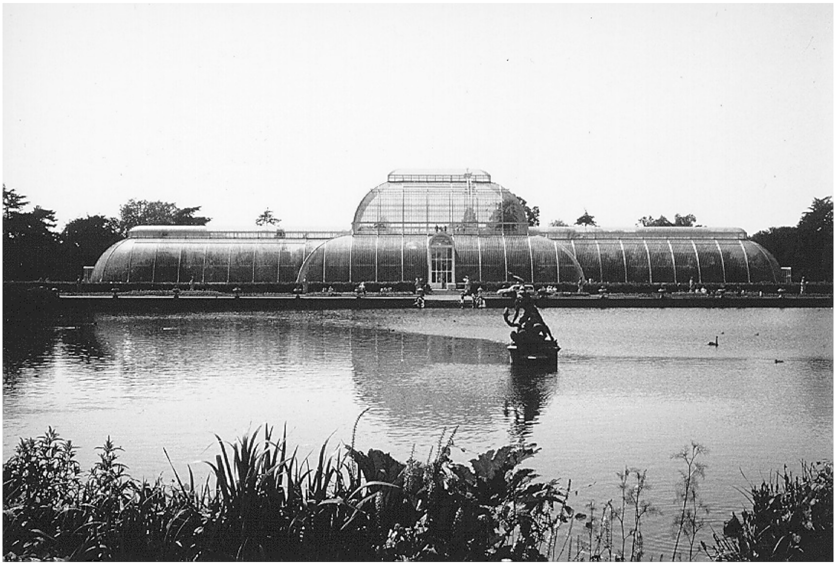


Figure 1.1 The Palm House in Kew Gardens outside London, 1844-1866.

The Palm House in Kew Gardens was one of the first glass buildings constructed with tax free glass in England. The tax on glass which had been levied in England was repealed in 1845 (Cornell, 1952). Previously it was only wealthy people who could use a lot of glass in their buildings. In Sweden a tax on glass was introduced in 1743 and repealed in 1806.

After the repeal of the tax in England, Joseph Paxton who was the gardener of the Duke of Devonshire had the economic conditions which he needed to experiment with glass. The great *world exhibitions* had *glass pavilions*. In view of his practical experience, Paxton was given the task of building the Crystal Palace for the Great Exhibition in Hyde Park, London, in 1851; see Figure 1.2. This huge glass building covered an area of over 70 000 m² and was constructed in less than one year. That this was possible was largely due to England's early industrialisation and a huge work force. The building consisted of standardised and prefabricated parts which greatly facilitated the work. The greatest proportion of the loadbearing structure was of cast iron but there were some timber structures also. The interior colour scheme was devised by the architect Owen Jones, using the colours blue, green and red.

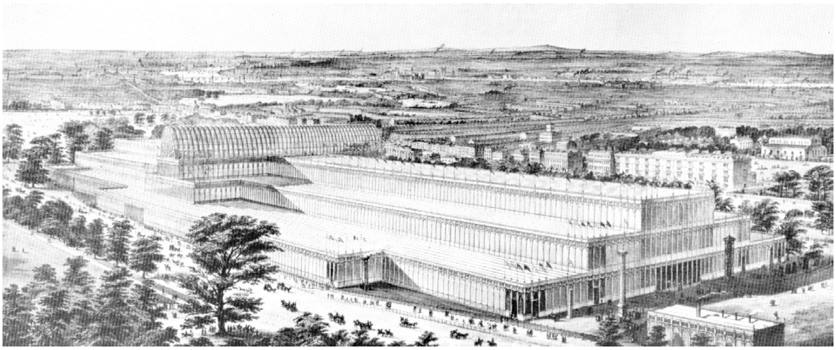


Figure 1.2 Crystal Palace, London, 1851 (Hix, 1974).

In 1854 the Crystal Palace was taken down and, after certain modifications, erected again at Sydenham outside London. In 1936 it was destroyed by fire. This building gave rise to an explosion of building in similar projects in different countries. A Crystal Palace was also constructed for the World Exhibition in New York, but it burnt down in 1858 although it was considered fireproof. For the 1889 Paris Exhibition, the Galerie des Machines was built; this was a large exhibition hall of 115 m width and 240 m length, of glass and steel. See Figure 1.3 (Pevsner, 1976). It was designed by the architect Dutert and the engineers Contamin, Pierron and Charton.

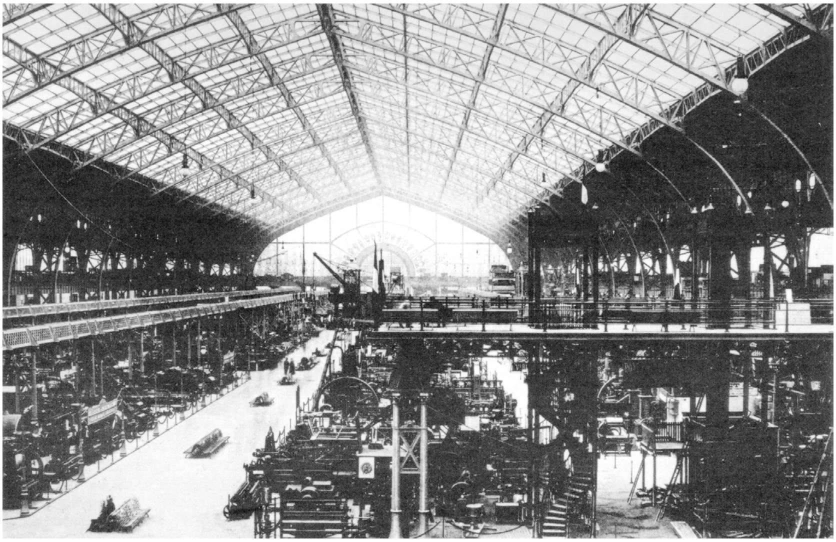


Figure 1.3 Galerie des Machines, Exhibition of 1889, Paris (Pevsner, 1976).

As development of railways began in earnest during the 1850s, railway stations also began to be built. These were often constructed as large halls of glass and iron, inspired by Paxton's Crystal Palace. Examples which may be mentioned are Paddington Station 1854 and St Pancras Station 1866, both in London.

The glazed room also began to be associated with ordinary buildings in the 19th century. In the 1870s and 1880s, *conservatories* opening from the music room or smoking and billiard room of the house were constructed.

During the 19th century, greenhouse building underwent development on a large scale. In order that the exotic plants could flourish, central heating and ventilation systems were invented. Such advanced technology was not used in ordinary buildings until some time in the 20th century when air conditioning also made its appearance.

Arcades also became popular. An arcade is characterised by a mixture of small shops with different types of goods (Pevsner, 1976). By making the street accessible only to pedestrians and also covering it over as protection against rain and snow, a pleasant passage or arcade was created. The possibility of using glass and iron for roofs was made great use of in the 19th century for arcades. Climatic protection was created and at the same time not much light was lost. A magnificent example is GUM in Moscow; see Figure 1.4. This bazaar consists of 16 blocks with longitudinal streets and three shorter cross streets. It was designed by Pomeranzev and built in 1888-1893 (Pevsner, 1976).

Figure 1.4 GUM in Moscow, 1888-1893 (Pevsner, 1976).

In Paris, Galerie d'Orléans was built as early as 1828-1830. The arched glass roof was new and inspired others to construct similar buildings. Several examples from the beginning of the 19th century are also to be found in London. One is Royal Opera Arcade by Nash and Repton, built in 1816-1818. Barton Arcade in Manchester came later, in 1871. This building is four storeys tall, the bottom floor consists of shops and the others house offices (Saxon, 1983). The glass roof is arched and is supported by an iron structure. Along the facades there are balconies; see Figure 1.5.

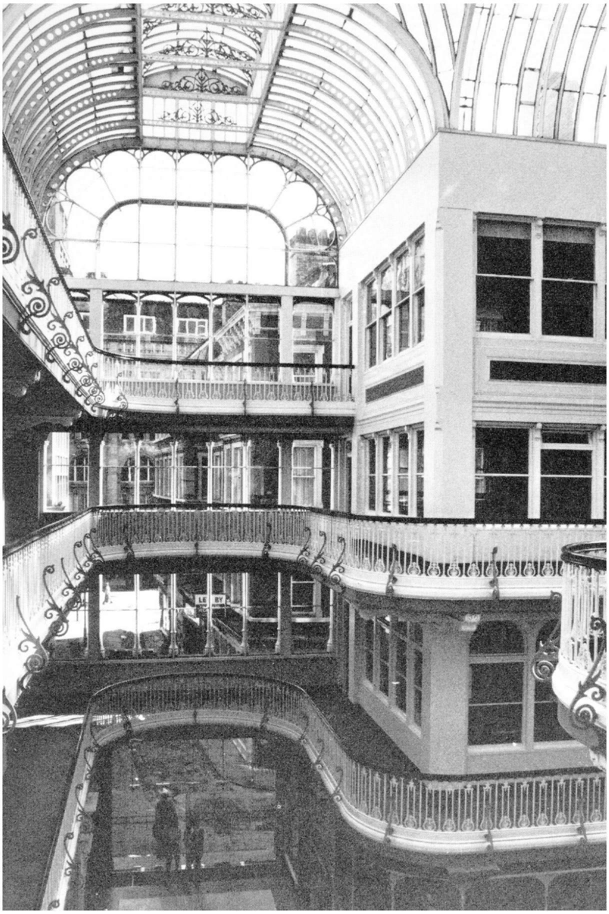


Figure 1.5 Barton Arcade, Manchester, 1871 (Saxon, 1983).

There is another well known arcade which must be mentioned, Galleria Vittorio Emanuele II in Milan. This was designed by Giuseppe Mengoni and built in 1865-1867. It consists of two streets in the form of a cross and has an arched glass roof; see Figure 1.6. This arcade is 29 m tall except where the streets intersect, where an octagonal place was formed with a glass dome over it. This place is 42 m tall and has a diameter of 39 m.

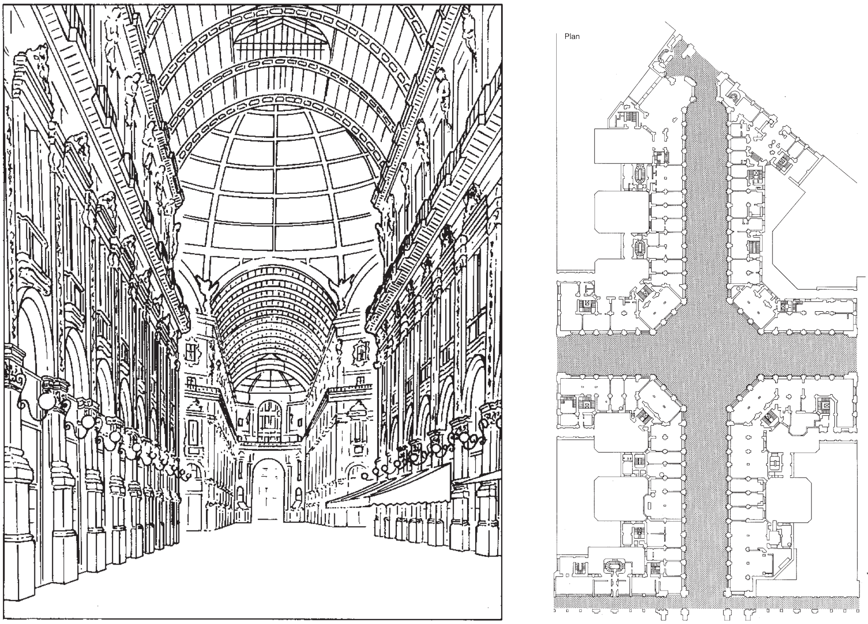


Figure 1.6 Galleria Vittorio Emanuele II, 1865-1867 (Saxon, 1983).

At the end of the 19th century, the interest in building this type of arcade declined. However, apart from GUM in Moscow, an arcade was built in Cleveland, Ohio, as late as 1888-1890. This is considered to be one of the finest in the USA; see Figure 1.7.

In Roman architecture, *atria* were often used. At the centre of the house there was an open courtyard - an atrium. A basin in the centre collected rainwater which came in through the open roof. This architecture first spread to the Middle East. The buildings face inwards where all activity takes place, while the back of the building is towards the outside (Saxon, 1983). This is seen plainly in the plan of the town of Isafahan in Iran; see Figure 1.8. All buildings have a courtyard in their centre and the main street is roofed over, but not with glass. This roofed market place is called a bazaar. The atrium courtyards are on the other hand open to the sky.

Figure 1.7 Arcade, Cleveland, Ohio, 1888-1890 (Saxon, 1983).

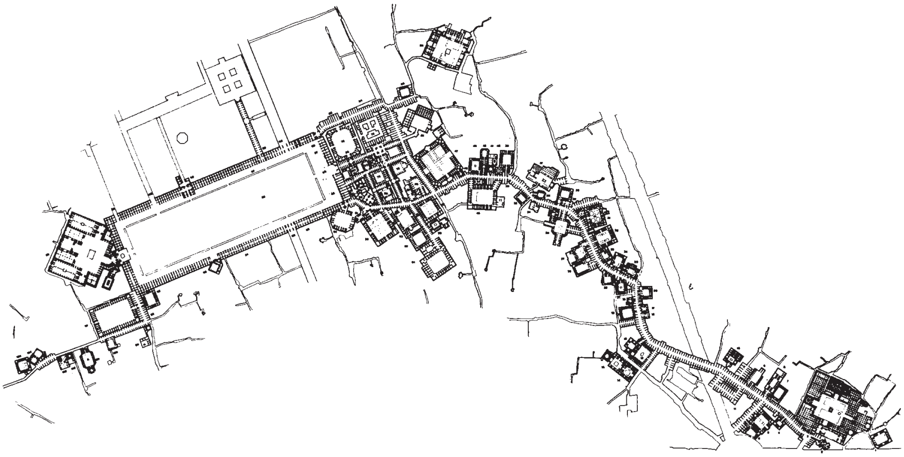


Figure 1.8 The city of Isafahan, Iran (Saxon, 1983).

The modern atrium which made its appearance at the beginning of the 19th century was in principle an indoor environment with a roof wholly or partly of glass. The developments which had taken place made it easier to build such roofs, and in this way more light was admitted into the building. This meant that the depth of the building could be increased.

One of the first modern atria was an art gallery in Shropshire in England, built by John Nash in 1806. The whole roof was not of glass here, but a considerable amount of light was nevertheless admitted. Using these light wells, magnificent and exclusive environments could be created; one example is the Reform Club in London, built by Sir Charles Barry in 1837.

Different exchanges also began to be constructed, and some made use of the new glass technique. One such example is the Coal Exchange in London which was built in 1846-1849 by J.B. Bunning; see Figure 1.9 (Pevsner, 1976). The circular central atrium was four storeys high, with a dome of glass and iron. The atrium was richly decorated.

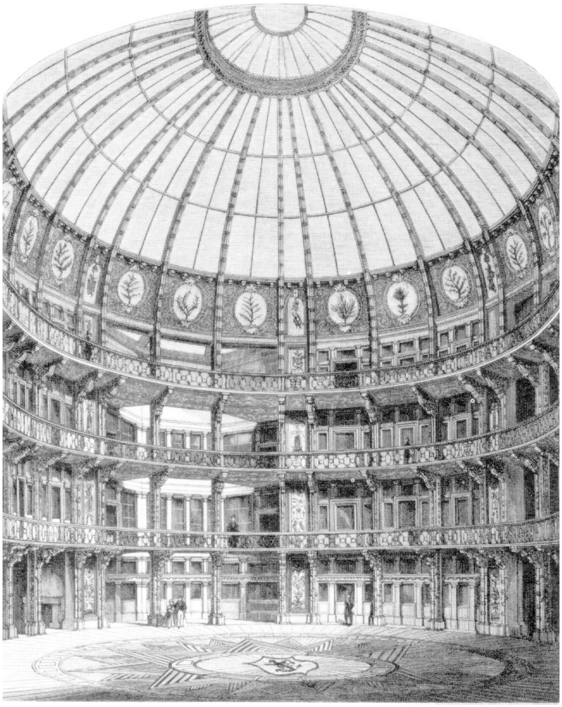


Figure 1.9 Coal Exchange, London, 1846-1849 (Pevsner, 1976).

In 1893, the Bradbury Building in Los Angeles was constructed by George Wyman. It contained a four storey atrium covered with a glass roof; see Figure 1.10 (Bednar, 1986). In the atrium there were staircases with access balconies on all sides, and two open lifts of iron construction. The atrium was decorated with palms, and the design of the building was based on science fiction speculations on what buildings would look like in the year 2000!

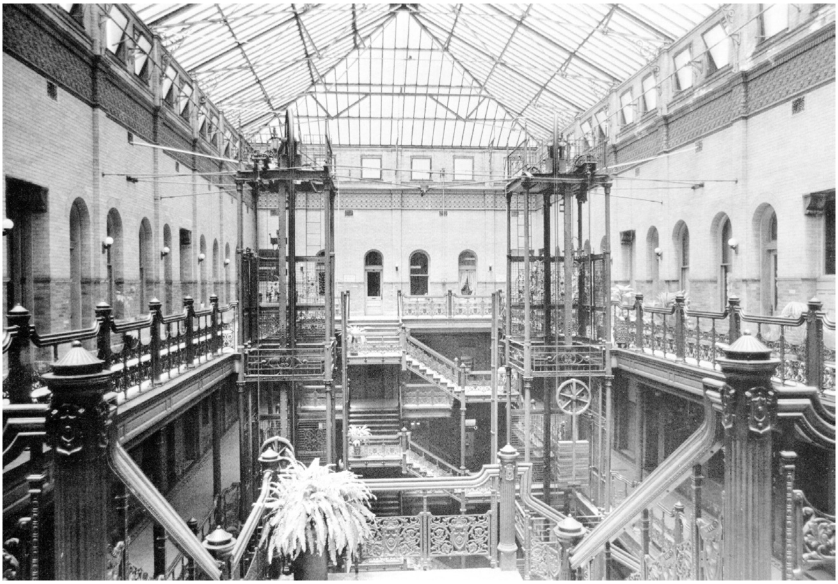


Figure 1.10 The Bradbury Building, Los Angeles, 1893 (Bednar, 1986).

Hotels in the 19th century also made use of the glass roof technique. Atria were used as access spaces to the hotel rooms, and at the bottom there was a bar or a lounge.

At the beginning of the 20th century a decline could be noted in glazed space construction. One well known building, the Amsterdam Stock Exchange, was however built in 1903. It was designed by the architect Berlage and contained an atrium with a roof partly of glass.

In Sweden, *verandas* began to be built already during the 19th century, but they had their greatest popularity during the first three decades of this century. They were based on the English country house. In the English house the veranda was a connecting link between the house and the garden. The glazed veranda, the "flower room", was most common. The English ideas provided the inspiration for the design of the Swedish summer houses of the 19th century (Svensson, 1974). The enclosed glazed veranda was often situated on one storey, but sometimes on two. It mostly served as a summer room, but this was changed to some extent when central heating was introduced. The walls of the veranda were then insulated and double glazing was installed so that it could be used all round the year. In the beginning the veranda was exclusively a flower room, a status symbol, but over time it became increasingly common even in ordinary buildings.

During this time, two different types of veranda can be distinguished in Sweden. One is the entrance veranda opening from the main entrance, the other a garden veranda which was often situated near the dining room and served as an access room to the garden. The garden veranda was used as an additional room, while the one at the entrance was a way of making this “refined” and more imposing.

When the first world war came, the popularity of glazed rooms declined. Glass was instead used in e.g. the US for the skyscrapers which were the buildings of the new modern architecture (Saxon, 1983). Land became more expensive, and there was no longer room for the atrium. One of the few examples of glazed spaces from this time is The Johnson Wax Headquarters in Wisconsin, USA. This was built in 1936 and was designed by the architect Frank Lloyd Wright; see Figure 1.11. The atrium is three storeys high and the roof is partly of glass.

Wright also made use of roof lights at the Guggenheim Museum in New York in 1959; this may have inspired other architects to start using the glass roof again in architecture.

Figure 1.11 The Johnson Wax Headquarters, Wisconsin, 1936 (Saxon, 1983).

The new glazing wave started in the 1960s. In the USA large hotels were built with atria with glazed roofs, for instance by the architect John Portman. In Sweden this type of construction increased in the 1970s when there was a new inducement for building glazed spaces. Energy saving suddenly became of very great interest after the energy crisis of 1973. Glazed spaces were seen as a kind of solar collector which would gather up large quantities of energy and would in this way reduce the energy requirements of adjoining buildings. Apart from energy conservation, there were also other motives. Some of the shopping centres built in Sweden during the 1960s had a poor environment with draughty pedestrian streets. To provide climatic protection and to make them more pleasant, they were glazed. One example is Skärholmen Centre outside Stockholm which was provided with glazing in 1984; see Figure 1.12.

Hotels were again being constructed with large glazed courtyards and atria. The Royal Garden Hotel in Trondheim, Norway, is an excellent example which the architect Per Knudsen of Henning Larsens Tegnestue designed together with the architects Clausen, Lund and Fasting, Trondheim. See Figure 1.13. The hotel was built in 1983. The reception, breakfast room and lounge are on the ground floor, and the hotel rooms are reached by staircases inside the courtyards. A lot of plants and water create a homely atmosphere.

Figure 1.12 Skärholmen Centre, Stockholm. Glazing constructed in 1984.

Figure 1.13 Royal Garden Hotel, Trondheim, 1983.

Office buildings with atria became even more common. Communications were also located inside the atrium, and the courtyard became a meeting point for the employees; see e.g. Figure 1.14 for the Block Stettin in Stockholm, built in 1981. This has two atria which are used as circulation spaces, foyer and coffee room.

Figure 1.14 Glazed courtyard in the Block Stettin, Stockholm, 1981.

Residential buildings have also been constructed with glazed spaces. The most common types in Sweden have been glazed verandas and glazed balconies. An early example is the TAHE building at Smålands Taberg, built in 1981, where each flat has a glazed veranda towards the south outside the living room; see Figure 1.15. The area was designed by Hidemark & Danielsson Arkitektkontor in collaboration with Professor Bo Adamson. The principal motive here was energy conservation. Various ecological villages also grew up in the 1980s, often with glazed verandas.

Figure 1.15 Blocks of flats with glazed verandas, Taberg, 1981.

Large glazed spaces in combination with dwellings are also found in Sweden, but they are not very common. The Block Gårdsåkra was built at Eslöv in 1983; this consists of 126 flats along two sides of a 375 m long street with a glazed roof. A Mediterranean climate had been hoped for in the glazed space, but this could not be realised without extensive heating in the street. In order to keep down the temperature in the summer, equipment for controlling vents and solar control curtains were installed, of the same type as those used in greenhouses. The Block Tärnan at Landskrona, built in 1983, is another example where the greenhouse technique is also used and which, in principle, has passive climatic control.

The demands concerning indoor climate seem to be getting more stringent, however, and new glazed spaces often make use of both cooling and heating where the building regulations permit. In Sweden, this is permitted, and there are many examples of large glazed courtyards which have both heating and cooling. One example is the Kabi Pharmacia research centre in Lund, built in 1991; see Figure 1.16. Air supplied to the glazed courtyard is preheated in the winter and cooled in the summer if necessary. The system works well in this case, but it is hoped that the glazed spaces of the future will to a greater extent rely on passive climatic control. But for this to become reality, it is necessary to have clear guidelines and simplified calculation programs which can be used already during the preliminary design stage.

In view of developments in glass technology, with different types of glass for different purposes, it is certain that the use of glazed spaces in architecture will continue. It is however essential that the new technical possibilities and the design aids needed for the study of e.g. the effect which low emission glass, solar control glass, absorbent or reflecting glass have on climate inside the glazed space, and not least on the perception of light in the space, are fully exploited.

Figure 1.16 Atrium at the Kabi Pharmacia laboratory, 1991.

1.1.2 Possibilities and limitations of glazed spaces

A glazed space has a lot of uses - a place in which to grow plants, to serve as a stairway or as a restaurant, to quote just a few examples. However, if the glazed space is to be regarded in a positive way and function as intended, it is essential that one thing is not forgotten. *It is an inherent property of a glazed space that it is greatly affected by the outside climate.* A lot of solar radiation enters through large glazed areas, and this can give rise to high temperatures in the summer. Since the insulation capacity of glass is inferior to that of a well insulated wall or roof, the glazed space is also greatly affected by the outside temperature. This implies, in turn, that low indoor temperatures can occur, especially during the cold and dark winter months. A well thought-out building design can make use of the outside climate to create the best possible climate inside the glazed space. It is only when this is not enough that heating or cooling must be provided - or the space must be redesigned! If a room must have a constant temperature all round the year, then a glazed space is not the thing to have. What is important is *to work with the climate,* *not against it.* One of the attractions of a glazed space lies precisely in the changes in light and temperature over the day and the year - naturally, within certain limits.

1.1.3 Aspects of glazed spaces

There are many aspects to consider when a building is constructed. This also holds for a glazed space, and in addition some aspects are more complicated than in the case of an ordinary building. Somebody must therefore assume overall responsibility and, with the help of specialists, produce properly thought-out solutions with regard to the various aspects. This person must at the same time ensure that the conflicts between the different aspects are resolved. The following are examples of important aspects with regard to glazed spaces:

- thermal climate inside the glazed space
- thermal comfort
- energy
- fire
- acoustics
- structure design
- aesthetics
- the users
- economy
- airtightness and raintightness
- snow
- ventilation, window opening
- daylight and lighting
- solar protection
- plants
- cleaning

This list can be made longer still, and it is easy to understand that what is the best option regarding one aspect need not be that with respect to another.

In the same way as in the construction process, this also poses a problem in research. A study in greater depth in one or more areas, with the aspects considered solved in the optimum way, does not guarantee that the whole system has been solved optimally. It is therefore essential that the unity is kept in mind. In research, this implies that one must be aware of the whole, but naturally one cannot be an expert in all areas. Delineation of research tasks is a practical necessity, but this does not mean that what is not considered is deemed unimportant.

1.2 Terms and definitions

Some of the terms used in this thesis are described below.

Atrium

According to the Swedish encyclopaedia Nationalencyklopedin [NE], an atrium is defined as a central room, with an opening in the roof, in Roman villas. In the middle of the atrium, underneath the roof opening, there is a sunken basin and the atrium is surrounded by small rooms. The origin of the word is in doubt, but according to NE it may be related to the Latin *ater* which means black, dark, and may in such a case refer to that part of the house which had been blackened by smoke from the fire.

In modern times, the German Bauhaus school in the 1920s created a new type of house, the atrium house. Atrium houses are small houses joined together and laid out internally in such a way that each house has access to an internal courtyard or patio, an atrium (NE). In Sweden, a large number of this type of atrium house were built in the 1950s and 1960s.

Bednar (1986) speaks of *the new atrium* for which the greatest difference in relation to the Roman atrium is that it is not open to the sky, i.e. it is roofed over, usually with glass. According to Bednar, a generally accepted new definition of an atrium is that it is an enclosed, daylit, centroidal space. An atrium is connected to one or more buildings, and Bednar uses the term *atrium building* as a designation for the whole building.

It has become more common for atrium to be used as a collective term, not only for a courtyard completely surrounded by buildings and roofed with glass, but also for all types of glazed spaces. Such a broad definition of atrium may be confusing. The term *linear atrium* is sometimes used for a glazed street or arcade which also has its ends glazed. According to Saxon (1983), an atrium has a vertical direction and is a place one comes to, an 'arrival point'. An arcade is a linear routeway passing through a building. According to Saxon's definition, a linear atrium is a place which may look like an arcade but which has an arrival point. Saxon uses the word atrium as a general term meaning (glass) roofed atrium.

In this thesis, no special definition is used for the word atrium in its modern meaning. The term *glazed spaces* is instead used as a general definition which is applied to both large and small glazed spaces. In specific examples, the terms glazed balconies, verandas, courtyards or streets are therefore used. The term sunspace is also used in reference to small glazed rooms, e.g. a glazed balcony or a glazed veranda. When the term atrium is employed, this refers to a glazed courtyard. The word atrium implies an atrium with a glass roof.

Passive climatic control

The term passive climatic control refers here to climatic control of buildings by means of methods and building design such that the desired climate can be achieved without major recourse to mechanical equipment. Use may be made of solar radiation, heat storage capacity, solar protection, vents, and a purposeful geometrical design of the building.

Active climatic control

When the desired indoor climate is obtained by heating and cooling using various types of building services, this is called active climatic control. In practice, there is often a mixture of active and passive climatic control. For the purposes of energy conservation, however, it is desirable that passive climatic control should be as comprehensive as possible.

Steady state calculations

Simple energy balance calculations in which conditions are constant over time are referred to as steady state calculations. These can be performed by hand, but computer programs are also available for steady state calculations.

Dynamic calculations

Energy balance calculations in which conditions change over time are referred to as dynamic calculations. In this type of calculation account is taken of the heat storage capacity of different materials. These calculations are considerably more complicated and extensive, and therefore require the use of computer programs.

CFD calculations

CFD, Computational Fluid Dynamics, is used for the calculation of air movements, air flows and temperatures with advanced computer programs. Air flows may be driven by fans, but natural convection can also be analysed. Calculations can be made under steady state conditions, but dynamic calculations can also be performed. At present, dynamic calculations for large rooms demand computers (PC) of large capacity and are very time consuming.

Radiation

Radiation from the sun can be regarded essentially as radiation from an ideal black body with a temperature of 6000 K. The spectrum of this radiation is split into ultraviolet radiation (UV), visible radiation (light) and infrared radiation (IR); see Figure 1.17. The proportions of energy carried by these are as follows:

7% ultraviolet radiation, wavelength region < 0.4 µm
46% visible radiation, wavelength region 0.4 - 0.75 µm
47% infrared radiation, wavelength region > 0.75 µm.

At the surface of the earth, however, there is a sharp cutoff point in the UV radiation of the solar spectrum at 0.29 µm owing to absorption in the ozone layer (Liljequist, 1979). On the infrared side, there is a gradual reduction in radiation. The boundary of solar radiation for this is usually put at ca 4 µm. Radiation which is absorbed in different materials is subsequently emitted as long wave radiation, also referred to as thermal or terrestrial radiation. This long wave radiation has a wavelength > 4 µm.

When studies are made of the effect of climate on the energy balance of buildings, solar radiation is one of the components measured. It is total solar radiation on a horizontal surface which is generally measured, and this is usually called global radiation. It thus comprises the wavelength region 0.29 - 4 µm. Global radiation is broken down into direct (directional) and diffuse radiation, and these can be measured separately. When the sky has full cloud cover, all radiation is diffuse. Measurement of long wave radiation (> 4 µm) is also of interest, especially in studies of glazed spaces.

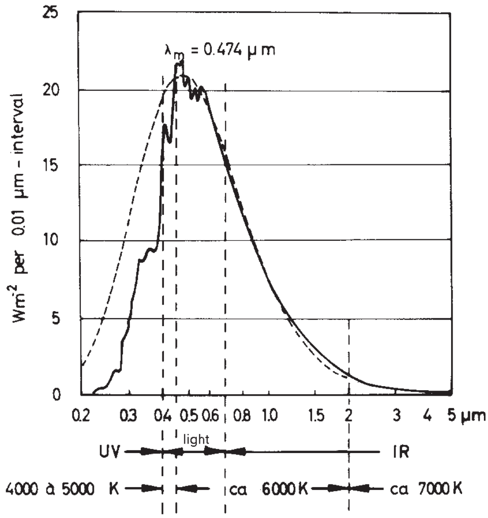


Figure 1.17 *Solar spectrum outside the atmosphere. The broken line represents radiation from an ideal black body at 6000 K temperature (Liljequist, 1979).*

1.3 Object and limitations

The new glazed space wave which arrived at the beginning of the 1980s was often motivated by ideas of energy conservation and the creation of a Mediterranean climate merely by erecting a glazed roof above a courtyard or a street. It has been found however that this is not quite so easy; instead of saving energy the glazed space might increase the need for energy, and the temperature in the glazed space may also drop below the freezing point in winter. Reality has not measured up to the visions, and there has been - and still is - a remarkable lack of guidelines and calculation methods for the assessment of climate and the energy requirement in a glazed space already at the preliminary design stage. The calculation programs and methods used for ordinary buildings are not suitable for glazed spaces. Research has therefore concentrated on these problems.

The object of this research is to elucidate the relationship between building design and the climate in the glazed space, and between building design and the energy requirement. This comprises the study of the factors which influence temperature in the glazed space and the energy requirement for the whole building, and the extent to which they do so. Only the energy requirement for heating and cooling is treated here. The aim is to give a simple illustration of these relationships and in this way to disseminate knowledge of what is important to take into consideration already at the preliminary design stage.

Apart from this general objective, the aim is to develop design aids for the estimation of temperatures and energy requirements in glazed spaces and adjoining buildings. The term glazed space refers here to both small glazed balconies and verandas, and large glazed courtyards and streets.

Finally, it is also intended to show the differences between different types of design aids and their limitations and uses.

The thesis does not deal with all the aspects set out in Subclause 1.1.3. The work has mainly concentrated on the following:

- passive and active climatic control
- thermal climate
- thermal relationship between the glazed space, the surrounding buildings and the outside climate
- energy requirement for heating and cooling
- the glazed space as part of the ventilation system of the whole building
- ventilation system - mechanical and through opening vents
- airtightness, infiltration
- solar control
- thermal properties of the glass
- heat storage capacity
- thermal comfort.

Finally, compilation of design guidelines is hard work in itself and necessitates cooperation between researchers and architects and engineers engaged in practical work. This thesis is intended only to show the way.

1.4 Earlier work

1.4.1 The work of others

In the 1980s when glazed spaces again became a common feature in architecture, discussions also commenced on why some glazed spaces worked well and others badly, and why the visions were sometimes so different from reality. As early as in 1983, Richard Saxon, a British architect, wrote that atria served as a buffer against the outside climate (Saxon, 1983):

> The energy economy of buffer spaces is only fully achieved if no attempt is made to keep the spaces themselves comfortable all year round. They are lightly constructed and are colder in winter, hotter in summer than the fully comfort-conditioned spaces they protect. Uses in the buffer zone need therefore to be seasonally appropriate. In winter, for example, cafés would be for use by people dressed for outdoors; in summer, resort wear would be better. Buildings with expensively heated and cooled atria are, therefore, missing the energy point.

Many of the less successful examples of glazed spaces can surely be explained by over-reliance on the energy gain from the sun in winter and an underestimate of this in the summer. The climate in a glazed space is greatly affected by the outside climate, much more than the climate in an ordinary well insulated building with windows of normal size. Myths in passive solar design may result in higher energy requirements for a passive solar building than for a conventional building (Hastings, 1995).

As much as eight years after Saxon's statement, this is what Frank Mills, England, says of atrium buildings (Mills, 1991):

> The problem is that there is currently little available as definitive design guidance, most architects tending to look towards exemplar projects for inspiration, or learning through trial and error.

Frank Mills works as a technical consultant for atria and other buildings. In the same article, Mills also notes:

> With careful attention to design, the ability of atria to capture solar energy can be used not only to create a comfortable as well as visually pleasant environment, but to reduce a building's energy consumption.

Glazed spaces are still being constructed, which means that there is a need for guidelines and different types of design tools. Over the past 10-15 years, a lot of research and studies of different kinds have in actual fact been carried out and described in research reports and handbooks. Richard Saxon was a forerunner with *Atrium Buildings, Development and Design* (1983). This comprehensive book was followed in the USA in 1986 by *The New Atrium* by Michael J. Bednar which shows many examples of atrium buildings. In Sweden the book *Spaces with glazed roofs*, which set out practical experiences of the design, construction and management of glazed spaces, was published in 1985 (Carlson, Almstedt, Thor & Wozniak, 1985). The conclusion often made here was that a number of aspects and points must be checked and elucidated at an early stage in order that a well functioning glazed space may be created. The glass trade in Sweden published in 1990 *Guidelines - Glazed Roofs* which deals with the choice of glass with respect to protection against falls of glass, reduction of snow load and a method for the design of sheets of glass. In the book *Glass - The Building Material with a Potential*, general information is given on glass in buildings (Carlson, 1992).

There are no Swedish building regulations specifically for atria, apart from fire safety aspects (Building Regulations BBR, Swedish Board of Housing, Building and Planning, 1994). This means that the requirements for a building permit may differ in different parts of the country. In other countries also there are no building regulations of this type. Clear and well defined guidelines would be desirable in order that the most obvious pitfalls may be avoided. A Norwegian proposal for new guidelines for heated glazed courtyards is described in *Oppvarmede glassgårder - Utformning og kravnivå for byggeforskrifter* (Thyholt & Granum, 1990). This found that double glazed sealed units with a low emission layer and argon gas were economically optimal for use in heated atria in Norway. The book *Glazed Roofs. Requirements and Methods* (Carlson, 1995) was recently published in Sweden. The book states that its object is to describe the requirements which exist, to describe methods and typical solutions, and to give advice. The book gives a general outline and may draw the attention of the reader to the problems associated with glazed roofs.

A proposal for a research and development programme in Norway with respect to glazed courtyards was published in 1985 (Børresen, Fjærvik, Knudsen & Salvesen, 1985). This concluded that field investigations are important. It was also considered that there was a need to develop methods for the calculation of radiation in glazed spaces. Børresen et al further say that the calculation tools for power, energy and temperature are unsatisfactory as regards glazed spaces. The calculation methods which are usually employed are not suitable for glazed spaces. Special design aids should therefore be developed, both tools for use at the preliminary design stage and more advanced methods. The authors consider that research on glazed spaces is needed in the fields of architecture and environment, building technology, climate and energy.

A lot of case studies of variable scope have also been carried out, both in regard to small glazed spaces such as verandas and balconies and larger spaces such as courtyards and streets. The glazed verandas at Smålands Taberg, Sweden, which were built in 1981, are one example of these. They are single glazed, are intended to serve as buffer zones, and are not heated. The intention was that they should save energy, but energy saving was found to be only marginal (Fredlund, 1989; Lundgren, 1989). On the other hand, the glazed verandas became very popular once the residents learned what limitations the climate imposed on their use.

Experiences from the 375 m long glazed street in the block Gårdsåkra at Eslöv, Sweden, show that a glazed space can easily become energy demanding. The block was ready for occupation in 1983. There were great expectations, and there was talk of the glazed street acting as a large passive solar collector which would make a substantial contribution to heating the 126 flats abutting on the street (Lange, 1986). The designers did not think that the temperature in the single glazed street would fall below +5°C. This temperature would in principle be attained through passive climatic control, i.e. through heat gains from the adjoining buildings and through solar radiation gains. This did not happen, however, and it was in actual fact necessary to provide heating to prevent the temperature from dropping below the freezing point. Instead of the glazed street making a contribution to energy supply, the total energy needed for heating increased and was considerably higher than if the glazed street had not been built in the block. On the whole, however, the block does not use a lot of energy, to a large extent due to the fact that the heating system in the buildings is based on heat pumps which take heat from the exhaust air and from the municipal sewers. The rule of thumb given in Lange (1986) is that a building must not use more energy with a glazed space than a similar building without one. This is a good rule, but if the glazed space is used as e.g. a restaurant, active climatic control should be permitted. The energy requirement with the glazed space included should thus be compared with that in a building without a glazed space, but with the functions in the glazed space moved inside the building.

Swedish experimental construction was extensively involved in the “Stockholm Project”. Different types of new approaches in construction were evaluated here. One example is the block Höstvetet, or Suncourt as it is called internationally, built in Stockholm in 1986. This consists of a glazed courtyard completely surrounded by flats. The courtyard is unheated, and when the temperature in the courtyard exceeds 18°C the excess heat is extracted by heat pumps. The excess heat is then stored in a borehole heat store and is used in the winter as a heat source for the buildings (Kellner et al, 1986). The store comprises 25 boreholes of 80 m depth. The excess heat from the glazed courtyard can also be used for the production of domestic hot water. The heat pumps are used for both charging and discharging the borehole store, and total electricity use is high. Energy contribution by the glazed roof is equivalent to a reduction in bought energy over the year by ca 3% (Hallstedt, 1993). The total energy contribution by the heat store, heat pumps and glazed roof is estimated to amount to ca 20% of total energy use. Apart from climate and energy, aspects relating to fire, acoustics, daylight and sociology were also studied. One conclusion which was drawn from the Stockholm Project in regard to glazed courtyards in combination with housing is that if the glazed courtyard is to be used by the residents, the designer must at an early stage establish how the courtyard is to be used and also specify the climatic requirements (Elmroth et al, 1989).

Glazed spaces have also been studied by the *International Energy Agency* [*IEA*]. Within Task 11A; *Passive and Hybrid Solar Commercial Buildings - Basic Case Studies* (IEA Task 11A; 1989), 48 case studies are presented for buildings with passive climatic control. Many of these had glazed spaces. These buildings are situated in countries with different climates, ranging from Latitude 36°N to 70°N, and the presentation provides a good overview of experimental construction in this field. Four of the case studies which are from the Nordic countries are described in Hestnes (1989). These four case studies all contain glazed spaces and preliminary results show promising energy performance.

Within Task 11, work has also been done regarding development of design recommendations for atrium spaces. A conclusion from this group is that atrium spaces can be designed to reduce heating, cooling and lighting energy requirements (Gordon, Kammerud & Hestnes, 1991). Through measurements and calculations, it was found that an atrium situated in a climate ranging from the south of the United States to the north of Norway can result in significant energy savings.

Within Task 12A3; *Building Energy Analysis and Design Tools for Solar Applications, Atrium Model Development*, work proceeded during the period 1989-1995 on the development and assessment of the usefulness of different calculation tools for the analysis of thermal comfort and energy requirements in buildings with glazed spaces. The work is described in the final report *Atrium Models for the Analysis of Thermal Comfort and Energy Use* (IEA Task 12A3, 1996).

IEA Task 13, *Advanced Solar Low-Energy Buildings*, deals with passive and active solar energy technology for dwellings. Within Subtask A, *Development and Evaluation of Concepts*, a Simulation Support Group was set up. The aim of this group is to provide information on the options for modelling various energy features with the aid of conventional computer programs. One of the energy features studied is atria (IEA Task 13A1, 1994). This group recognises the potential of developing existing dynamic energy calculation programs so that account is also taken of air movements, temperature stratification, natural and mechanical ventilation, the effect of wind speed and wind direction, etc. It shall still be possible for the energy balance to be calculated for each hour with a reasonable calculation time, in contrast to the case if CFD programs had been used. It shall in addition be possible for a dynamic calculation to be performed, which poses difficulties at present when large volumes such as atria are studied using CFD programs. The computer programs SERIRES and SUNCODE have been developed in this direction. A simplified calculation method for the assessment of the effect of an atrium on the energy requirements of adjoining buildings has also been developed in this project. The method is called ASCA - Atrium Simple Calculation Analysis, and is intended for use at an early stage of design (IEA Task 13A1, 1994). It is planned that Task 13 will be terminated in winter 1996.

At the Technical University of Norway NTH and the Central Institute for Industrial Research SINTEF in Trondheim, Norway, a number of researchers have studied glazed spaces from different aspects. Thermal climate, energy, economy, sociology etc have been studied, and a building which has been the object of various studies is the Electrical Energy Department building at NTH (Thyholt, 1988; Jacobsen, 1989; Aschehoug & Thyholt, 1989; Tjelflaat & Kvikne, 1992).

Glazed spaces have also been used in order to improve existing environments. One example is Skärholmen Centre in Stockholm, a shopping centre built in 1968 which had a poor external environment with draughty pedestrian streets. More than half of these pedestrian streets, ca 4000 m^2, were glazed in 1984. The object was to create a better environment and a better climate, and also to increase the turnover of the shops. The design temperature in the glazed streets was 18°C in winter, but the temperature was allowed to drop to 15°C overnight. The glazed spaces are mainly heated by underfloor heating and by the heat lost from the surrounding buildings. An interdisciplinary evaluation has been performed (Öman, 1992) and this shows that the thermal climate has largely improved and energy use for heating the whole building has been reduced by ca 10%.

In order to enhance knowledge of the design process and thus be able to create good and energy efficient buildings with atria, *Energy Technology Support Unit* (ETSU, 1993), UK, made a theoretical study of four existing buildings which were to be reconstructed with atria. Energy, climate, ventilation, daylighting, heating, cooling, economy, fire etc are discussed in the report, and different strategies are used to demonstrate the potential of atrium buildings. One of the conclusions is that an atrium can save energy, but although, depending on building design and use, a lot of free energy in the form of e.g. solar radiation, heat from lighting and appliances, can reduce the energy requirement for heating it can at the same time increase the energy required for cooling. A holistic approach is essential (ETSU, 1993):

> The design must balance positive and negative effects since it would appear from the case studies that it is not always possible to achieve energy benefits in all categories within a single design.

In order that different designs of atrium buildings may be evaluated, there is a need for calculation tools in the form of simple manual calculation methods or computer programs at the preliminary design stage and for more advanced computer programs at a later stage and for research purposes. Dynamic computer programs for the calculation of energy and temperature conditions have been tested and compared with measurement results from existing buildings or from laboratory experiments. Moser et al stresses the importance of considering solar radiation, long wave radiation and air movements when atria are studied (Moser, Schälin, Off & Yuan, 1995). In tall buildings with atria, there may be considerable temperature stratification. Kolsaker and Frydenlund propose a simplified model for calculating temperature stratification in atria. This model has been coupled to the Norwegian computer program FRES (Kolsaker & Frydenlund, 1995). Thermal comfort can also be calculated with FRES, based on Fanger's equations in accordance with ISO 7730.

Nowadays, CFD programs are also used for the calculation of air movements and temperature stratification in atria. However, these still demand a lot of computer power even though they can be run on a personal computer. Research is in progress on the development of methods which can handle large volumes, the heat storage capacity of buildings, natural and forced ventilation and the great influence of solar radiation, i.e. the properties of large glazed spaces (Chika-moto, Murakami & Kato, 1992; Ozeki, Higuchi, Saito, Ohgaki & Sonda, 1992a; Sonda, Higuchi, Saito, Ohgaki & Ozeki, 1992b). CFD programs and dynamic energy calculation programs can be used in parallel in order to obtain reasonable results iteratively, but this is very time consuming. Development of CFD programs for large volumes such as atria has only begun and the user of such a program must have a lot of knowledge and experience of CFD. It is far too easy to put trust into colourful pictures of air movements and temperature stratifications, and guidelines from experts in this field are badly needed. One good example of guidelines is the article *Guidelines for CFD Modeling of Atria* (Schild, Tjelflaat & Aiulfi, 1995).

Work on design aids with respect to climate and energy requirements has started in a number of countries. In the UK a simplified calculation method for buildings has been drawn up by Nick Baker, University of Cambridge; *The LT Method*, which is an energy design tool (Goulding, Lewis & Steemers, 1993). This calculation method is a manual one, i.e. all that is needed is paper, pen and a minicalculator. It is intended for use by architects at an early stage of design in order that different options may be compared, but is not designed to provide exact answers. The method also comprises estimation of temperature in unheated glazed spaces without ventilation and solar radiation, i.e. estimation of the minimum temperature. The effect of the glazed space on the energy needs of surrounding buildings can also be estimated.

Studies of atrium buildings and work on guidelines are also proceeding in Holland. An information brochure in Dutch on atrium buildings was published in 1990; this deals with daylighting, energy, climate, air movements, acoustics and investment costs. Examples of existing glazed spaces are also given (BOUW, 1990). Another book on atria has recently been published in Holland, with *Blesgraaf Office for Building and Environment* as project leader (NOVEM, 1996). This book is an updating of previous books and has been augmented with international experiences. The project also comprised field studies. As before, the target group is architects, planners and others involved in early stages of design. The organisations which started up the project are the Government Buildings Agency which comes under the Dutch Ministry of Housing, Physical Planning and the Environment, the Netherlands Agency for Energy and the Environment [NOVEM] and the Organisation for Building and Construction Research [SBR].

In Belgium also, an information booklet on atria has recently been published by *top E*, European Consulting Engineering Network (top E, 1996). This describes different buildings containing glazed spaces.

The *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.* [ASHRAE] is planning a section with guidelines on atrium buildings in its next handbook. This is the first time such a section will be included.

Sunergy, a computer program for the simulation of solar energy systems for buildings (e.g. a glazed space) is under development by SINTEF Vermeteknikk og Programbyggerne by commission of the Norwegian Research Council. This type of program can at an early stage give an idea of how different systems work, but does not perform any exact calculations.

The ability to make systematic use of data from CAD programs and data bases for calculations at the preliminary design stage would make things much easier, and this has been discussed in e.g. the doctoral thesis of Ida Bryn, *An Energy Information System For Atrium Design* (1992).

1.4.2 Work by the author

The work on which this thesis is based has gone on for a long time, parallel with the above research, and has largely been published in reports and articles. A brief description of this work is given below. The degree of Tekn. Lic. was awarded in 1991 and forms part of this work (Wall, 1991c).

In cooperation with researchers at the Department of Building Science, measurements have been made on a number of glazed spaces such as the verandas at Smålands Taberg, a glazed courtyard in the block Tärnan, Landskrona, the glazed street in the block Gårdsåkra, Eslöv, and a glazed courtyard in the block Piggvaren, Malmö, which was part of the Housing Fair Bo86 (Wall, 1993). Evaluation of the housing estate at Smålands Taberg is described in Fredlund (1989) and Lundgren (1989). An outline description of the measurement projects is given in Lange (1986). The block Piggvaren has been analysed by Blomsterberg (1993; Blomsterberg & Wall, 1993b).

Parametric study

A fundamental parametric study has been carried out in which the computer program DEROB-LTH was used to calculate temperatures in different types of glazed courtyards and the energy requirements in surrounding buildings (Wall 1989a, 1989b, 1990b, 1991b). The results of calculations from the different theoretical cases were then compared. Changes in the parameters in one and the same model were studied and comparisons were also made regarding the significance of one and the same parameter in the different models. The parameters which were varied in different combinations in each model are mainly the number of panes, area of glazing, thermal inertia, orientation and the air change rate. This work also involved a thorough review of the computer program DEROB-LTH. Errors were put right, unacceptable simplifications were removed and the program was subjected to development in order to meet the needs encountered. The development which is still in progress was performed in collaboration with Professor Bertil Fredlund and research engineers Hasse Kvist and Kurt Källblad at the Department of Building Science.

Glass roof over the abbey church ruins at Hamar, Norway

The Central Office of Historic Monuments in Norway examined the possibility of erecting a superstructure over the abbey church ruins at Hamar. The ruins are in a very poor condition and need climatic protection which will prevent exposure to the elements and frost damage. In February 1987 an architectural competition was announced for a superstructure over the ruins. The winning proposal involves the erection of a glass roof and has been put forward by Kjell Lund and Nils Slaatto, Architects MNAL. Professor Kristoffer Apeland was technical consultant. The Department of Building Science carried out a study in order to assess what consequences the winning proposal will have on climate and energy requirements (Wall, 1990a). Additional studies were also made later on parallel with the development of the project proposal (Wall, 1992b).

Glazed courtyard at Tärnan, Landskrona

In order to increase knowledge, measurements and calculations were carried out for a glazed courtyard with passive climatic control at the block Tärnan, Landskrona (Wall 1991a, 1992a). Seven terrace houses are placed in two rows with a 200 m^2 glazed courtyard between them. The measurements comprised, inter alia, the outside climate, the temperature at different levels inside the glazed space, control of vents and solar control curtains, and the energy requirement in the surrounding buildings. Air leakage was also measured using the fan pressurisation method and the tracer gas method. The temperature in the courtyard was calculated and compared with the measurements. Calculations were also made to study alternative configurations. The effect due to changing single glazing to double or triple glazing, and changing heat storage capacity and orientation, was discussed.

Long wave sky radiation

In comparisons between temperatures measured just below the glass roof at the block Tärnan and the corresponding calculations with the computer program DEROB-LTH, it was found that the long wave sky radiation may have a considerable influence on the temperature below the glass roof. In earlier versions of DEROB-LTH the sky temperature was assumed to be the same as the air temperature outside, which is a common simplification in energy balance programs. This simplification is acceptable when there is cloud cover but not when the sky is clear. On cold winter nights, it was found that the temperature measured below the glass roof was even lower than the outside temperature.

DEROB-LTH has been developed so that the program takes sky radiation into consideration. The notional sky temperature is needed as input data. If the long wave sky radiation is not measured, a method is needed in order that the sky temperature may be estimated with the assistance of normally measured climatic data. Such normally measured data may be the outside temperature, solar radiation, relative humidity and barometric pressure.

Airtightness and ventilation in atria

Unintended ventilation in atria may have great significance for comfort and energy needs. Knowledge in this area is very limited, the main reason being that measurements regarding the airtightness of atria and ventilation in these are complicated and expensive. In order to increase knowledge of ventilation in atria, measurements of airtightness and calculations of ventilation were carried out in four atria (Wall & Blomsterberg 1993, 1994; Blomsterberg & Wall, 1994b). The four atria were the atrium in the laboratory of Kabi Pharmacia in Lund, the atrium in the office complex Scandinavian Center in Malmö, the atrium in the office building Siriushuset in Malmö and the atrium in the Oncological Clinic in the University Hospital of Lund. Pressurisation tests were made to measure the airtightness of the atrium and the surrounding buildings. For two of the atria, the magnitude of unintended ventilation under normal conditions was calculated using an air flow program.

Housing for the elderly with glazed spaces and solar collectors at Sätuna, Stockholm

One further case study, of lesser scope, was carried out. At Sätuna outside Stockholm an estate with housing for the elderly was constructed. The estate which was designed by the Hidemark & Danielsson architectural practice was ready for occupation in the autumn of 1990. It consists of service flats and communal premises. Each flat has a glazed space of ca 12 m². Solar collectors are installed along the bottom of the outside wall of the glazed space. Ventilation in the flats is based on an extract air system. The intention is that supply air should be preheated by taking outside air into the glazed space through the solar collectors and further into the flat via ventilation terminals in the wall between the glazed space and the living room. Supply air is drawn in by the negative pressure created in the flat by the extract system. The Swedish Council for Building Research financed an evaluation of climate and energy and a study of what the occupants think of their flats and glazed spaces (Sundbom, Nilson & Blomsterberg, 1996). The Swedish Testing and Research Institute [SP] carried out measurements and calculations of air flows. Calculations were made already during the preliminary design stage with the energy balance program DEROB-LTH, and a comparison was later made with the temperatures measured by SP in the solar collectors and glazed spaces. Calculations were also made to estimate the energy gain due to the solar collector and glazed spaces as preheaters of the supply air. (Wall 1994a; Blomsterberg & Wall 1993a, 1994a).

Glazed courtyard, Oncological Clinic, University Hospital of Lund

One example of work as a consultant is the glazed courtyard at the Oncological Clinic, University Hospital of Lund. A building for radiation treatment of patients was to be constructed with a glazed courtyard to serve as a central waiting room. These types of premises are usually located below ground. During the preliminary design stage calculations were made of the temperature inside the glazed courtyard and the energy required for heating and cooling. Calculations were made for different configurations. The building was constructed in 1992.

IEA Task 12A3: Building Energy Analysis and Design Tools for Solar Applications, Atrium Model Development

Within the *International Energy Agency* [IEA] a research project on glazed spaces was conducted with respect to energy use, climate and comfort. Those participating in this research project were SINTEF in Norway, SBI in Denmark, Sorane S.A. in Switzerland, Lund University in Sweden and the Fraunhofer-Institut für Bauphysik in Germany. Norway was project manager, and the project was carried out between 1989 and 1995. The object was to evaluate and develop calculation methods for glazed spaces with respect to thermal comfort and energy. The project included case studies with measurements and calculations. Dynamic calculation programs for energy and temperatures and CFD programs for calculation of air movements were used. Thermal comfort, temperatures, energy, ventilation, infiltration etc were studied both in theory and in practice. Calculation methods for thermal comfort, temperature stratification, shading, insolation into atria and ventilation have been reported (IEA Task 12A3, 1996). The Department of Building Science was responsible for Chapter 6 of the final report, *Solar Radiation*. This chapter sets out the fundamental physical relationships (Kurt Källblad and Bertil Fredlund) and describes the calculation programs used (Sweden: Hasse Kvist, Denmark: Kjeld Johnsen, Norway: Kell Kolsaker and Switzerland: Dominique Chuard). A method for calculating shadows is also described (Kjeld Johnsen). A comparison is made between different calculation programs for incident, transmitted and absorbed solar radiation in a simple glazed space, and a simplified calculation program is presented for solar utilisation in different types of glazed spaces (Maria Wall).

Simplified calculation method

The climate and the energy required in a glazed space are greatly affected by the outside climate, and in particular by solar radiation. In calculations for a glazed space, solar radiation must therefore be treated considerably more accurately than for an ordinary building with windows of normal size. This was one of the findings in the studies made within IEA Task 12A3. In order to calculate the proportion of solar radiation utilised in different types of glazed spaces, calculations were made with the computer program DEROB-LTH. These studies comprised the effect of type of glazing, the trans-missivity of the glass, the absorptivity of surfaces inside the glazed space (i.e. dark and light surfaces), geographical position, orientation and time of year. On the basis of these studies a simple manual calculation method has been drawn up for the assessment of temperatures and energy needs in glazed spaces (Wall, 1994b). The effect of the glazed space on the energy requirements of surrounding buildings can also be estimated. The intention is that the calculation method should be used at the preliminary design stage to provide an idea of the difference between different configurations. The method has not been fully developed. It must be augmented with assessments of thermal comfort, maximum temperature and the effect of solar control curtains. In order to demonstrate how the method works, the glazed courtyard at the block Tärnan was used as an example. See also the articles *A Design Tool for Glazed Spaces, Part 1: Description* and *Part 2: Examples* (Wall, 1995; Fredlund, 1995) which also includes as an example the glazed verandas at Smålands Taberg.

Thermal comfort

The obtained degree of thermal comfort is influenced by the air temperature, radiant temperature, solar radiation, clothing, physical activity, local air velocity, draught and humidity. Thus, the air temperature alone is not a sufficient parameter of how people will experience the thermal environment in glazed spaces. Thermal comfort in glazed spaces was the subject of recent work. In order to study thermal comfort, calculations were made for three types of glazed courtyards. The study was based on calculations with the dynamic energy simulation program DEROB-

LTH together with a post processor which calculates thermal comfort according to the International Standard ISO 7730.

1.5 Choice of method

Since different types of glazed spaces became popular during the 1980s and these glazed spaces had both a positive and negative reception by the public, there was reason, and the possibility, to perform studies of different kinds in existing glazed spaces. These *case studies* include physical measurements and discussions with designers and users to obtain further information. During these physical measurements, the factors which influence the climate inside the glazed space were measured at the same time as the climate in the space. In this way it is possible to determine the effect of the environment on climate in the glazed space. Practical details regarding operation and maintenance are obtained from the users. This type of case study is mainly used as a way of finding out what problems there are and makes it easier to further delineate the research area. The case studies are also used as *examples* of how a glazed space functions.

By using a *calculation program,* a simplified picture of reality can be simulated. Studies of existing glazed spaces can be made in this way to verify and develop computer programs or to test alternative configurations in the computer. Systematic calculations for typical buildings also provide data for the production of e.g. guidelines. Calculations in this research work have been mainly used for the following purposes:

- Comparisons between calculations and measurements from case studies to verify computer programs
- If comparisons between measurements and calculations show that certain parts of the computer program need improvement, the program has been developed
- Aids for the analysis of case studies and tests on alternative building configurations in the computer
- Performance of parametric studies on theoretical models of typical buildings. The effect of individual parameters is studied and the results are used to describe general relationships which can be used in guidelines
- Calculations ranging from simple manual calculation methods to computer programs of different degrees of complexity in order to study the usefulness and limitations of different types of design tools
- Advanced calculation programs are used to produce simplified calculation methods which are more suitable at the preliminary design stage

Case studies and theoretical studies complement one another and have accounted for most of this research work. Through collaboration with other researchers in the field, it has been possible to learn from one another and to see more easily this research within a broader context.

2 Design tools – possibilities and limitations

This chapter discusses design tools for the assessment of climate and energy needs. The chapter gives an overview of the types of design tool which are available and briefly describes some examples in each group. The main reason for the choice of most of the examples is that they are discussed later on in the thesis.

2.1 The right tool for the right purpose

At an early stage of design, the need is for design tools which are easy to use and yield results quickly. By varying certain parameters, changes in indoor climate and energy requirements can be studied. At this stage, accuracy is not the most important consideration. Orders of magnitude are sufficient to assess the effect of different measures and the difference between configurations. Such a tool may be a simple manual calculation method which needs only pen, paper and a minicalculator. This type of steady-state model may also be formulated as a simple computer program which makes for even quicker results.

For the design of e.g. heating and cooling systems at a later stage, a dynamic calculation program may be needed. In such a program, conditions are changed over time. One factor which inexorably changes is the climate, and the energy balance is often calculated hour by hour, with new values of the outside climate input every hour. The heat storage capacity of the building is significant here. The outside climate such as solar radiation and outside temperature varies over the day and the year, and is described in a climate file. Other factors which may vary in time but can be controlled are the heating and cooling system, ventilation, the use of solar control, etc.

Dynamic calculation programs may be more or less advanced. In each part of the calculation, simplified methods may be used to make the calculations faster. In such a case accuracy is often sacrificed. Owing to developments in computers, however, calculation programs can be made more and more detailed without the calculation time being increased. In most cases the user may wish to have both accurate *and* fast results, and a balance must then be struck. This type of dynamic calculation program is used by consultants and researchers, but it takes quite a long time to become proficient in their use, and they demand more prior knowledge than steady-state calculation methods.

2.2 Special properties of glazed spaces

The use of calculation programs for the assessment of the climate and energy requirements of buildings is not a new development. Traditionally, however, it has been only a small part of the building facade which has consisted of glass (windows), and the buildings have been poorly insulated. When buildings became better insulated, solar radiation and other energy gains assumed greater importance for the heating requirement, and demanded calculations of a higher degree of detail.

As glazed spaces became more common, often with energy conservation as one of the reasons, conditions were further changed. The large glazed surfaces in the form of glazed facades and glazed roofs admit large quantities of solar radiation which can heat up the glazed space. At the same time, owing to the relatively poor insulation capacity of glass surfaces, energy losses are high and this also means that the glazed space is greatly affected by the outside temperature. The effect of solar radiation and outside temperature varies considerably over the day and the year. Adjoining buildings are in turn influenced by the climate in the glazed space; the extent of this influence is governed by how well the surfaces in contact with the glazed space are insulated and what proportion of these consist of windows. Some buildings are also constructed with a smaller amount of insulation along surfaces in contact with the glazed space.

Regardless of whether the glazed space has active climatic control, i.e. the heating and cooling load must be calculated, or passive climatic control, i.e. the variable temperature must be calculated, calculation of solar radiation and the "greenhouse effect" is essential. The greenhouse effect means that a large proportion of short wave solar radiation is admitted through glazed surfaces, impinges on walls, floors and ceilings, and the proportion that is absorbed is transformed into long wave thermal radiation. It is not quite so easy for this long wave radiation to be re-transmitted outwards through the glass - in other words, a solar collector has formed.

Physical description of the route taken by solar radiation, from the time it reaches the building until it has been absorbed or has left the building again, is complicated. When solar radiation is incident on the glass surfaces in a glazed space, some is reflected directly, some is absorbed in the glass, and the remainder is transmitted into the space; see Figure 2.1. In the space it meets different surfaces, e.g. the floor or a wall. Some of the radiation which meets an inside surface is reflected further onto other surfaces while the remainder is absorbed and is later emitted as long wave radiation. If, on the other hand, solar radiation meets another glazed wall on the inside, some of this radiation is in addition transmitted out of the glazed space. If the radiation impinges on windows which face other buildings, some of the radiation is naturally directly transmitted further into these buildings. Through repeated reflection, transmission through glass and absorption, all radiation is in the end distributed. Dark surfaces absorb a large part of incident solar radiation and light surfaces a small part, i.e. at these surfaces it is reflection that is high. Since the position of the sun in the sky varies over the day and the year, the orientation and geometry of the building are of great importance for the amount of solar radiation that can be transmitted into the glazed space. If a large proportion of the surfaces in contact with the outside is of glass, a lot of the solar radiation will be transmitted outwards again without any benefit to the glazed space.

In the case of buildings with windows of normal size, practically all solar radiation which is admitted will stay in the building and will be transformed into long wave radiation which may during the heating season contribute to the heat supply of the building. It is therefore a common simplification in calculation programs to include in the energy balance of the building all the solar radiation which has entered the building. It is also a common simplification to assume that solar radiation spreads in the room diffusely in proportion to the sizes of the internal surfaces. The route taken by direct solar radiation is not calculated. With these simplifications, the distribution of solar radiation need not be calculated for every hour during the year. In the simplified calculation, the percentage distribution is constant over a day and the year. In this way, calculation time in the computer is reduced.

However, when rooms with large glazed surfaces are to be studied, these simplifications give rise to large errors in the results. In these cases, air temperatures, surface temperatures, energy needs and comfort in the building are estimated erroneously, with the result that the building will not function as intended.

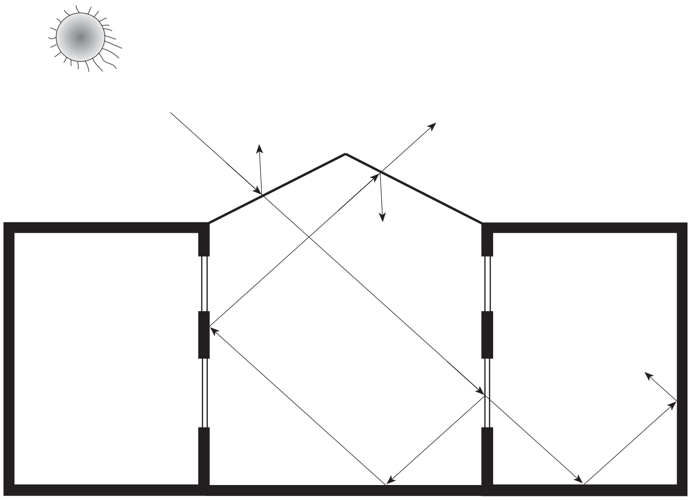


Figure 2.1 Distribution of solar radiation.

In a glazed space there may also be considerable temperature stratification, especially if the space is high. Solar radiation heats up different surfaces which in turn heat the air and cause it to rise. Cold surfaces, for instance in a glazed facade, may give rise to a cold downdraught and will in this way also influence air movements in the space. Air movements and temperature stratification may affect comfort. Energy balance programs do not calculate air movements. Detailed studies demand CFD programs, but these are as yet very time consuming if dynamic calculations are to be made using CFD. Verification of CFD programs is complicated and demands a lot of detailed and expensive measurements. In order that a rough estimate may be made of the significance of temperature stratification in large volumes, simplified methods have been developed in some energy balance programs (e.g. FRES).

2.3 Manual calculation methods

At an early stage of design, it must be possible for the architect to study the effect of building configuration on climate and energy needs. Since many of the parameters have not yet been determined at this stage, the design tool must demand few input data. Only certain parameters must be capable of alteration, the remainder should be predetermined by the calculation method. The parameters which must be capable of alteration are those determined at an early stage and which are significant for the climate in the glazed space and for the energy required by the whole building for heating and cooling. Examples of such parameters are the geometry and orientation of the building, the design of walls and ceilings, ventilation principles and heating and cooling principles. A manual calculation method gives an idea of the orders of magnitude, but does not yield exact results. This type of method must be used when different building configurations are compared, so that a decision may be made as to which is most suitable with respect to climate and energy requirement.

Manual calculation methods are often organised in such a way that, with the help of a few simple equations and perhaps some kind of questionnaire to be filled in, a rough calculation can be performed relatively quickly. The appropriate values which are needed in the manual calculation method are obtained from diagrams and tables produced by a more advanced calculation method. The calculations performed in advance, which are usually summarised in the form of tables and diagrams, have often been comprehensive to give results which can be used in a simplified calculation method.

2.3.1 The LT Method

One example of a manual calculation method is the *LT Method*. This has been developed by Dr Nick Baker of the University of Cambridge in England. The LT Method has several versions.

LT Method 1.2 is an energy design tool for non-domestic buildings (Goulding, Lewis & Steemers, 1993). This version was developed for the European Architectural Ideas Competition "Working in the City" as part of the ARCHISOL programme coordinated by the Energy Research Group, University College Dublin, and funded by the Commission of the European Communities. This competition focussed attention on energy conservation and passive design in non-domestic buildings, and in particular on the design of daylighting.

The calculation method has been produced for four climatic zones in Europe. The energy need of the building for heating, cooling and lighting can be estimated with the help of diagrams produced by a mathematical model. Since daylighting is also studied, the method takes into consideration shadows cast by the surroundings. Information on roof, facade and window areas in different orientations is needed as input data. In order that shading may also be calculated, information regarding the surroundings is also required. If a glazed space is planned, the ventilation principle must also be chosen. By filling in a special form (LT Worksheet), the user is guided through the calculations. If the building contains a glazed space, the energy saved due to the effect of the glazed space as a buffer can be assessed. The energy saved per year and per metre length of the facade which abuts onto the glazed space can be read from a table. These tables are produced by the calculation program ATRIUM which is however not a dynamic program. The *LT Method* also describes as a complement a method for estimating the minimum temperature in the glazed space when the effect of solar radiation and ventilation is ignored; see Figure 2.2. By defining the term “protec-tivity ratio” as the relative areas of glazing in the external wall and the separating wall of the buffer space, the minimum temperature can be read from the diagram.

According to LT Method 1.2, the south of Sweden comes into Climatic Zone 1. For Swedish conditions, however, the calculation method is based on too poor a standard of insulation in the buildings. It is also assumed that the windows and glazed space in the building are single or double glazed. Triple glazed windows should also be given as an option. One development of the method may be to have different predetermined parameters for buildings in each climatic zone, depending on current building codes and standards of construction in different countries.

The authors say it is possible to enter the LT Worksheet into computer based spreadsheets, so that results may be obtained more quickly when different configurations are studied. This is something which, in principle, all manual calculation methods would benefit from.

LT Method 3.0 is a version produced for the south of Europe (Baker & Steemers, 1996). In this version the influence of solar control on daylighting and cooling requirements can be assessed to a limited extent.

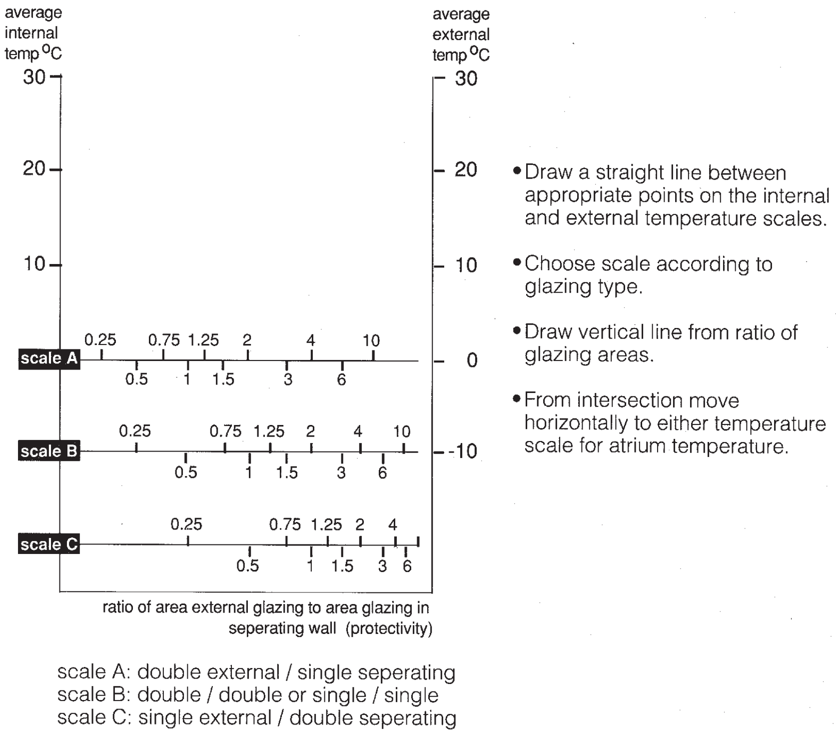


Figure 2.2 *Buffer space average temperature nomogram (Goulding, Lewis & Steemers, 1993).*

2.3.2 New Method 5000

New Method 5000 is also a manual calculation method which calculates energy requirements in passive solar buildings (Goulding, Lewis & Steemers, 1993). The method is based on a set of blank forms to be filled in. The method estimates the monthly solar and internal gains which are then subtracted from the calculated gross heat losses. It also estimates the gains from sunspaces used as buffer spaces. The monthly mean temperature without solar radiation and also with solar radiation can be calculated for the sunspace. In order to calculate the useful solar gains, coefficients are given which take into account the geometry of the sunspace, glazing type, absorptance of floor and floor insulation. In this way the buffer effect can be estimated. The main subject in this method is the building itself, not the sunspace. For the building itself, the thermal inertia can be taken into account (Lefebvre, 1987).

2.3.3 TEMPO

TEMPO is a manual calculation method for calculation of temperature variation and cooling needs in rooms, primarily with respect to solar radiation (Børresen, 1979). Simple forms are filled in step by step. By calculating the mean temperature for the room, the variation in power due to heat gains over the day and the variation in room temperature, the cooling requirement can be determined. Solar radiation and shading factors for windows with curtains and venetian blinds can be read from diagrams as data for the calculation. Account is taken of heat storage capacity by defining three types of room, of light, medium and heavy construction.

2.4 Steady-state computer models

Now that computers have become increasingly common, it is also possible to use computerised aids at an early stage of design. More and more tools are available in the PC environment, and calculation programs for energy and climate are one example of these. It is hoped that in a not too distant future most of these design tools will be able to import information from the CAD program directly into the calculation program so that e.g. climate and energy needs may be assessed.

Computerisation of the calculation method makes for more accurate calculations and also faster results when many alternative configurations are to be compared. If the method is to be used at an early stage of design, however, it is essential that more accurate calculations should not be synonymous with longer calculation times. The quantity of input data should still be limited, but if a more flexible program is desired a number of input data may be fixed as default values which can however be altered by an experienced user.

2.4.1 BKL Method

One example of a computerised calculation method which is based on steady-state calculations is the *BKL Method* which was in actual fact initially a manual calculation method before personal computers became common. The BKL Method has been developed at the Department of Building Science, Lund University, Lund Institute of Technology (Källblad & Adamson, 1984; Källblad, 1994a).

The method is intended for calculation of the energy needed for heating buildings. Account is taken of adventitious gains such as solar radiation and gains from occupants. The energy requirement is calculated month by month on the basis of the mean outside temperature each month. Solar radiation is on the other hand calculated daily and is sorted according to decreasing global radiation values so that a regression line can be used for further calculations of energy gains and heating requirements. In this way it is only necessary for the energy balance to be calculated for two or three days in a month in order that the energy requirement for the whole month may be estimated. The advantage of calculating solar radiation on a daily basis is that e.g. a sunny period at the beginning of the month is not included as an energy gain at the end of the month. If monthly means of solar radiation are used, it is possible for solar utilisation to be both overestimated and underestimated to a major extent. This risk is naturally still present during the day, between day and night. The building may however be expected to have a certain heat storage capacity which makes it possible for heat to be stored from day to night.

The geographical position of the building and its orientation are given as input data for the BKL Method. The areas and U values of the different parts of the building and also horizontal and vertical solar control screens fixed to the windows are also given. These solar control screens can be used to describe projecting eaves and the case when windows are situated deep inside the facade. The ventilation system and infiltration can also be described. Adventitious energy such as gains from occupants must also be given as input data.

The BKL Method shall be used for buildings with windows of normal size and not for rooms with large glazed areas. All transmitted solar radiation is assumed to remain inside the building and is thus regarded as an energy gain in the energy balance.

The *KGK Method* is a development of the BKL Method (Källblad, 1994b). This method is also based on steady-state calculations but the energy needed for heating is calculated for each day and is then summated into an annual requirement. Calculation of convective heat transfer and long wave radiant heat transfer in the building is treated separately, which is not done in the BKL Method. By using an equivalent outside temperature, account is taken of the solar radiation which is absorbed in external surfaces. The transmitted solar radiation which is treated as diffuse radiation is distributed to inside surfaces using distribution factors, and is not used as a direct convective heat gain. This also makes it possible for some of the radiation which is distributed to a window to be re-transmitted outwards. However, the KGK Method is not suitable for extreme buildings such as glazed spaces, and this is also pointed out in Källblad (1994b). The method is not available as a complete computer program.

2.4.2 Sunergy

The computer program *Sunergy* is in the process of development by the Central Institute for Industrial Research SINTEF and Program-byggerne in Norway. Sunergy is intended for use at an early stage of design to give a rough idea of e.g. the energy needs of buildings and the effect of solar radiation. Solar collectors, swimming pools and glazed spaces can also be studied. The type of building, the heated floor area of the building and the year of construction are given as input data. The year of construction determines what insulation standard is used, infiltration and any heat recovery from the exhaust air. The areas and orientations of windows and the type of window are also given as input data. Since the indoor temperature, energy price and the locality, i.e. the climate, are also determined, results can be directly obtained. If a glazed space is to be studied, it may be situated on the outside of the building or be an integral part of the building. The height, width and depth of the glazed space must be specified together with type of glass and orientation.

The results presented comprise an annual heat balance, the contribution due to solar radiation, energy saved due to glazed spaces and solar collectors, costs and profitability. The mean temperature inside the glazed space is also given.

Clear diagrams and figures and a simple menu layout make the program easy to use. Sunergy is a good example of what a simple design tool for use at an early stage of design can look like. However, if the program is to be used for the study of glazed spaces it must be developed, both by increasing the number of building configuration options and by improving the accuracy of the calculation method.

2.5 Dynamic models, general

At a later stage of design, more advanced computer programs may be needed. The calculations must then be more accurate and, if passive climatic control is used wholly or partly, what is mainly required are studies of not only energy needs but also temperature variations and thermal comfort. This also applies to a very high degree for glazed spaces.

Computer programs for dynamic calculations take account of climatic variations over the day and the year, and calculate how this affects the building through the heat storage capacities etc of different materials. There are a large number of calculation programs of this type, with different approaches and degrees of detail. Examples of calculation programs used in an empirical validation test within IEA Task 12 and Annex 21 are given in Table 2.1 (Lomas, Eppel, Martin & Bloomfield, 1994).

Table 2.1. Features of programs participating in the empirical validation test, International Energy Agency, Task 12 and Annex 21 (Lomas, Eppel, Martin & Bloomfield, 1994).

		ESPv6.18a (DMU, UK)	ESP-Rv7.7a (ESRU; UK)	ESP+v2.1 (DMU, UK)	SERI-RESv1.2 (BRE, UK)	SUNCODEv5.7 (Ecotope, US)	TRNSYSv12 (BRE, UK)	TRNSYSv13 (BRE, UK)	TRNSYSv13.1 (Brussel, B)	TRNSYSv13.1 (UWISC, US)	TASEv3.0 (Tampere, FIN)	BLASTv3.0 (Torino, I)	BLASTv3lvl143 (CSU, US)	S3PASv2.0 (Sevilla, E)	DEROBvlth (Lund, S)	CLIM2000v1.1 (EDF, F)	HTB2v1.2 (FHT, GER)	HTB2v1.10 (UWCC, UK)	APACHEv6.5.2 (Facet, UK)	3TCv1.0 (Facet, UK)	CHEETAHv15.2 (CSIRO, AUS)	ENERGY2v1.0 (Arup, UK)	TASv7.54 (DMU, UK)	DOE2.1E (LBL, US)	TSBI3v2.0 (DBRI, DK)	WG6TCv1992 (Udine, I)
Program type	Public domain	X	X		X						X			X	X	X	X	X							X	
	Commercial			X		X	X	X	X	X		X	X						X		X		X	X		
	Prototype																			X		X				X
Solution Method	Response factor						X	X	X	X	X	X	X	X							X		X	X		
	Implicit fin diff														X				X						X	X
	Explicit fin diff				X	X											X	X				X				
	Other	X	X	X												X				X						
Window model	Fixed U-value				X	X					X								X	X	X	X			X	
	Variable U-value						X	X	X	X					X											
	TMC [1]	X	X	X								X	X	X		X	X	X					X	X		X
Internal heat transfer coeff	Fixed				X	X	X	X	X	X				X					X	X	X	X		X	X	
	Varying	X	X	X							X	X	X		X	X	X	X					X			X
Air cavity model	Fixed resistance	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Varying																									
External longwave loss	Explicity modelled	X	X	X							X	X	X	X		X	X	X	X	X	X	X	X	X		
	Not modelled/fixed				X	X	X	X	X	X					X										X	X
Diffuse sky model	Isotropic					X	X				X	X	X	X	X	X	X	X			X		X			X
	Anisotropic	X	X	X	X			X	X	X									X	X		X		X	X	
Internal solar distribution	To floor	X		X												X					X					
	To various surface		X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X	X	X	X

1 Transparent Multi-layered Combination

Some of these programs are research tools while others are commercial. The table gives an outline description of the degree of detail in the programs and their solution methods. When glazed spaces are to be studied, it is essential that a detailed calculation is made of solar radiation through windows. Correct distribution of solar radiation inside the glazed space and adjoining buildings is also important. Table 2.1 states only whether all solar radiation is distributed to the floor or to different surfaces. In the case of glazed spaces it is also important that diffuse and direct solar radiation should be calculated separately, so that radiation is not spread uniformly inside the space. The surface resistances of the surfaces should also be treated as temperature dependent variables. Long wave sky radiation is more significant for glazed spaces than for ordinary buildings, and therefore this should also be calculated.

Further information on some of these programs is contained in Judkoff and Neymark (1995).

2.6 Dynamic models without geometrical description

A brief description is given below of some calculation programs without a geometrical description of buildings, which have been used within IEA Task 12A3; *Building Energy Analysis and Design Tools for Solar Applications, Atrium Model Development.*

2.6.1 FRES

The Norwegian program FRES is a design tool for the simulation of the power and energy needs of buildings and their indoor climates (Kolsaker, Frydenlund & Bratsberg, 1990). FRES is used for research purposes but is also applied by consultants in Norway as a design tool.

The input data needed for calculations with FRES are the geographical position, orientation and areas of the building, the thermal properties of materials, ventilation systems, climate control installations for heating and cooling, and the transfer of air between rooms.

The calculation results obtained are hourly values of air temperatures, operative temperatures and power requirements. The energy needed for heating, cooling, ventilation, humidifiers etc over the specified simulation period is also given. Relative humidity is also calculated if required.

The calculations are based on hourly values. A two zone model and a model with linear temperature stratification are also implemented in FRES. When the temperature is to be calculated for large rooms such as an atrium, there may be considerable temperature stratification which this method takes into account (Kolsaker & Mathisen, 1992). FRES also provides a postprocessor for analysis of thermal comfort (Rømen & Frydenlund, 1992).

In calculating solar radiation, FRES takes account of shading from projecting eaves and other features that throw shadows. The program does not base calculations on a geometrical description of the building and the following method has therefore been chosen for the distribution of the transmitted solar radiation in the building (IEA Task 12A3, 1996):

The solar radiation transmitted through windows is distributed only over the *opaque* surfaces in proportion to their areas, a certain proportion applicable for the whole room, specified by the user, being absorbed. The remainder is reflected as diffuse radiation. The default value of the absorption factor is 0.7. The part of radiation which is reflected is spread to *all* surfaces, distributed in proportion to the areas of these surfaces. In this step all reflected radiation which impinges on opaque surfaces is absorbed. Windows absorb that part of the reflected radiation which is not transmitted. A mean transmittance is used for all windows to calculate the proportion of the reflected radiation impinging on the windows which is re-transmitted outwards. This part is thus not used as an energy gain for the building. The radiation which has been transmitted into e.g. a glazed space and thereafter impinges on windows facing adjoining buildings can in this way be transmitted further into adjoining rooms.

This method of calculating the distribution of solar radiation requires that a large proportion of the room consists of opaque surfaces, i.e. not large glazed surfaces as in the case of glazed spaces. Otherwise utilisation of solar radiation can be overestimated (IEA Task 12A3, 1996).

2.6.2 tsbi3

The calculation program *tsbi3* (Johnsen & Grau, 1994) is the Danish counterpart of the Norwegian program FRES. tsbi3 is used as both a design tool and a research tool.

In tsbi3, the building is described with the assistance of different rooms or zones which are in turn subdivided into surfaces. The thermal properties of the constituent materials shall also be described, as well as infiltration, ventilation, lighting and the heating and cooling systems. The program does not use any geometrical description of the building.

The calculations are based on hourly values of climatic data. Just as in FRES, tsbi3 performs dynamic calculations which take account of the heat storage capacity of the building. Power and energy requirements, temperatures, moisture balance, infiltration, daylighting etc can be calculated. Complete mixing of the air in each zone is assumed, i.e. only one air temperature is calculated in each room.

In calculations with tsbi3, solar radiation can be reduced by shading windows. Shading objects can be described for each window. The solar radiation which is transmitted through the windows is distributed as follows (IEA Task 12A3, 1996):

Lost refers to that part of radiation which is expected to be lost for a given volume, for example radiation transmitted back through a window.

To air represents the part of the transmitted solar radiation which is assumed to be transferred to the air by convection. This part is said to lie typically between 0.10 and 0.30.

To surfaces alludes to the part that will be absorbed by the surfaces. The relative distribution between surfaces is also given as input data.

The distribution of solar radiation shall in this way be estimated by the user, and is thus given as input data for the program.

2.6.3 TRNSYS TYPE 56 (Version 1.3)

TRNSYS is made up of a number of modules and is designed to simulate transient processes in energy systems (Klein & Beckmann, 1991). The program has routines for standard components, but the user can also describe his own components and couple them to TRNSYS. The available standard components are e.g. utility components, building loads and structures, solar collectors, hydronics, thermal storage, controllers, equipment, heat exchangers and output. During 1996 a version for MS Windows, TRNSYS V14.2, has also been published.

In TRNSYS TYPE 56, the thermal behaviour of multizone buildings is modelled. A building is allowed to have up to 25 different thermal zones. Air in each zone is assumed to be completely mixed, and no thermal stratification is calculated. Nor does TRNSYS use any geometrical description of the building (IEA Task 12A3, 1996). Transmitted solar radiation is distributed to inside surfaces in proportion to their areas and absorptivities. One limitation of the standard TYPE 56 is that internal transparent surfaces are not treated, which means that solar radiation which is incident on windows placed in a facade between a glazed space and an adjoining building cannot be transmitted further into the building.

The results which can be obtained from calculations with TRNSYS TYPE 56 are the air temperature in each zone, energy and cooling requirements, energy balance and relative humidity. Surface temperatures and more detailed energy transfers can also be described.

2.7 Dynamic models with geometrical description

A calculation program based on a geometrical description of the building can use this to advantage for a more detailed calculation of the distribution of solar radiation in and between rooms and for the calculation of that part of solar radiation which is lost by re-transmission outwards. Some examples of such programs are described briefly below.

2.7.1 SUNREP/TRNSYS

In the research project IEA Task 12A3, *Atrium Model Development*, the calculation program MODPAS by Dominique Chuard and Dario Aiulfi, Sorane S.A., Switzerland, was used. The solar processor in MODPAS was used to calculate incident solar radiation and that transmitted through windows. This processor is derived from the TRNSYS processor based on Duffie and Beckman (1974).

For calculation of the distribution of transmitted solar radiation inside the building, the program *SUNREP* was developed by Sorane S.A. (IEA Task 12A3, 1996). Direct solar radiation is calculated here for the day in the middle of the month, i.e. 12 times a year. Diffuse solar radiation is treated as isotropic. Diffuse solar radiation spreads equally in all directions, and this isotropic spreading is independent of the time of day and year. There is therefore no need for the relative distribution of diffuse solar radiation between surfaces to be calculated more than once. The results from SUNREP are stored in a file and can then be read by an energy calculation program. SUNREP therefore *distributes* the solar radiation which has been calculated by some other program as having been transmitted through windows into the building in question. The solar radiation distributed by SUNREP can then be used as input data for an energy calculation program.

The calculation method in SUNREP divides windows into a number of rectangular areas. If one of these areas is shaded, solar radiation is not calculated for this area. The solar radiation which is incident on an inside surface is divided into three parts, one of which is absorbed and the remainder is reflected, some diffusely and some directly. Distribution is determined by specifying for each surface an absorption factor and a factor for directional reflection. Directional reflection occurs once, further reflections are treated as diffuse reflection. This diffuse reflection is calculated with reference to view factors. Reflections proceed until all radiation has been absorbed or transmitted out of the room. Calculations are performed for each part area of the window and are summated for each inside surface and for each hour.

When the distribution of solar radiation shall be calculated between different rooms, e.g. between a glazed space and an adjoining building, distribution in the glazed space is calculated first. The part which is transmitted further into the adjoining building is then calculated; this is distributed both as diffuse and direct radiation. Temperature stratification can also be calculated, and examples of this are given in the final report from IEA Task 12A3 (1996, Chapter 3).

2.7.2 ESP

ESP is an acronym for Environmental Systems Performance. ESP is a transient energy simulation system which models energy and mass flows within combined building and plant systems. It has been developed at the University of Strathclyde, the Energy Systems Research Unit, Glasgow (Clarke, 1985). ESP is available both as a research tool and as a commercial tool, and is continuously developed.

This program uses a geometrical description of the building. ESP is a tool which has a lot of applications. Inputs are geometry, constructions, operation, plant components, shadings, leakage distribution, casual gains, etc. The program calculates e.g. temperatures, distribution of solar radiation, energy requirements, air flows and moisture transfer.

ESP has a linkage with CAD tools such as AUTOCAD, which may be used to define geometry and topology. According to general information about the program, ESP now also incorporates a CFD module in order to calculate air velocity and temperature distribution within a zone. It is also possible to export data to other programs, for example RADIANCE which calculates daylight and artificial light.

2.7.3 DEROB-LTH

DEROB is an acronym for Dynamic Energy Response of Buildings and was originally developed by Francisco Arumi-Noé at the School of Architecture at the University of Texas. The program has since been developed at the Department of Building Science, University of Lund, Lund Institute of Technology, under the name DEROB-LTH. The program is developed continuously as new needs arise (Arumi-Noé & Wysocki, 1979; Arumi-Noé, 1979; Fredlund, 1989).

The program consists of seven modules, each of which can be executed as an independent program. Information between the different modules is transferred with the help of a number of files in which the output data from one module constitutes the input data for the next module. The advantage of this system is that, depending on which input data are altered, only the module or modules affected by the alteration need be restarted for a new calculation. For instance, if only climatic data are altered, the modules which handle building geometry and material data need not be re-run. This cuts down the calculation time. The modules are briefly described below.

1 DIG	Input data concerning the geometry of the building are translated into a representation in an orthogonal system of coordinates. A check on the input data is provided in Module 7 where the building is directly plotted.
2 GF	Calculation of view factors for radiant heat transfer between all surfaces, volume by volume.
3 LUM	Calculation of distribution factors for short wave and long wave radiation between surfaces. The term distribution factor is used here to denote calculation of the distribution of radiation using

	the view factors and absorptivities for short wave radiation and the emissivities for long wave radiation.
4 WAL	Input data for the thermal properties of the constituent building elements in order to generate the necessary calculation network. A maximum of seven internal and two external nodes are used per building element. The program assumes that heat transfer is unidimensional.
5 SOL	For the day in the middle of each month, the proportion of solar radiation which is incident on each surface in the building is calculated once per hour. The middle day represents the whole month.
6 TL	Calculation of energy balances for the whole building, volume by volume, due to the influence of the specified climatic data. The results are obtained in the form of solar radiation incident on windows, transmitted and absorbed solar radiation in each volume, surface temperatures, air temperatures and the energy needed for heating and cooling. The results can be obtained as hourly values and also as monthly values. The results are output into files which can be read in Excel for further processing.
7 ALKAZAM	This program module gives a graphical presentation of the building as described in the first module DIG. Visualisation makes possible a check on the input data. Since the sun can be specified as the viewing point when the perspective is to be drawn, it is also possible to study which parts of the building will be sunlit at different times of the day and over the year.

In order to make the program more user friendly, a version for MS Windows has been produced (Kvist, 1995). This new version is much easier to use and the manual is linked to help menus in the program. A postprocessor which calculates thermal comfort in the form of directional operative temperature, Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), in accordance with ISO 7730 (Källblad, 1996), has also been coupled to the program.

Thanks to the geometrical description of the building, calculation of the distribution of solar radiation can in this case also be handled with greater accuracy than is normal in energy calculation programs. Solar radiation is divided into diffuse and direct radiation. Diffuse solar radiation is transmitted and spread diffusely. Direct solar radiation is treated as direct until it meets an internal surface for the first time. Reflected radiation is on the other hand treated as diffuse radiation.

Solar radiation can also be transmitted into adjoining rooms through windows between the rooms. If the direct solar radiation is transmitted into the first volume and directly meets a glazed surface which faces another volume, some of the radiation is transmitted further as direct solar radiation. Thereafter, in the secondary volume also, the solar radiation is reflected as diffuse radiation. If some of this radiation is re-reflected towards the glazed surface through which the solar radiation had entered, this can be re-transmitted back into the first volume. Solar radiation can in addition be transmitted out of the building again through windows which face the external air, and in this case it is not included in the energy balance.

In order to find what proportion of a surface is exposed to solar radiation, an approximation is employed in which each surface is divided up into a 5 times 5 mesh. If the midpoint of every part surface is exposed to the sun, the whole part surface is assumed to be exposed. In this way account can be taken of shading objects. In some cases this simplification can give rise to unacceptably large errors, especially if the volume has only a small window and the room inside the window is of extreme size (Fredlund, 1989). In order that a correct solar energy balance may be obtained, a check has therefore been introduced in the program to ensure that the solar radiation which has been distributed in the volume agrees with the solar radiation which has been transmitted into the volume.

DEROB-LTH can deal with shading objects in two ways. *Shading walls* can be placed into the system of coordinates to describe surrounding buildings, trees etc. These are used only to calculate shadows. In order to describe solar control devices and e.g. night-time insulation, *movable insulation* linked to windows can be used in DEROB-LTH. Solar control devices and insulating curtains can be described by specifying their properties for transmission of solar radiation, absorption and thermal resistance. Solar radiation which is transmitted through the curtain is treated as diffuse radiation. The time of day and year are also specified in order to describe when the curtains are used.

DEROB-LTH calculates only one air temperature for each volume. Temperature stratification, for instance in large glazed spaces, cannot therefore be correctly calculated with the present version of the program. There are plans for development of the program so as to make this possible. With the present version, a simplified but not entirely physically correct method can nevertheless be used for the study of temperature stratification. The volume is divided up in the vertical direction by means of horizontal glazed surfaces which have 100% transmission of direct solar radiation and negligible U value, and the air temperature for each part volume is calculated. Solar radiation is then treated as though there were only one volume, apart from the fact that transmission of diffuse radiation is fixed in the program at 92% of direct solar radiation. This means that 8% of diffuse solar radiation is absorbed in the notional glass. However, long wave radiant heat transfer between different surfaces only takes place within each part volume, which is a serious defect. Air movements between the different part volumes cannot be calculated in the program, but the flow must be specified as input data.

2.8 Summary

There are many different calculation programs for the assessment of climate and energy needs in buildings. The programs have varying degrees of simplifications, and the way these simplifications affect the calculation results for glazed spaces is a subject of discussion within research (IEA Task 12A3, 1996). At an early stage of design, some simplifications are obviously necessary, but for the final assessment more accurate calculations are needed. *The simplifications must in addition take account of the special properties of glazed spaces.* These properties are that glazed spaces are greatly affected by the outside climate, and that, in the case of passive climatic control, the climate in the glazed space varies considerably according to the time of year. A development of the design tools used by consultants is necessary, and researchers and others have the responsibility for ensuring that information and better design tools are made available to the building industry.

3 A design tool for glazed spaces – Description

The climate in a glazed space and the energy requirement in this are greatly affected by the outside climate and in particular by solar radiation. When calculations are made for a glazed space, solar radiation must therefore be treated considerably more fully than for a conventional building with windows of normal size.

It is extremely important that it should be possible, already during the preliminary design stage, to assess how the climate and the energy requirement, if any, will be affected by the design. Since the climate in a glazed space can be influenced to a very high degree by the building design adopted, energy demanding solutions and a low standard of comfort can be avoided in this way. This naturally also applies to the energy requirement for the whole building complex, i.e. the glazed space plus the surrounding buildings.

This chapter describes a manual calculation method for the assessment of temperatures and energy requirements in glazed spaces. The effect of the glazed space on the energy requirements of surrounding buildings can also be estimated. The way the method has been developed is described and the assumptions and simplifications are set out.

The method does not provide any exact answers, but is intended to work as an aid in designing glazed spaces so that an idea may be gained of the difference between alternative designs.

A more detailed description of this work is given in Wall (1994b) in Swedish. This method is also presented in English in Wall (1995) and Fredlund (1995).

3.1 Structure and limitations

When a new building is planned, it is necessary first of all to set out the aims and the requirements which must be satisfied. Depending on the function which the glazed space shall perform, the required temperature and comfort levels may be considerably different.

The intention is that, when the design begins to take shape, it should be possible using the method described in this chapter to assess alternative solutions with regard to temperatures and energy requirements; see Figure 3.1.

What mainly affects the climate inside a glazed space is the geometry, orientation and geographical position of the building, the thermal properties of the materials, ventilation and infiltration, the properties of the glazed surfaces and solar control. When a preliminary design has been drawn up, this can be analysed.

In a glazed space subject to passive climatic control, the rise in temperature above the outside temperature is mainly due to heat losses from the surrounding buildings and to solar radiation. If the glazed space is to be unheated, the lowest temperature in the space during the winter should first be estimated. If this is unacceptable, there are different ways in which this can be remedied. The configuration of the space can either be altered so as to achieve a higher temperature level, or it may be decided to heat the space (or both). One way of achieving a higher minimum temperature without supplying heat may be to reduce the glazed surfaces of the space which are in contact with the external air, or to increase the level of insulation, i.e. to change from double to triple glazing. Another solution may be to change the orientation of the building or to redesign the ventilation and heat recovery system of the building. The strategy selected depends on the given conditions. Once the lowest acceptable temperature has been determined, the power which may be needed to heat the glazed space can be estimated.

By testing different configurations, an idea may be gained of what effect an alteration will have. In this way a good idea will at the same time be gained in the course of the work of what in the configuration is important for the attainment of an acceptable temperature level and a low energy requirement.

The mean temperature each month in a glazed space with passive climatic control can also be estimated and e.g. compared with the mean temperature outdoors, to see what effect the glazed space will have. Estimation of the mean temperature also forms the basis for an assessment of the effect which the glazed space will have on the energy requirements of the surrounding buildings. If the space is to be heated to a certain temperature, the energy needed for this can be estimated.

If the mean temperature in the summer is too high, the effect of increased ventilation and cooling requirement can be studied.

The maximum temperature is also of interest in order that the ventilation requirement and the power which may be required for cooling may be estimated. Different types of solar control must be evaluated so that their effect on the temperature in the glazed space may be assessed.

By studying in this way the effect which different configurations will have on the climate in the glazed space and on the energy requirement, these and other aspects can be subjected to a balanced consideration, and a final design can be decided on.

Through calculations with the dynamic calculation program DEROB-LTH, certain general relations have been produced which show that, with the help of these relations, the gains due to solar radiation can be assessed without recourse to advanced computer programs at the preliminary design stage. This is made use of in the calculation method which has been developed. Transmitted solar radiation is read from tables, and the solar radiation utilised by the glazed space can be read off in different diagrams, depending on the geometry of the building in question.

With the help of the method described below, it will be possible to calculate the minimum and mean temperature in the glazed space in conjunction with passive climatic control. The energy needed for heating or cooling, and the effect of the glazed space on the energy requirements in the surrounding buildings, can also be estimated.

This method does not yet have the capability to calculate the maximum temperature in a glazed space. Nor is it therefore possible to estimate the maximum power required for cooling or to study whether the opening of vents is sufficient on extremely hot occasions.

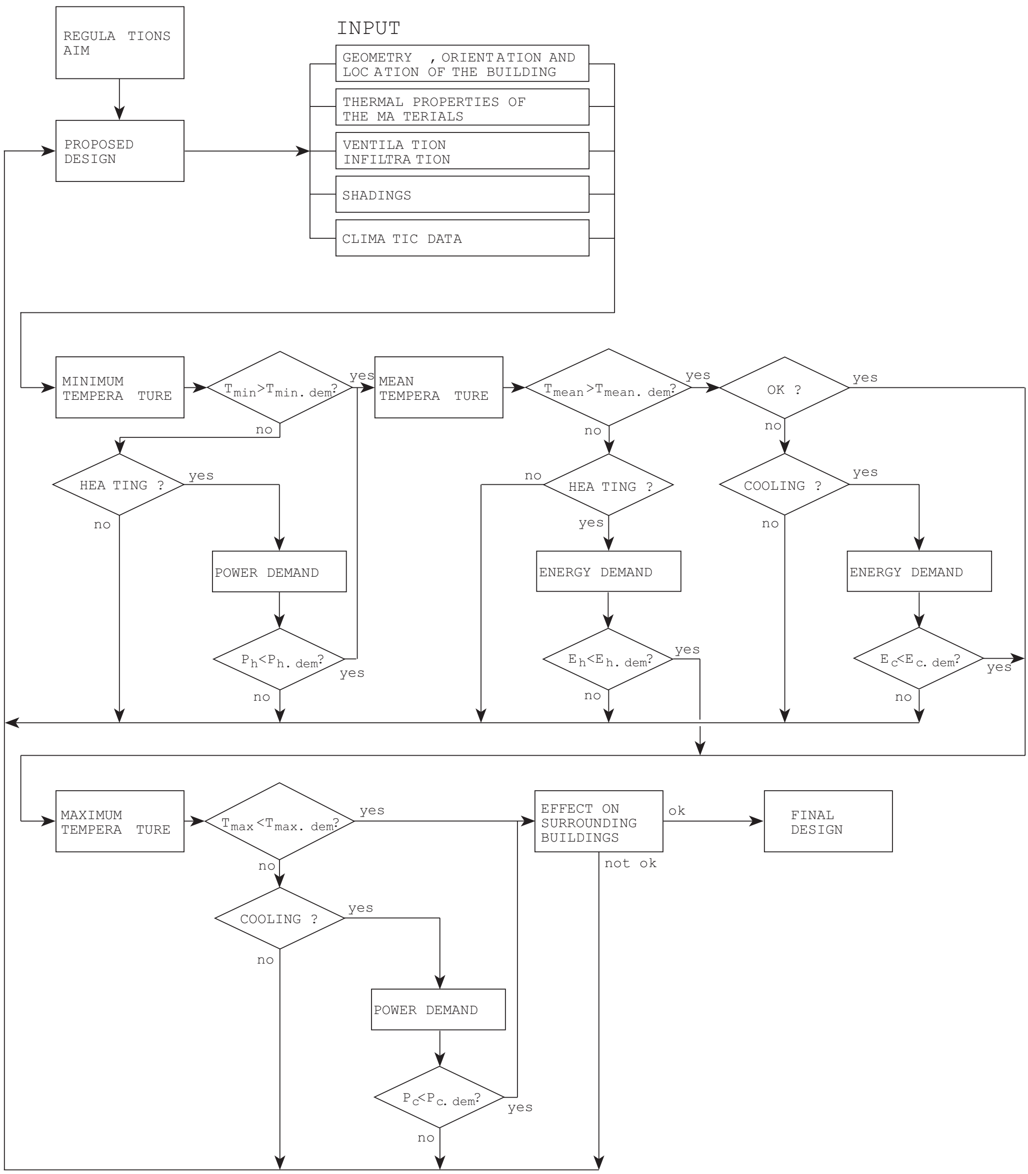


Figure 3.1 *Procedure in designing a glazed space (Wall, 1994b).*

In order that the temperature and energy requirements in a glazed space may be assessed, certain basic information is needed. It is necessary to estimate losses from the glazed spaces; these may consist of fabric losses and ventilation losses. It is also necessary to know what increments will accrue to the glazed space, in the form of transmission gains from surrounding buildings and possibly gains from the air exhausted from the surrounding buildings. The energy gain due to solar radiation is also needed for calculation of the mean and maximum temperature in the glazed space and of the energy requirement. By setting up an energy balance for the glazed space in which the gains are equal to the losses, unknown quantities can be solved. The expressions which are needed to do this are described below.

3.2 Expressions for the calculation of temperature, energy and power requirement

3.2.1 Calculation of energy losses from the glazed space

Those surfaces of the glazed space which are in contact with colder surroundings will emit energy. These fabric losses can be calculated from the following expressions:

$$Q^t_{from} = (T_g - T_o) \cdot \Sigma_{from} U \cdot A \qquad (3.1)$$

where

Q^t_{from} = fabric losses (W)
T_g = temperature in the glazed space (°C)
T_o = outside temperature (°C)
U = thermal transmittances of the constituent surfaces (W/m²°C)
A = areas of the constituent surfaces (m²)
$\Sigma_{from} U \cdot A$ = the sum of the areas of all surfaces in contact with the outside, multiplied by their U values ($U_1{\cdot}A_1 + U_2{\cdot}A_2 + {} + U_3{\cdot}A_3 + \ldots$)

Ventilation losses may occur as a result of controlled ventilation and unintended ventilation, also called infiltration/exfiltration. These losses can be written as

$$Q^v_{from} = V_g \cdot n_g \cdot \rho \cdot c_p \cdot (T_g - T_o) \qquad (3.2)$$

where

Q^v_{from} = ventilation losses (W)

V_g = volume of glazed space (m³)
n_g = number of air changes per hour (1/h)
$\rho \cdot c_p$ = density · heat capacity of air = 0.33 Wh/m³°C
$V_g \cdot n_g$ can also denote the controlled air flow (m³/h)

If heat from the exhaust air from the glazed space is recovered and the recovered energy is returned to the glazed space, Q^v_{from} shall be multiplied by (1-η) where η denotes the energy efficiency of the heat exchanger.

The total losses from the glazed space can therefore be written

$$Q_{from} = Q^t_{from} + Q^v_{from} \qquad (3.3)$$

where
Q_{from} = total losses from the glazed space (W)

3.2.2 Calculation of energy gains in the glazed space

Losses from those surfaces of the warmer surrounding buildings which are in contact with the glazed space will provide an energy gain in the space. These transmission gains can be written

$$Q^t_{to} = (T_i - T_g) \cdot \Sigma_{to} U \cdot A \qquad (3.4)$$

where
Q^t_{to} = transmission gain (W)
T_i = temperature in adjoining buildings (°C)
$\Sigma_{to} U \cdot A$ = the sum of the areas of all surfaces between the glazed space and the surrounding buildings, multiplied by their U values. A heated basement storey which is situated below the glazed space can also be included in this. ($U_{wall} \cdot A_{wall} + U_{window} \cdot A_{window} + U_{floor} \cdot A_{floor} + \ldots$)

There may also be gains in the form of ventilation losses from the surrounding buildings if, for instance, the exhaust air from the buildings is supplied to the glazed space. The gain due to ventilation can be written

$$Q^v_{to} = V_i \cdot n_i \cdot \rho \cdot c_p \cdot (T_i - T_g) \qquad (3.5)$$

where

Q_{to}^{v} = ventilation gain (W)
V_i = total volume of surrounding buildings (m³)
n_i = number of air changes per hour (1/h)
$V_i \cdot n_i$ can also denote the controlled air flow (m³/h)

The total transmission and ventilation gain in the glazed space can therefore be written

$$Q_{to} = Q_{to}^{t} + Q_{to}^{v} \tag{3.6}$$

where

Q_{to} = total gain in the glazed space (W)

If there are other gains, for instance in the form of lighting and heat producing activities, these can be added. A significant gain can be provided by the sun. The solar radiation which is transmitted into the space through the glazed portions will impinge on different surfaces. Some of the transmitted solar radiation will be reflected outwards or will pass into adjoining buildings, but some will be absorbed in the glazed space and will contribute to a rise in temperature.

The total gain in the glazed space can be written

$$Q_{to} = Q_{to}^{t} + Q_{to}^{v} + S \cdot P_{sun} \tag{3.7}$$

where

S = solar collection property of the glazed space (-)
P_{sun} = transmitted solar radiation, mean over time (W)

The solar collection property S of the glazed space is defined as that part of the transmitted solar radiation which is retained inside the space and therefore affects the energy balance.

If the glazed space shall be heated by a heating system, there is yet another factor which is however not adventitious energy but bought energy. The total gain can then be written

$$Q_{to} = Q_{to}^{t} + Q_{to}^{v} + S \cdot P_{sun} + P_{heat} \tag{3.8}$$

where

P_{heat} = heating requirement (W)

3.2.3 Energy balance

When the gains and losses of the glazed space have been defined, an energy balance is set up in which gains are equal to losses. This energy balance can be written

$$Q_{from} = Q_{to} \tag{3.9}$$

$$Q^t_{from} + Q^v_{from} = Q^t_{to} + Q^v_{to} + S \cdot P_{sun} + P_{heat} \tag{3.10}$$

where

$Q^t_{from} = (T_g - T_o) \cdot \sum_{from} U \cdot A$

$Q^v_{from} = V_g \cdot n_g \cdot \rho \cdot c_p \cdot (T_g - T_o)$

$Q^t_{to} = (T_i - T_g) \cdot \sum_{to} U \cdot A$

$Q^v_{to} = V_i \cdot n_i \cdot \rho \cdot c_p \cdot (T_i - T_g)$, provided that the air is supplied to the glazed space

Obviously, some of the terms are not applicable in all cases and others may have to be added in certain cases. Depending on whether power, energy, the temperature in the space, ventilation requirement etc is unknown, the system of equations can be solved for this. A more detailed description is to be found in Wall (1994b).

3.3 Estimate of solar energy utilisation

The effect of solar radiation on the temperature in the glazed space and the energy requirement can be considerable. In the energy balances set out in Section 3.2, the contribution of solar radiation to the energy balance for the glazed space is written $S \cdot P_{sun}$, where P_{sun} (W) is defined as the solar radiation transmitted to the glazed space, summated for the period concerned and divided by the time. Of the transmitted radiation, some will be reflected outwards, some will pass into the surrounding buildings, and some will be absorbed inside the glazed space. That proportion which is retained inside the glazed space, *S*, will be entered into the energy balance for the space and will contribute to a temperature rise. This proportion may vary considerably depending on the design of the glazed space. Even though simpler computer programs can calculate how much of the solar radiation is transmitted, i.e. P_{sun}, it is considerably more difficult to calculate what proportion is retained inside the glazed space. This requires a calculation model which makes use of a geometrical description of the buildings. In this section, a study is made to find whether it is possible to assess in a simplified manner the contribution of solar radiation in four principal types of glazed space.

3.3.1 Climatic data

Climatic data relating to four places in Sweden, supplied by the Swedish Meteorological and Hydrological Institute [SMHI], have been used. See Figure 3.2. The year 1988 has been selected as representative for the period 1983-1992. Table 3.1 sets out the latitudes, longitudes and altitudes of the four climatic stations. Tables 3.2-3.3 set out the outside temperatures at these stations for 1988.

Figure 3.2 Map of the Nordic countries showing the SMHI climatic stations in Lund, Göteborg, Stockholm and Luleå (Wall, 1994b).

Table 3.1 Latitudes, longitudes and altitudes of the climatic stations (Wall, 1994b).

place	latitute	longitude	altitude (m)
Lund	55.72°N	13.22°E	73
Göteborg	57.70°N	12.00°E	5
Stockholm	59.35°N	18.07°E	30
Luleå	65.55°N	22.13°E	17

Table 3.2 Outside temperature in Lund and Göteborg, 1988 (Wall, 1994b).

month 1988	outside temperature (°C) Lund			outside temperature (°C) Göteborg		
	min	mean	max	min	mean	max
January	-1.6	2.8	9.0	-3.4	3.1	8.6
February	-4.9	1.7	6.0	-5.1	1.5	6.6
March	-7.7	0.8	9.8	-12.6	0.4	9.7
April	-3.6	5.4	21.7	-3.5	5.0	14.5
May	3.7	12.5	25.4	3.9	13.4	27.7
June	8.2	16.5	27.0	8.1	17.8	29.6
July	11.7	16.9	24.5	10.4	17.3	28.2
August	10.7	15.8	24.4	8.2	16.2	28.8
September	6.8	13.4	21.0	5.4	13.7	19.7
October	-3.4	7.9	14.9	-5.5	7.7	16.1
November	-9.1	2.5	8.4	-10.6	2.3	10.2
December	-6.0	2.4	8.0	-10.7	2.4	8.7
year	-9.1	8.2	27.0	-12.6	8.4	29.6

Table 3.3 Outside temperature in Stockholm and Luleå, 1988 (Wall, 1994b).

month 1988	outside temperature (°C) Stockholm			outside temperature (°C) Luleå		
	min	mean	max	min	mean	max
January	-5.7	0.5	6.5	-21.9	-7.5	3.4
February	-9.2	-0.4	4.6	-25.4	-9.7	1.4
March	-11.6	-1.9	6.3	-22.5	-5.5	1.8
April	-4.5	3.4	16.7	-13.6	-0.1	12.2
May	1.6	12.2	26.4	-3.1	7.4	23.2
June	5.8	16.0	28.2	1.1	15.0	27.9
July	11.7	18.0	26.5	11.1	18.8	30.7
August	8.5	15.2	22.0	5.0	14.0	23.4
September	5.4	13.0	21.9	-1.7	10.3	18.5
October	-5.6	5.9	15.1	-14.4	2.8	13.1
November	-13.7	-1.4	6.4	20.7	-5.6	7.3
December	-14.4	-2.8	6.4	-27.4	-8.8	4.4
year	-14.4	6.5	28.2	-27.4	2.6	30.7

3.3.2 Tables for incident and transmitted solar radiation

In order to find how much solar radiation is transmitted into the glazed space for different orientations and inclinations of the glazing and for different glass types, a number of examples have been calculated and the results tabulated. The incident radiation for single, double and triple (clear) glazing without any special coatings has been calculated for 1988 for Lund, Göteborg, Stockholm and Luleå. The properties of the three glass types are set out in Table 3.4.

Table 3.4 Properties of the glass types for perpendicular incidence (Wall, 1994b).

glass type	transmisson	reflection	absorption	U value ($W/m^2 °C$)
single-glazing	0.85	0.08	0.07	5.88
double-glazing	0.72	0.13	0.15	2.94
triple-glazing	0.62	0.17	0.21	1.96

Table 3.5 Incident and transmitted solar radiation for vertical and horizontal single glazed surfaces, Lund 1988 (Wall, 1994b).

month 1988	incident solar radiation (W/m²)					transmitted solar radiation (W/m²)				
	north	east	south	west	horiz	north	east	south	west	horiz
Januari	6	6	12	7	11	5	5	10	6	8
February	16	21	38	24	34	13	16	31	19	26
March	37	49	82	62	84	29	39	68	50	66
April	58	92	114	106	152	46	75	91	87	121
May	85	139	151	165	244	66	113	117	136	198
June	94	123	123	138	217	74	99	96	113	177
July	87	114	117	124	198	69	93	92	101	161
August	69	92	113	106	164	54	74	90	86	133
September	39	65	94	70	103	31	53	76	57	81
October	22	37	78	43	57	17	30	65	36	43
November	10	22	65	24	28	8	17	55	19	19
December	5	8	30	12	12	4	6	26	9	8
year	44	64	85	73	108	35	52	68	60	87

The calculations have been made for vertical and horizontal glazed surfaces and for the inclinations 30° and 60°. An example is shown in Table 3.5. The other calculations are to be found in Wall (1994b). Solar radiation is given in the unit W/m², in actual fact summated solar radiation during the month divided by the time in hours. Secondary transmission, i.e. the proportion of solar radiation absorbed in the glazing which is supplied to the space, is included. The computer program used is called SUNHIT (Källblad, 1994c).

3.3.3 Method for calculation of transmission for different types of glass combinations

There is a large number of different glass types such as solar control glass, low emission glass, absorbent glass, reflecting glass etc. Obviously, the proportion which is transmitted through the glass combination depends on the constituents of the combination. The glass manufacturers quote transmission, reflection and absorption for perpendicular incidence, and the U values, for their different types. Note that values of solar energy and not daylight should be chosen. It is not practical to set out the calculations for all these variants. For this reason, the following simplified method is proposed for calculation of the transmitted solar radiation.

$$Q_{trans} = \frac{T_{\perp} \cdot Q_{trans,clear}}{T_{\perp,clear}} \tag{3.11}$$

where

Q_{trans} = transmitted solar radiation for the glass combination in question (W/m²).

$Q_{trans,clear}$ = transmitted solar radiation for the clear glass combination with the same number of panes as the glass combination in question (W/m²). See the example given in Table 3.5 and the complete set of tables for single, double and triple glazing in Wall (1994b).

$T_{\perp}$ = transmission for the glass combination in question, for perpendicular incidence (-)

$T_{\perp,clear}$ = transmission for the clear glass combination for perpendicular incidence (-), see Table 3.4.

This approximation will give rise to an error in the range of about 1 - 2%.

3.3.4 Estimate of the proportion of transmitted solar radiation which is retained inside the glazed space

Having determined how much solar energy is transmitted to the glazed space during the period concerned, an estimate must be made of the proportion of this transmitted solar radiation which is retained inside the glazed space and causes a temperature rise (or reduced energy requirement). It is evident that the magnitude of this proportion (here denoted *S*) can be affected by a lot of factors. These factors may be

- geographical position (latitude)
- the geometry of the glazed space and the proportion of glazed areas
- orientation
- time of year
- properties of the glazed construction
- absorptivity for short wave radiation of the surfaces inside the glazed space (i.e. dark or light surfaces)

In the following, the effect of these factors on the solar collection property *S* will be studied for four types of glazed space. The calculations have been performed using the computer program DEROB-LTH. DEROB requires a geometrical description of the building and uses this for an accurate calculation of solar radiation. The program calculates which surfaces and which parts of these the sun reaches. The proportion which is not absorbed in the surface undergoes repeated diffuse reflection until it has all been absorbed. The absorption factor for each surface is given as input data.

The types of glazed space used in this study can be most simply described as a glazed space which has adjoining buildings on one, two, three or four sides. See Figure 3.3. The size of the glazed space is the same the whole time, viz 18×9 m with a height of 9 m. The glazed roof is horizontal. The surrounding buildings also have flat roofs and have the same height as the glazed space. Generally, 20% of the facade surfaces between the glazed space and the adjoining buildings consists of double glazed windows (with properties as set out in Table 3.4). The height of the buildings and the glazed space has not been varied, but can obviously influence the results when the deviations are large. The fundamental calculations have been made for the orientation shown in Figure 3.3. Three of the four glazed spaces have previously been studied regarding temperatures and energy requirements (Wall, 1991b).

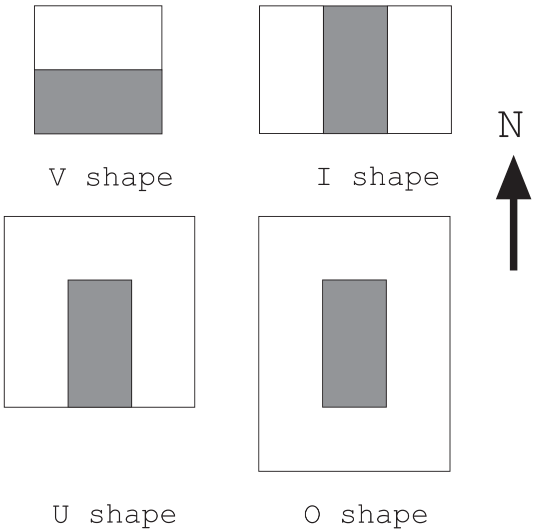


Figure 3.3 *Plan and orientation of the studied glazed spaces (Wall, 1994b).*

The solar collection property *S* may be defined as

$$S = \frac{\text{absorbed solar radiation}}{\text{transmitted solar radiation}} \tag{3.12}$$

The solar collection property thus has a value between 0 and 1. In reality, the factor is greater than 0 since otherwise no solar radiation at all would be absorbed inside the glazed space. It is also less than 1 since otherwise all solar radiation would be absorbed inside the space, which would in turn imply that all surfaces are black, there are no windows towards the surrounding buildings, and the glazed surfaces of the space do not re-transmit any radiation outwards.

Figure 3.4 shows an example of how *S* can vary over time. The calculation has been made for the atrium which has buildings on three sides, U shape, and is situated in Lund. The glazed gable is oriented towards the south, and it is double glazed. The absorptivity of the walls and floor of the atrium is 0.5. The example relates to the period 25-31 May 1988. In this case, the solar collection property varies between about 0.6 and 0.7. This means that between 60 and 70% of the transmitted solar radiation is retained inside the atrium, the remainder is reflected outwards or is transmitted further into the surrounding buildings. The sum of the absorbed solar energy divided by the sum of the transmitted energy gives an average value of *S*.

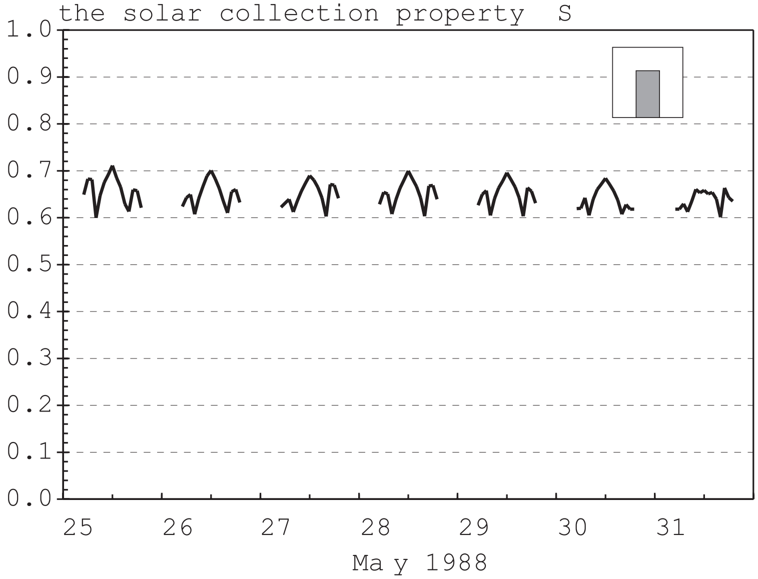


Figure 3.4 *Variation of the solar collection property during a week in May in Lund for the double glazed U shaped atrium (Wall, 1994b).*

By summating the calculated solar radiation month by month, monthly values of *S* are obtained. As an example, Figure 3.5 shows monthly values of the factor *S* for the whole of 1988 for a U shaped atrium surrounded by three buildings. In this case, the construction is single glazed and the glazed end is oriented towards the south. The absorptivity of the walls and floor of the atrium is 0.5. Values are given for all four locations in order to illustrate the significance of the latitude and the variation over the year. It is seen that the solar collection property *S* is hardly affected at all by the location of the building in Sweden, nor does it vary much at all over the year.

In order to study if the solar collection property *S* can also be used outside Sweden, calculations were carried out for Denver, Colorado. Denver is situated at latitude 39.8°N and longitude 104.9°W. Climatic data from 1959 in Denver were used in these calculations. In Figure 3.6, a comparison between Lund in 1988 and Denver in 1959 is shown for the same single glazed U shaped atrium as in Figure 3.5. The difference is very small and the yearly mean value of *S* is 0.64 for Denver and 0.62 for Lund.

For the other glazed spaces also, the variation over the year and between different locations is not large. The I shaped atrium has the greatest variation over the year, but the use of a constant value to simplify matters is nevertheless quite acceptable. The mean value of *S* which should then be used is the sum over the year of the absorbed solar radiation, divided by the sum over the year of the transmitted solar radiation. When these annual means are used instead of monthly means in the calculations in Section 3.2, the difference in the results is negligible. On the other hand, there is considerable variation in the solar collection property between different geometries and between different numbers of panes (i.e. transmission). For the V shape, with a building on one side only of the glazed space, the value of *S* for single glazing is only about 0.4 while for the O shape which has buildings on all four sides and thus has only a glazed roof, the value of *S* for triple glazing is about 0.7 (Wall, 1994b).

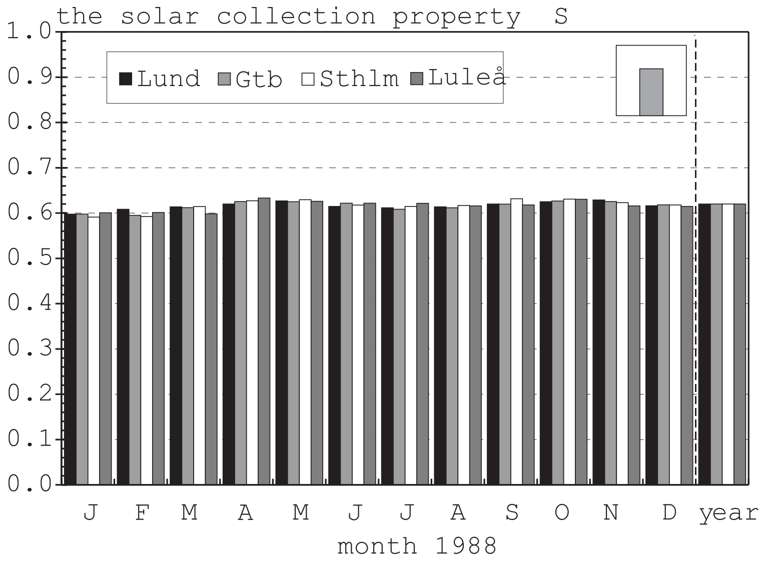


Figure 3.5 *Solar collection property during 1988 for the single glazed U shaped atrium with buildings on three sides (Wall, 1994b).*

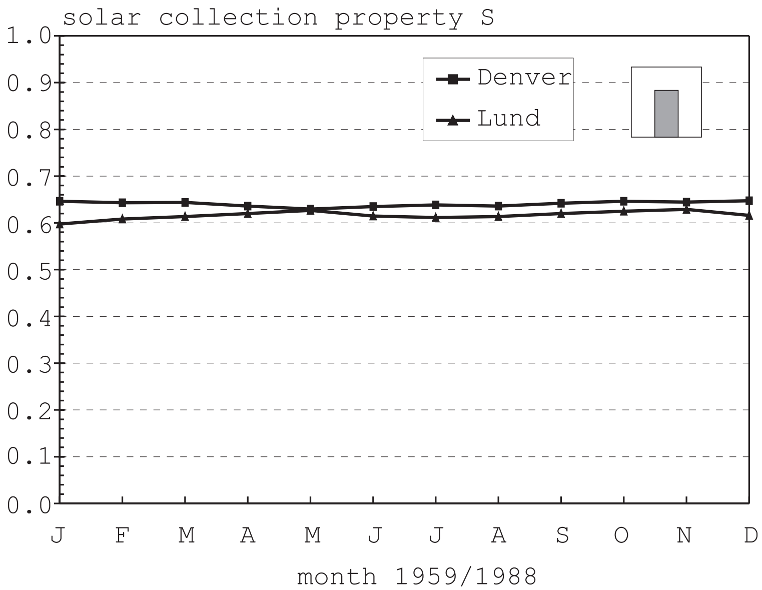


Figure 3.6 *Solar collection property during 1988 in Lund and 1959 in Denver for the single glazed U shaped atrium with buildings on three sides.*

The orientation of the glazed space may also be thought to have an effect on the solar collection property *S*. Calculations for the four glazed spaces have therefore also been made for an orientation different from the one used above. These calculations have however only been made for single glazing and for climatic data for Lund. In these calculations, the absorptivity of the inside surfaces is 0.5. Monthly values of the solar collection property *S* are shown in Figure 3.7 for the U shaped atrium, i.e. a glazed space with buildings on three sides, for the glazed end oriented towards the south (as before), west and north. When the end is oriented towards the south, a somewhat larger proportion of the solar radiation is retained inside the space, mainly in the spring and autumn. In winter there is hardly any difference at all. The difference is greatest between south and north, 0.03 over the year. Similar calculations for the other glazed spaces show that the variation is small and that for the glazed space with only the roof glazed (O shaped atrium), the factor *S* is practically constant (Wall, 1994b).

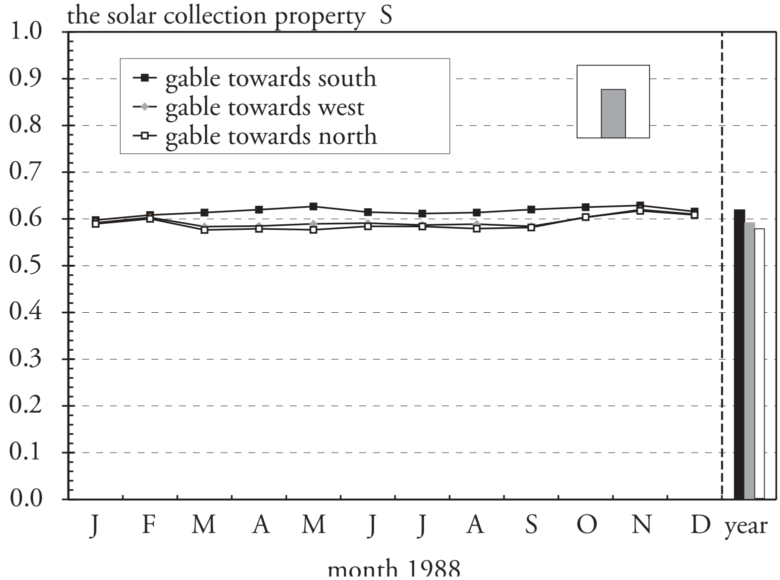


Figure 3.7 *Solar collection property during 1988 in Lund for a single glazed U shaped atrium, i.e. buildings on three sides, of different orientations (Wall, 1994b).*

The effect of the absorptivity of the surfaces inside the glazed space has also been studied. The absorptivity for short wave radiation is high if the surface is dark, and low if it is light. Table 3.6 shows examples of absorptivity for different surfaces (Arumi-Noé & Wysocki, 1979). For instance, if a concrete surface is painted, the absorptivity used is that for the colour of the paint.

Table 3.6 Absorptivity for short wave radiation (Arumi-Noé & Wysocki, 1979).

surface	absorptivty
asphalt	0.93
concrete	0.80
black paint	0.90
red paint	0.74
yellow paint	0.30
white paint (ZnO)	0.18

As an example of how the value of absorptivity can affect the solar collection property *S*, calculations are shown for the U shaped atrium, with buildings on three sides and the glazed end towards the south. The value of *S* is set out for each month in 1988 for Lund. Figure 3.8 is for single glazing. The absorptivities of the floor and walls of the atrium are put equal for the same calculation case. Calculations have been made for absorptivities of 0.1, 0.3, 0.5, 0.7, 0.9 and 1.0 and are plotted in Figure 3.8. The extremely high and low values of absorptivity are not realistic, but have been included to show the theoretical range. The value of *S* is greatly affected by whether the atrium has very dark or very light surfaces, but the increase in *S* gradually slows down as the value of absorptivity increases.

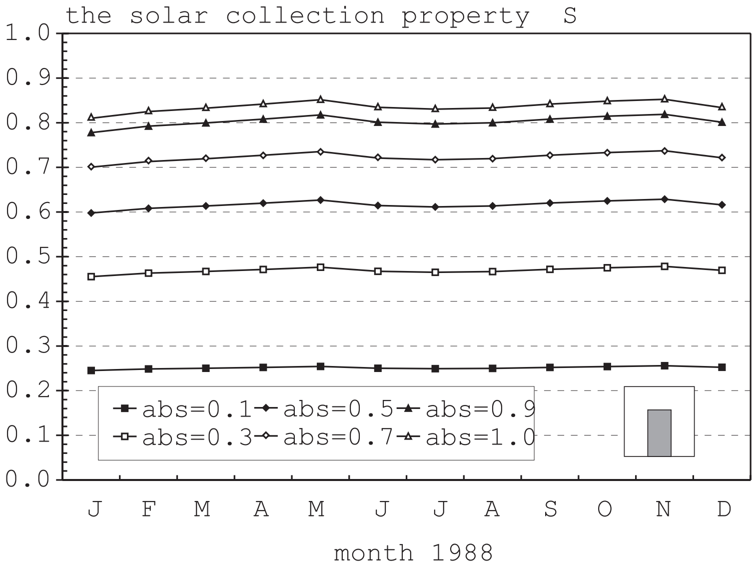


Figure 3.8 *The effect of absorptivity on the solar collection property in 1988 in Lund for a single glazed U shaped atrium, with buildings on three sides (Wall, 1994b).*

The effect of the investigated factors on the solar collection property *S* can now be ranked in order of significance. The ones at the top have the greatest significance, and those at the bottom the least.

- Absorptivity for short wave radiation of the inside surfaces of the glazed space (i.e. dark or light surfaces)
- The geometry of the space and the proportion of glazed surfaces
- The properties of the glazed construction
- Orientation
- Time of year
- Geographical position (latitude)

Broadly speaking, this holds for all the cases which have been studied. This means that the solar collection property *S* need not be calculated for different places. It can also be considered constant over the year. On the other hand, the properties of the glazed space with regard to transmission of solar radiation cannot be ignored, nor can the geometry or the absorptivity of the inside surfaces.

The solar collection property *S* must therefore be calculated for the different types of glazed spaces for single, double and triple glazing. The value of *S* must also be calculated as a function of absorptivity for each of these 12 variants. Obviously, there are many different variants of glazed space design, but all these cannot be predicted or shown here. The above examples are intended to give an idea of the solar collection properties which different types of glazed spaces have, so that an approximate assessment of temperatures and energy requirements, calculated according to Section 3.2, may be made.

3.3.5 Summary of solar collection property for variable absorptivity and geometry

The mean value of the solar collection property *S* over the year has been calculated for different values of absorptivity for the walls and floor which adjoin the glazed space. Climatic data from Lund for 1988 have been used, and the orientations are as shown in Figure 3.3. The results can however be used for other locations and for other orientations; see Section 3.3.4.

Values of the solar collection property *S* as a function of absorptivity are plotted for the four types of glazed space in Figure 3.9-3.12. The glazed spaces are described earlier in this chapter. Calculations have been made for single, double and triple glazing in the roof and glazed facades in contact with the external air for each type of glazed space. The curves show the calculated relationship between the factor *S* and the absorptivity (*a*) according to the following equations.

V-1 $S = 0.60 \cdot (a)^{0.613}$ (3.13)
V-2 $S = 0.64 \cdot (a)^{0.477}$ (3.14)
V-3 $S = 0.67 \cdot (a)^{0.375}$ (3.15)

I-1 $S = 0.73 \cdot (a)^{0.563}$ (3.16)
I-2 $S = 0.75 \cdot (a)^{0.463}$ (3.17)
I-3 $S = 0.77 \cdot (a)^{0.384}$ (3.18)

U-1 $S = 0.87 \cdot (a)^{0.529}$ (3.19)
U-2 $S = 0.87 \cdot (a)^{0.442}$ (3.20)
U-3 $S = 0.87 \cdot (a)^{0.380}$ (3.21)

O-1 $S = 0.93 \cdot (a)^{0.475}$ (3.22)
O-2 $S = 0.92 \cdot (a)^{0.408}$ (3.23)
O-3 $S = 0.92 \cdot (a)^{0.364}$ (3.24)

The magnitude of the exponent is affected by the transmissivity of the glazed surfaces of the space in contact with the external air and by the type of glazed space in question. The constant before (*a*) is mainly dependent on the geometry of the glazed space. Note that the relationship does not hold when *a* is less than approx 0.1. No detailed analysis has been made of why these relationships are obtained. It should for the moment be sufficient to know that if calculations are made with the computer program DEROB-LTH, the results will follow these curves. Bear in mind that the choice of curve in the above diagrams is governed by the transmissivity of the selected glazing and not by the number of panes. The properties of the glass used in the calculations are set out in Table 3.4.

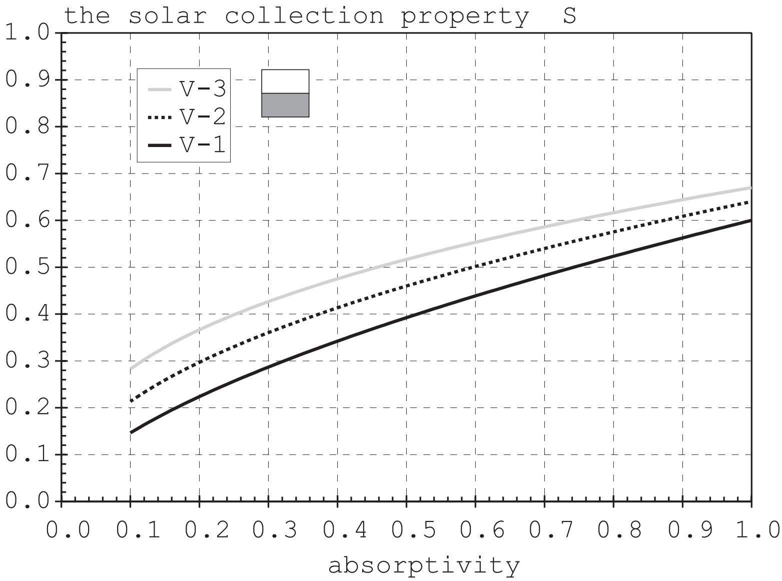


Figure 3.9 *Solar collection property as a function of absorptivity for the glazed space with a building on one side (Wall, 1994b).*

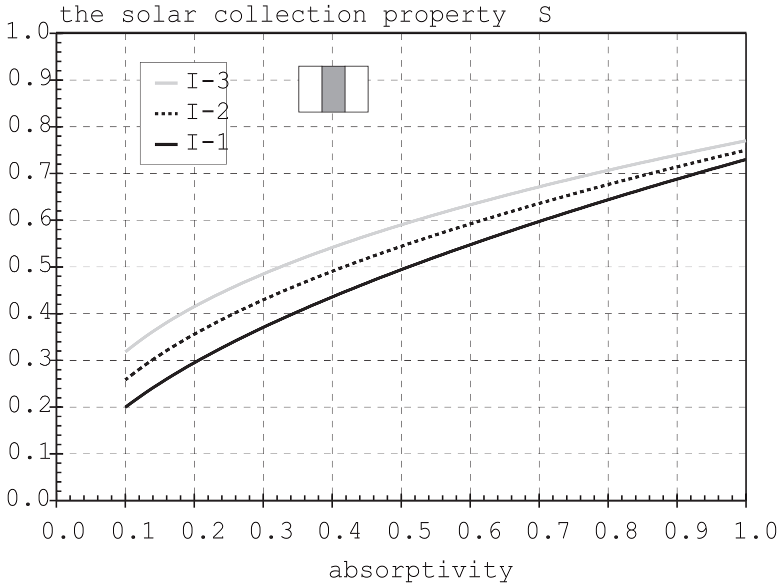


Figure 3.10 *Solar collection property as a function of absorptivity for the glazed space with buildings on two sides (Wall, 1994b).*

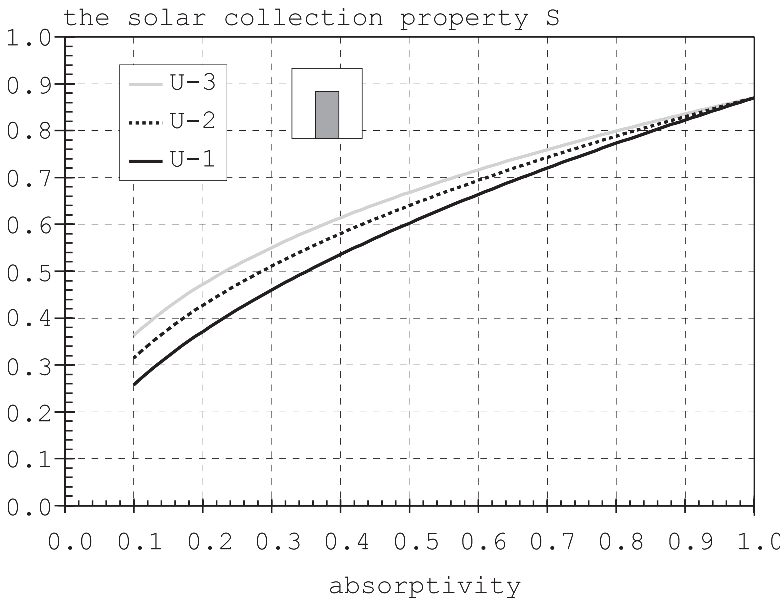


Figure 3.11 *Solar collection property as a function of absorptivity for the glazed space with buildings on three sides (Wall, 1994b).*

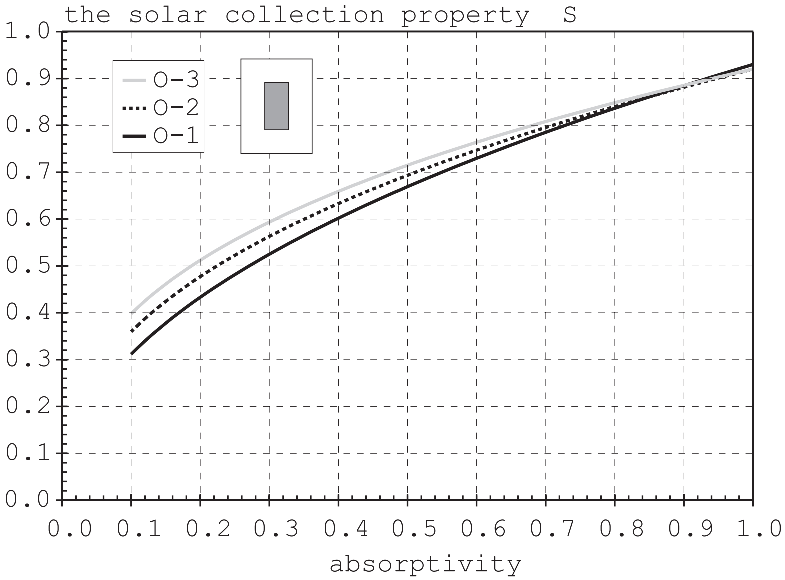


Figure 3.12 *Solar collection property as a function of absorptivity for the glazed space with buildings on four sides (Wall, 1994b).*

3.3.6 The effect of inclined surfaces

To see how the solar collection property is influenced by the angle of the roof, calculations were also made with a 30° pitched roof. The results show that the solar collection property *S* is reduced by about 0.05-0.10 compared with a horizontal roof when the glazed space has buildings on two, three or four sides. The error in calculating the utilised solar radiation will be minimized if the above calculated values of *S* are used in combination with transmitted solar radiation for a simplified horizontal roof. With this simplified geometry, the calculation error will be less than 1% for single glazing. For triple glazing, the error will be about 3-4%.

The solar collection property *S* for the glazed space with a building on only one side will increase by about 0.05 when the roof has an angle of 30° instead of being horizontal or the glazed wall an angle of 60° instead of being vertical. In this case the transmitted solar radiation should be calculated for the actual angle of the surfaces. In combination with the above calculated values of *S*, the utilised solar radiation will be underestimated by about 10%. In order to reduce this error further, add 0.05 to the chosen value of *S* in Figure 3.9; the error will then be a minimum.

3.4 Discussion and conclusions

By using this calculation method, an estimate can be made of temperatures and energy requirements in glazed spaces and the surrounding buildings. Perhaps the principal advantage of such a method is not that a lot of numerical data can be produced, but that it is possible to get a feel, right at the preliminary design stage, of how the configuration of the glazed space will affect temperatures and energy requirements. If the design of the space in combination with the surrounding buildings is determined in view of these and other aspects simultaneously, the prospects that the glazed space will perform satisfactorily are greatly enhanced. By means of calculations with the computer program DEROB-LTH, certain general relationships have been produced which demonstrate that the gains due to solar radiation can be determined without resort to advanced computer programs. These are made use of in the calculation method which has been developed.

The calculation method gives a good idea of the minimum and mean temperatures in the glazed space for passive climatic control, i.e. the case when the increase in temperature in the glazed space above the outside temperature is due mainly to heat losses from surrounding buildings and to solar radiation. Assessment of the energy requirement is better if there is a heating or cooling requirement during the whole period; the estimate is not as good if heating or cooling is required during only a part of the month or the day. The calculation method can be made more accurate if it is developed into a simple computer program.

This method is not yet fully developed. One important element which is still missing is estimation of the maximum temperature in the glazed space and the effect of different types of sun blinds. When this is possible, vents can be sized, sun blinds designed and the active cooling load calculated. By calculation with a dynamic energy calculation program such as DEROB-LTH, this can be estimated if the necessary input data are available. The influence of different types of solar control in combination with glazed roofs and glazed facades has not been studied, however, and this must be investigated in a test building with a glazed space where accurate measurements can be made. Calculations with DEROB-LTH in combination with these measurements will then make it possible for a simple method to be produced for estimating the maximum temperature in the glazed space, so that this simple manual calculation method will be as complete as possible. Account must then also be taken of the thermal storage capacity of the building.

The ultimate goal is to turn the manual calculation method into a computer program. Solar radiation data can then be calculated for any location, and for glazed spaces of any orientation and glazed surface inclination. It will be easier to change input data and to repeat calculations, which is always an advantage compared with a manual method. And if the program can read data relating to the building directly from a CAD program, it will obviously be even easier.

3.5 Summary

The climate and the energy requirement in a glazed space surrounded by buildings are greatly affected by the outside climate. Calculation of temperatures and the energy requirement for a glazed space therefore demands considerably more accurate treatment of solar radiation than for an ordinary building with windows of normal size.

Comparisons have often been made between different calculation programs and between measurements and calculations regarding the amount of solar radiation which impinges on glazed surfaces of different orientations, and the proportion of this solar radiation which is transmitted through the glazing. Most calculation methods can therefore calculate this satisfactorily. Of the solar radiation which is transmitted into a room with a window of normal size, about 95% will be retained in the room (IEA Task12A3, 1996). If the room is surrounded by large glazed surfaces such as a glazed roof and perhaps one or more glazed facades, a large proportion of the solar radiation will be retransmitted outwards or pass into adjoining buildings either directly or via reflections. If the surfaces in the glazed space are very light, much less of the solar radiation will be retained and contribute to a temperature rise or a reduction in heating requirement than if the floor and walls are dark. The proportion of the transmitted solar radiation which is retained in the glazed space is greatly affected by geometry, the proportion of glazed surfaces and the ability of the glazed space to absorb solar radiation. The proportion which is retained may vary between about 30 and 85%. It is therefore inappropriate to use a calculation method which applies only for the conditions which obtain in buildings with windows of normal size.

In order to find how the proportion of utilised solar radiation varies for different types of glazed space, glazed structures of variable transmission properties, absorptivities, geographical positions, different orientations and times of year, calculations have been made with the computer program DEROB-LTH. DEROB-LTH is a dynamic energy calculation program which requires a geometrical description of the building and makes use of this for an accurate calculation of solar radiation.

The calculations demonstrate that the type of glazed space, the transmission properties of the glazing and the absorptivity of the surfaces inside the glazed space have a great significance for the proportion of the transmitted solar radiation which is retained inside the glazed space. On the other hand, the geographical position, orientation and time of year are of less importance. Correct assessment of what proportion of the solar radiation will be retained inside the glazed space is particularly important when solar radiation is powerful, i.e. in the spring, summer and autumn. Faulty assessment can have a considerable influence on estimation of temperature in the glazed space and the energy required for heating or cooling.

A simple manual calculation method has been produced for the assessment of the temperature and energy requirement in glazed spaces. The effect of the glazed space on the energy requirements of the surrounding buildings can also be estimated. The results of the above calculations have been used to assess in an easy way the gain due to solar radiation without having to use advanced computer programs. It is intended that the method should be applied as early as during the preliminary design stage so that the effect which the design of the building will have on climate and energy requirement may be determined. The calculation method does not provide exact answers, but shall be used to get an idea of the difference between alternative configurations and to see which parameters are significant for climate and energy. It is hoped that the use of this method right at the preliminary design stage will prevent energy demanding solutions and a poor standard of comfort. In addition, it is hoped that the method will provide an insight into how glazed spaces behave with regard to climate and energy.
The calculation method gives a good idea of the minimum and mean temperatures in glazed spaces for passive climatic control, i.e. the case when the increase in temperature in the glazed space above the outside temperature is due mainly to heat losses from surrounding buildings and to solar radiation. Assessment of the energy requirement is better if there is a heating or cooling load during the whole period; the estimate is not as good if heating or cooling is required during only a part of the month or the day. The calculation method can be made more accurate if it is developed into a simple computer program.

The method is not yet complete. A way must be found to calculate the maximum temperature in the glazed space. In such a case it will be necessary to take account of the thermal storage capacity. In connection with this, the effect of different types of solar control will also have to be studied to see how much they can reduce solar radiation. Thermal comfort should also be treated.

4 The influence of design on climate and energy requirements

In order to methodically study the effect of different parameters on the climate in a glazed space and the energy requirements in the surrounding buildings, a dynamic building energy simulation program is very useful. The purpose of the parametric studies is to provide guidelines and a feel for what is important. It is not the absolute figures which must be remembered, but the relationships between them. The use of a computer program has one great advantage compared with studies on real buildings, and this is that one single parameter can be easily changed and the effects of this studied.

This chapter comprises both simple calculations for steady-state conditions and comprehensive calculations of the climate in different theoretical models of glazed courtyards. The simple steady-state calculations are based on the method described in Chapter 3. The dynamic building energy simulation program used is DEROB-LTH, briefly described in Section 2.7.3. These calculations are in some cases compared.

Three types of courtyards have been studied. Changes in the parameters in one and the same type of building are studied, and comparisons are also made regarding the significance of one and the same parameter in the different types of buildings. This study in its entirety is presented in Wall (1991b). Some new calculations have also been made.

A study is also presented in which the distribution of solar radiation in a simple glazed space with a room behind is estimated by four computer programs. The results from the different programs are then compared. A part of this study has also been presented in IEA Task12A3 (1996).

4.1 Description of the building types studied

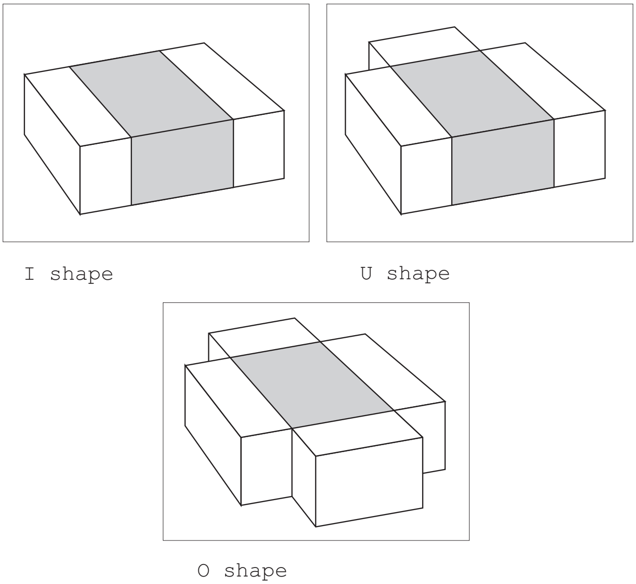


Figure 4.1 The three building types studied (Wall, 1991b).

The studies were confined to three basic building types, see Figure 4.1. The first comprises two parallel buildings with an intermediate glazed courtyard measuring 18 × 9 m (I shape). The second type has a further building so that the courtyard is surrounded by buildings on three sides (U shape). In the third type of building, the courtyard is completely enclosed, (O shape). The buildings are 9 m high and 7 m deep. They have windows only towards the courtyard. 20% of the facade surface towards the courtyard consists of double glazed windows. The glazed roof over the courtyard is horizontal. The reason why the buildings do not overlap at the corners is that it shall be possible to make a direct comparison of the volumes which are then the same in the three principal types. This causes no additional heat losses at the corners since the computer program calculates in one dimension. The walls towards the courtyard are varied, 26 mm plasterboard, 120 mm brickwork or 120 mm concrete, and are given the necessary mineral wool insulation on the inside. All other surfaces consist of 150 mm mineral wool. The floor in the courtyard is made of 70 mm brick pavers. The thermal resistance of the ground is calculated in accordance with the old Swedish Building Code SBN 80, and is 3.1, 3.3 and 3.4 m^2°C/W for the I, U and O shapes.

It is a reasonable requirement that the building shall not have a heat input demand higher than the same building without a glazed courtyard. It is therefore a fundamental condition for this parametric study that the U value of the walls facing the courtyard is such that the fabric losses calculated under steady-state conditions are the same irrespective of what the courtyard looks like. The U value of the facade towards the courtyard, *inclusive* of the glazed courtyard, is thus constant at U = 0.60 W/m²°C. This U value is based on the assumption that a typical facade of a building in Sweden contains 20% windows with a U value of 2.0 W/m²°C and 80% walls with a U value of 0.25 W/m²°C. The fact that the total U value is constant implies, for instance, that the U value of the walls facing the courtyard is lower when the glazed roof and end walls in the courtyard are single glazed than when they are triple glazed in the same type of building. In the same way, obviously, the walls facing the courtyard have a lower U value in the I shaped building with single glazed roof and end walls, than in the U shaped building with single glazing.

Another strategy could be not to reduce the insulation towards the courtyard but to retain triple glazed windows and well insulated walls. This would after all provide a better standard than SBN 80 and result in a direct saving of energy. But the courtyard would then at the same time be colder, and the energy gain due to the solar collection properties of the courtyard would be effectively rejected.

In order that direct comparisons may be made, the basic cases have been designed so that losses are the same in the different variants under steady-state conditions without solar radiation. The difference in energy demand and temperatures is then ascribed to the properties of the glazed space. Note that in these basic cases the ventilation losses are put equal to zero as a simplification.

The parameters which were varied in different combinations in the models of each type of building are

- The number of panes between the courtyard and the outside but with constant total losses under steady-state conditions. There is either single or triple glazing with clear glass. In order to simplify calculations, double glazing has been omitted since it has properties intermediate between single and triple glazing. Nor have special types of glazing been studied, such as glass with low emissivity coating, high reflectance or high absorptance.
- Thermal inertia. The walls facing the courtyard consist either of plasterboard, brick or concrete with the necessary insulation in order to achieve the insulation standard set up for the basic cases.
- Orientation. In the I shaped courtyard two directions were studied: the glazed end walls oriented north-south or east-west. The same applies to the orientation of the roof in the case of the O shaped courtyard. The U shaped courtyard was varied with the glazed end wall facing south, east or west.

- Air change rate between the courtyard and the outdoors. In the basic cases there is no ventilation. However, calculations were also made with varying degrees of ventilation.
- Apart from geometry, the three types of glazed courtyard are also characterised by the size of the glazed surface separating the courtyard from the external air. The area of glazing in the three courtyards is 324, 243 and 162 m² respectively.

The parametric studies were made for a winter week and a spring week in Malmö, Sweden. Changes in the parameters in one and the same type of building were studied, and comparisons were also made regarding the significance of one and the same parameter in the different types of buildings. Special studies were also made of the use of sunshades and window opening for some of the cases during a summer week. Calculations were also made for a longer period for some selected cases.

One limitation in this study was that the temperature in the courtyard was assumed to be the same in the whole space, thus no stratification was calculated. Another limitation was that the angle of the glazed roof was not varied, and a study was not made of the significance of changing the width to height ratio of the courtyard. Such a study of the format of the courtyard changes the relationship between warm and cold surfaces in the courtyard and will therefore have a considerable effect on the conditions relating to a certain temperature level in the glazed courtyard. This in itself may give rise to a fairly comprehensive study.

The calculations have been made by an earlier version of the program DEROB-LTH, the shortcomings of this version are described in Wall (1991b).

Not all the results are shown in this chapter. More results are found in Wall (1991b).

In this chapter, new studies have also been made regarding different ventilation systems and auxiliary heating and cooling of the glazed courtyard. These studies have been made using the steady-state calculation method described in Chapter 3.

4.1.1 Description of the climate used in DEROB-LTH

Climatic data for Malmö in 1971, which is a reference year, have been used in the parametric studies. These data were obtained from the Swedish Meteorological and Hydrological Institute [SMHI]. Malmö is situated in the south of Sweden at latitude 56°N and longitude 13°E.

Three different weeks were chosen. The first period was used to see how the glazed courtyard stands up to a really cold winter period, since it is the minimum temperature which governs how the glazed space can be used in the winter. For this purpose the period 1.1 - 7.1.1971 was chosen. The mean outside temperature is -4.6°C, the minimum temperature -14°C and the maximum temperature 2°C. The maximum global insolation is 187 W/m², see Figures 4.2 and 4.3.

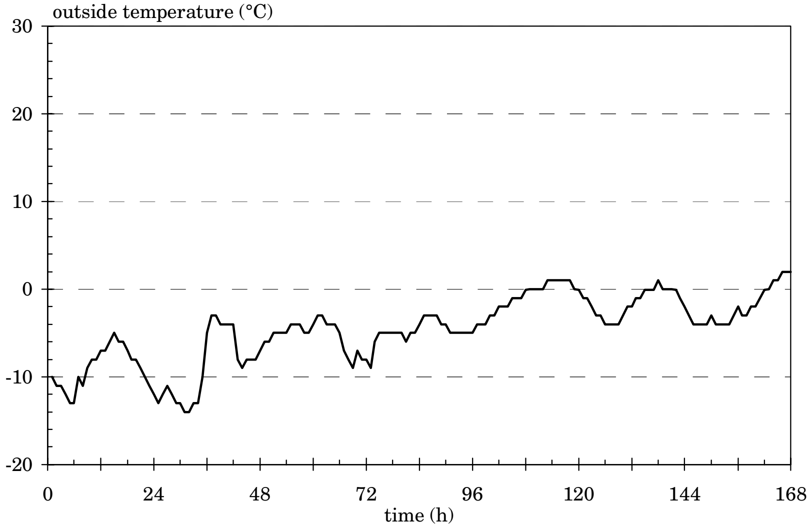


Figure 4.2 *Outside temperature in Malmö, 1.1 - 7.1.1971 (Wall, 1991b).*

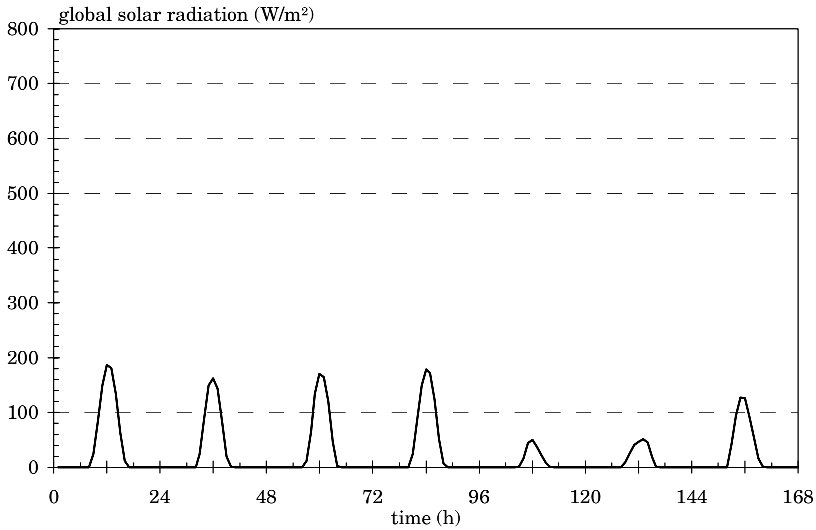


Figure 4.3 *Global insolation on a horizontal surface in Malmö, 1.1 - 7.1.1971 (Wall, 1991b).*

During the spring week, there are e.g. large variations in outside temperature. It is then that the thermal inertia of the glazed space and insolation are of the greatest benefit, since the surrounding buildings still have a heating requirement. A week in March, 16.3 - 22.3.1971 was therefore chosen, see Figures 4.4 and 4.5. The mean outside temperature is 4.1°C, the minimum temperature -1°C and the maximum temperature 10°C. Maximum global insolation is 505 W/m², i.e. there is considerably more sun than during the winter week.

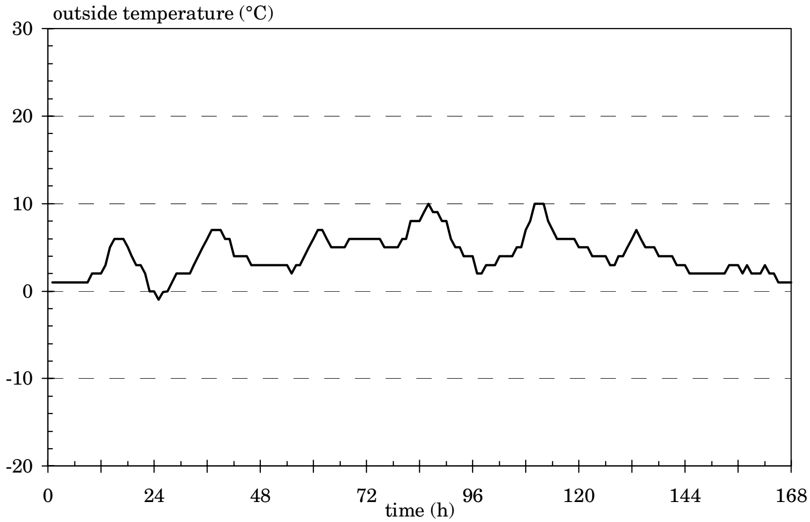


Figure 4.4 Outside temperature in Malmö, 16.3 - 22.3.1971 (Wall, 1991b).

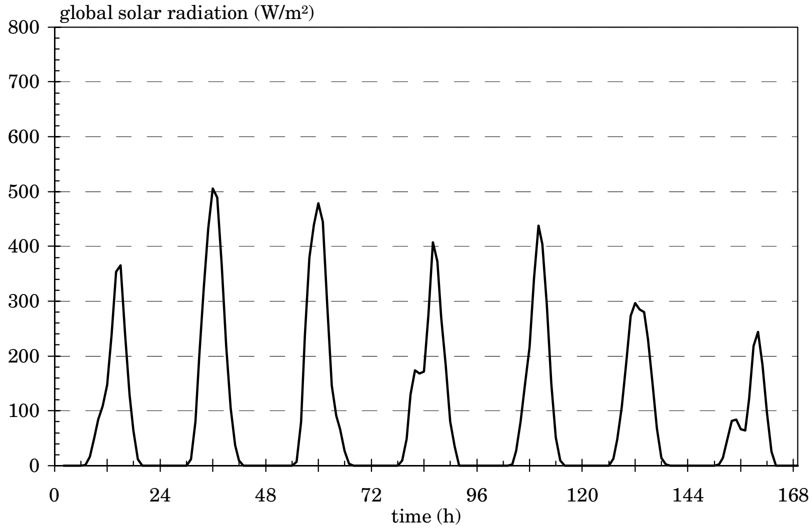


Figure 4.5 *Global insolation on a horizontal surface in Malmö, 16.3 - 22.3.1971 (Wall, 1991b).*

The glazed space must naturally also be able to provide a reasonable temperature in the summer. In order to study how the different building types manage this, a warm and sunny summer week, 3.7 - 9.7.1971 was chosen, see Figures 4.6 and 4.7. The mean outside temperature is 20.1°C, the minimum temperature 11°C and the maximum temperature 26°C. Maximum global insolation during the week is 771 W/m². This week was used in order to show how the temperature can be kept down in the different types of buildings by opening windows and using sunshades.

In addition to these studies, some cases were selected for calculations for an eight-month period, September - December 1971 and January - April 1971. In Table 4.1 the outside temperature and global solar radiation are shown over these eight months.

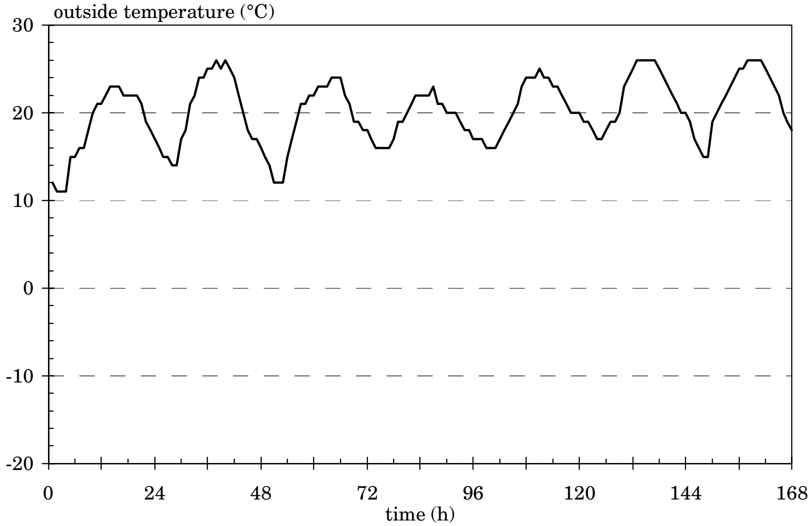


Figure 4.6 *Outside temperature in Malmö, 3.7 - 9.7.1971 (Wall, 1991b).*

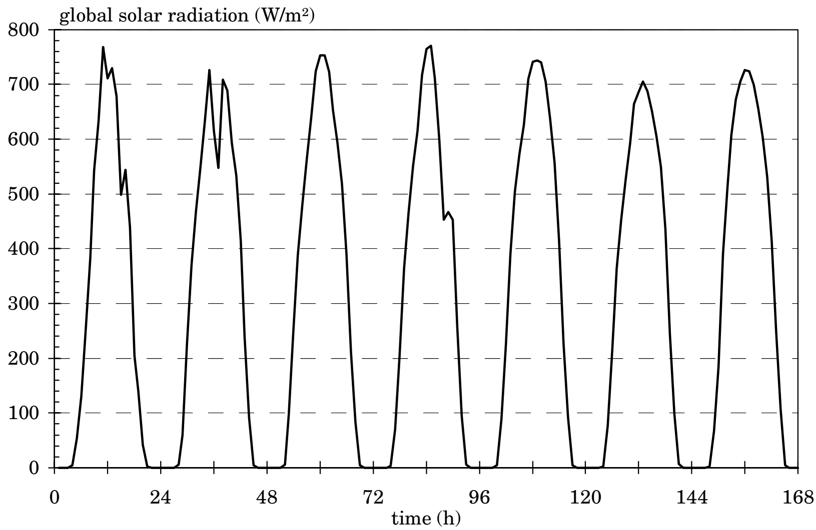


Figure 4.7 *Global insolation on a horizontal surface in Malmö, 3.7 - 9.7.1971 (Wall, 1991b).*

Table 4.1 Outside temperature and global solar radiation on a horizontal surface over 8 months in Malmö, 1971 (Wall, 1991b).

month	outside temperature			global solar radiation		
	min (°C)	mean (°C)	max (°C)	mean (W/m²)	max (W/m²)	sum (kWh/m²)
September	2.0	12.3	19.0	131	771	94
October	-3.0	9.8	18.0	73	546	54
November	-7.0	5.0	13.0	27	344	20
December	-4.0	4.9	10.0	15	214	11
January	-14.0	0.3	7.0	21	209	16
February	-8.0	1.8	7.0	49	427	33
March	-12.0	0.5	10.0	95	700	71
April	-4.0	6.1	14.0	181	824	130

4.2 The influence of the geometry of the building and the distribution of fabric losses

4.2.1 Steady-state calculations

Simple manual calculations can initially be made to find what are the fundamental differences between the three types of buildings. The effect due to the thermal inertia of the glazed space is ignored and a constant climate without any insolation is assumed in these steady-state calculations.

In order to find the significance of covering the courtyard with a single, double or triple glazed roof in the different types of buildings, calculations were made to show what increase in thermal resistance (m²°C/W) the courtyard gives rise to in the wall between the building and the courtyard; see Table 4.2.

Table 4.2 Approximate increase, due to the courtyard, in the thermal resistance ($m^2°C/W$) of the walls facing the courtyard (Wall, 1991b).

number of panes	increase in thermal resistance ($m^2°C/W$)		
	I shape	U shape	O shape
1	0.20	0.32	0.58
2	0.32	0.53	0.93
3	0.48	0.78	1.36

Owing to the fact that the surfaces between the courtyard and the external air are much smaller in the O shaped courtyard than in the I shaped one, the increase in resistance produced by e.g. single glazing is almost three times as high in the O shaped courtyard as in the I shaped one.

Figures 4.8, 4.9 and 4.10 show the temperature in the courtyard in relation to the outside temperature at a constant total U value of 0.60 $W/m^2°C$. There is no solar radiation. The air change rate between the courtyard and the external air is put equal to zero. This steady-state calculated temperature in the glazed space is in fact an estimation of the minimum temperature. The choice of triple instead of single glazing in the I shaped courtyard increases the temperature in the courtyard by 6.7°C at an outside temperature of -20°C, while it raises the temperature by 11°C in the U shaped courtyard and by 18.7°C in the O shaped courtyard.

Obviously, the reason why the differences are so large, as seen in Figures 4.8 - 4.10, is that the more enclosed the courtyard becomes, the more favourable are the relationships between the courtyard-outside and building-courtyard specific losses. A "good" relationship is characterised by a small surface with a low U value between the glazed courtyard and the outside, and a large surface with a high U value between the building and the glazed courtyard.

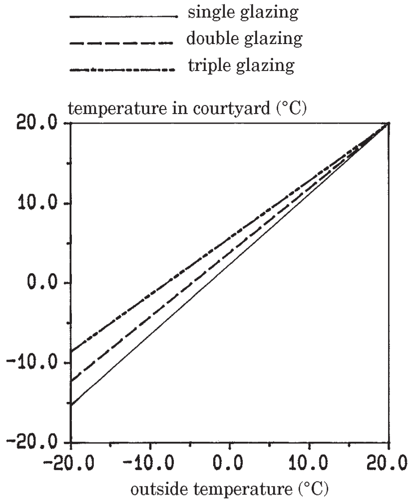


Figure 4.8 *Temperature in the I shaped courtyard at different outside temperatures (Wall, 1991b).*

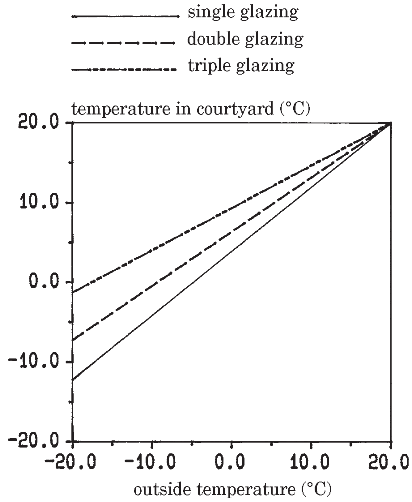


Figure 4.9 *Temperature in the U shaped courtyard at different outside temperatures (Wall, 1991b).*

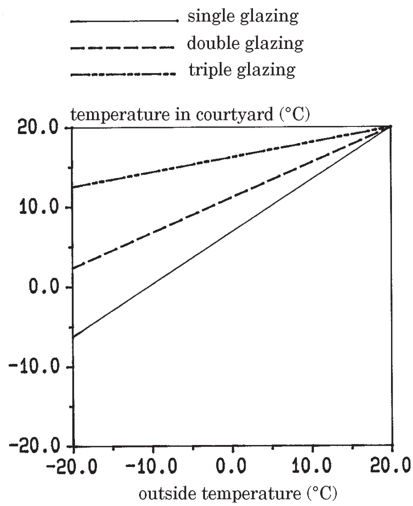


Figure 4.10 *Temperature in the O shaped courtyard at different outside temperatures (Wall, 1991b).*

In most cases the aim is to keep the temperature level in the glazed space as high as possible during the winter months at high latitudes. What mainly determines this temperature level is the relationship between the specific losses and the energy gains in the glazed space. This relationship can be written

$$G = \frac{\textit{specific losses from the glazed space to the outside}\ (\mathrm{W/°C})}{\textit{specific gains from the buildings to the glazed space}\ (\mathrm{W/°C})} \qquad (4.1)$$

For each glazed space, the value of G can be calculated and this can be used to give a direct assessment of the temperature level. The smaller the value of G, the higher the temperature level is in the glazed space. This guaranteed temperature level, or minimum temperature, in the glazed space can easily be calculated as

$$T_g = T_o + \frac{1}{1+G} \cdot (T_i - T_o) \qquad (4.2)$$

where

T_g = temperature in the glazed space (°C)
T_o = outside temperature (°C)
T_i = temperature in adjacent buildings (°C)

A greenhouse without any adjacent warmer buildings has a value of G which is infinitely large. An atrium with G equal to 1 has a guaranteed temperature which is the mean value of the outside temperature and the temperature in adjacent buildings. For example, if the temperature in adjacent buildings is 20°C, it will not be freezing in the atrium unless the outside temperature is below -20°C.

Figure 4.11 shows the temperature in a glazed space as a function of the relationship for G. The theoretically lowest temperature in a glazed space at different outside temperatures can be read off the figure. The temperature indoors is assumed to be 20°C. This relationship applies under steady-state conditions without insolation. In principle this is the temperature that really occurs overnight, especially after a cloudy day. When in this thesis a calculation is made as to what temperatures will occur in the glazed space under steady-state conditions without insolation, this is the relationship that is used.

In Figure 4.12 the three courtyards with single, double and triple glazing are plotted at an outside temperature of -20°C. It is seen that even if the value of G in the I shaped courtyard is changed from 7.5 for single glazing to 2.5 for triple glazing, it does not have very much effect on the overnight temperature in the courtyard. When the relationship between the specific losses and gains is so unfavourable, a change from single to double or triple glazing is a costly measure which does not produce much of a yield even if, as in this example, the insulation in the walls abutting on the courtyard is reduced in order to keep the total U value the same.

Consequently, the geometry of the building and the distribution of the specific losses and gains are very important when the glazed space is to be made as warm as possible.

Note also that in all the marked calculation cases in Figure 4.12 the total losses from the buildings are the same in steady-state calculations. The calculated temperatures are therefore dependent *only* on the geometry and the distribution of the total thermal resistance between the glazed surfaces of the courtyard and the walls separating the buildings and the glazed space, and *not* on any additional supply of heat.

In principle, the fluctuations in temperature in the glazed space will also be influenced by the factor *G*. In conjunction with normal fluctuations in outside temperature, but without insolation, the character of the temperature in the glazed space varies depending on what conditions are like. The more conditions are like the indoor climate, the smaller the fluctuations; see Figure 4.13.

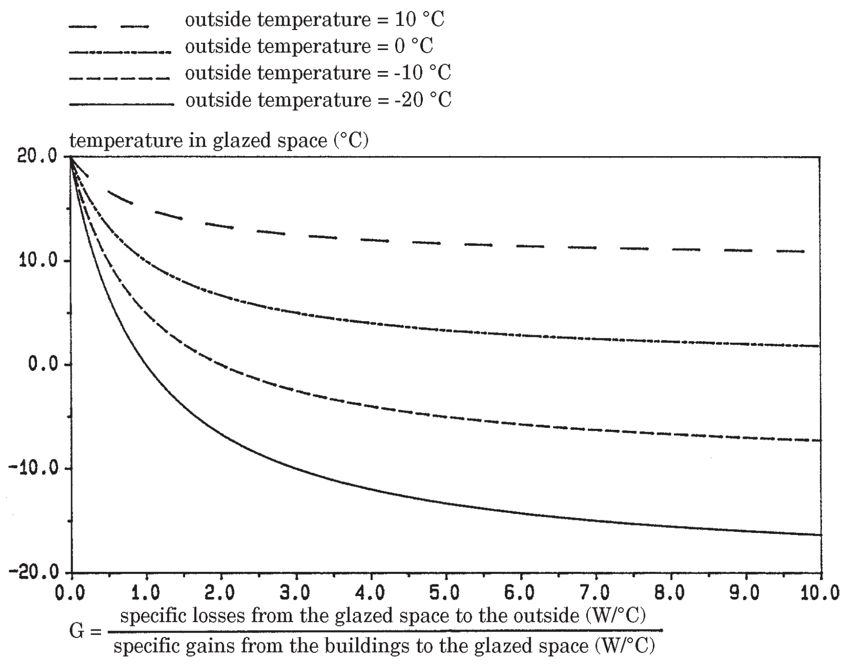


Figure 4.11 *Temperature in a glazed space for different values of the ratio between the specific losses and gains (Wall, 1991b).*

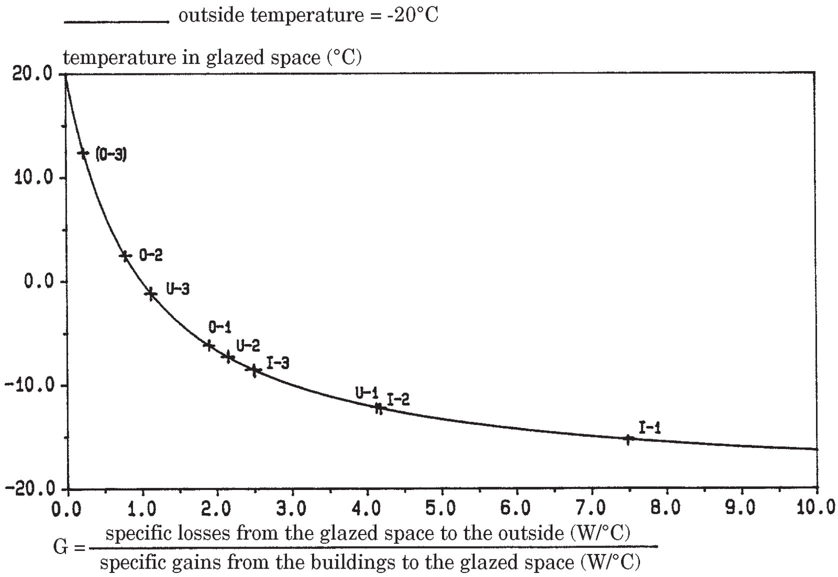


Figure 4.12 *Temperature in the courtyards for different numbers of panes. I-1 = I shape, single glazing; I-2 = I shape, double glazing, U-1 = U shape, single glazing, and so on (Wall, 1991b).*

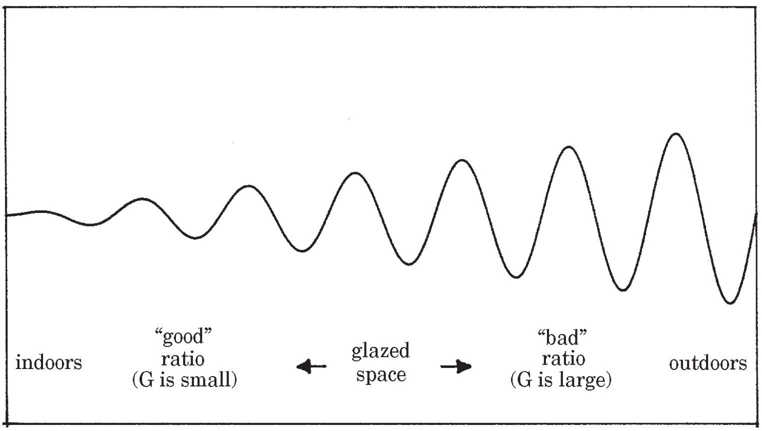


Figure 4.13 *The character of the temperature inside the glazed space for different values of the ratio between specific losses and gains (Wall, 1991b).*

4.2.2 Dynamic calculations

The above simple steady-state calculations show the basic conditions for the different types of glazed space. Computer calculations with the dynamic building energy simulation program DEROB-LTH demonstrate how the buildings will perform in a real climate, taking into account solar radiation and the thermal inertia of the buildings.

In the dynamic calculations with DEROB-LTH, it is however not possible to glaze the O shaped courtyard with triple glazing and at the same time keep the total U value at 0.60 W/m²°C. The walls between the buildings and the courtyard cannot have the high U-value which would have been required. The O shaped courtyard with triple glazing gives rise to such a high insulation that even with a poorly insulated wall between the courtyard and surrounding buildings, the total U value will be lower than 0.60 W/m²°C. The dynamic calculations for the O shape were therefore limited to single glazing. However, both single and triple glazed I shape and U shape were studied.

Since the two long buildings are present in all three building types and any differences in their energy requirement are due to changes in conditions in relation to the courtyard, one of these buildings was selected for comparisons; see Figure 4.14. There is however some difference towards the outside, since the short buildings at times shade the ends of the other buildings. This difference is however considered to be marginal. Only one orientation has been selected, see Figure 4.14, and the thermal inertia is varied with plasterboard or concrete walls. There is no ventilation and no shading of the courtyard.

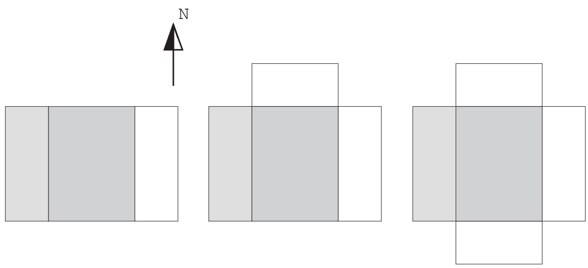


Figure 4.14 The three courtyards. The shaded buildings are compared (Wall, 1991b).

Figure 4.15 sets out the energy required by the selected building to maintain a temperature of 20°C during the winter week described in Section 4.1.1. The use of plasterboard or concrete in the walls between the buildings and the courtyard determines whether the walls have a low or high thermal capacity. The calculations were made with the computer program DEROB-LTH. The higher bar shows the energy requirement without insolation and the lower one that with insolation for the different cases.

Since all the outer walls, roofs and floors are simplified to 150 mm mineral wool and there are no windows towards the outside, heat losses are lower than in a building constructed to the Swedish Building Code SBN 80. In addition the buildings in the models have no ventilation losses, which real buildings do have. In order that the approximate percentage change for buildings constructed in accordance with SBN 80 may be seen, 665 kWh must be added for further fabric and ventilation losses during the winter week for this specific building.

Without any solar radiation, the energy requirement in the building is the same regardless of the geometry of the building, type of glazing and thermal inertia. This is consistent with the basic conditions for this study and therefore also consistent with the steady-state calculations.

For the I shaped courtyard with buildings in accordance with SBN 80 standards, the contribution of solar radiation during the winter week is about 5-9% of the energy need in the building to maintain 20°C without insolation. For the U shaped courtyard the contribution is approx. 6-11.5%. The contribution is least, about 3.5%, in the O shaped courtyard.

In Figure 4.16, the minimum, mean and maximum temperatures in the glazed courtyards are shown during the same winter week. In order to show the influence of solar radiation, calculations were also made assuming no insolation at all. The lowest bar shows the minimum temperature in the glazed courtyard which would have occurred if there had been no sun at all.

The U shaped courtyard is warmest, and even though the minimum temperature in the O shaped courtyard is not so low, there are no high maximum temperatures. The solar altitude is low in the winter and only a small amount of solar radiation will enter the O shaped courtyard. It is thus not only the relationship between the specific losses and gains of the glazed space that is important, but also the proportion of the glazed space which is glazed and can let in solar energy. Among these courtyards it is the U shaped one that is best at collecting and retaining solar energy. The use of triple instead of single glazing in the courtyards in addition results in better “efficiency” as regards utilisation of available solar energy. If the endeavour is to maintain the temperature above 0°C without any additional supply of heat, the chance of this is greatest in the U shaped triple glazed courtyard or an O shaped double or triple glazed courtyard.

By choosing in this parametric study, presented in Wall (1991b), between all the different basic cases which have the same losses under steady-state conditions, a minimum temperature ranging from -8.0°C to +8.3°C can be obtained in the courtyard. This is during the winter week when the minimum outside temperature is -14°C. Note that the energy requirement in the surrounding buildings is not higher when the courtyard temperature is high, but the opposite!

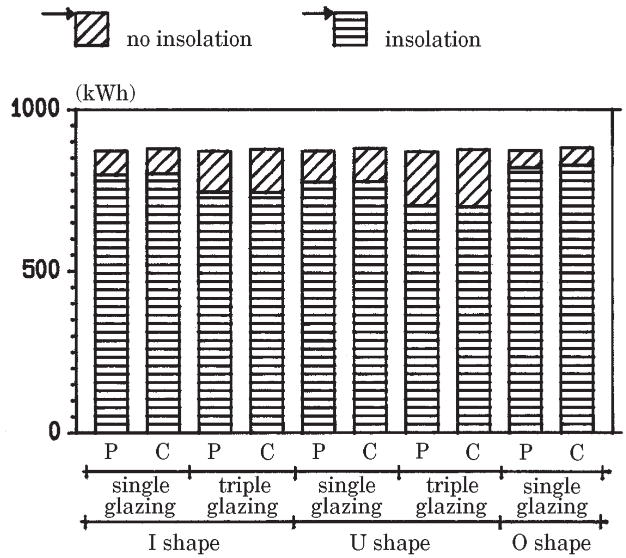


Figure 4.15 *Energy requirement in the building during the winter week. P = plasterboard, C = concrete (Wall, 1991b).*

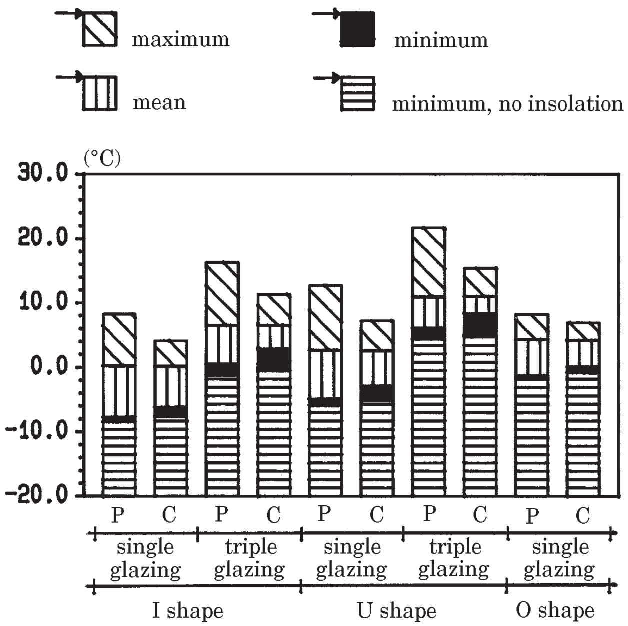


Figure 4.16 *Temperature in the courtyard during the winter week. P = plasterboard, C = concrete (Wall, 1991b).*

Figures 4.17 and 4.18 give the same diagrams for the spring week. The maximum temperature permitted in the surrounding buildings is 25°C since it is assumed that higher temperatures cannot be accepted. In practice, the buildings would have been ventilated. The contribution of solar radiation for the I shaped courtyard, as regards the energy requirement of the selected building, is about 18-32% of the energy requirement of the "SBN 80 building" without insolation. For the energy requirement with SBN 80 standards, 430 kWh is added for this week. For the U shaped courtyard the contribution is approx. 22-39%. For the O shaped courtyard, the contribution is about 21%. The contribution from the sun is thus much higher than during the winter.

In Figure 4.18 the temperatures in the different courtyards are shown for the spring week. There is still no ventilation and shading of the courtyard. The temperatures are of course much higher than in the winter. During this week also the U shaped courtyard makes the best use of the available solar energy. The single glazed O shaped courtyard is quite similar to the single glazed I shaped courtyard, even though its minimum temperatures are not so low. The maximum temperature in the triple glazed U shaped courtyard with plasterboard walls is as high as 43°C but in the O shaped single glazed courtyard with concrete walls it is only 19°C. Obviously, in reality high temperatures will be avoided by ventilation and solar curtains.

The minimum outside temperature during the spring week is -1°C. The coldest calculated temperature, 4.5°C, appears in the I shaped single glazed space with plasterboard walls. This can be compared with the highest minimum temperature, 16°C, which appears in the U shaped triple glazed courtyard with concrete in the walls.

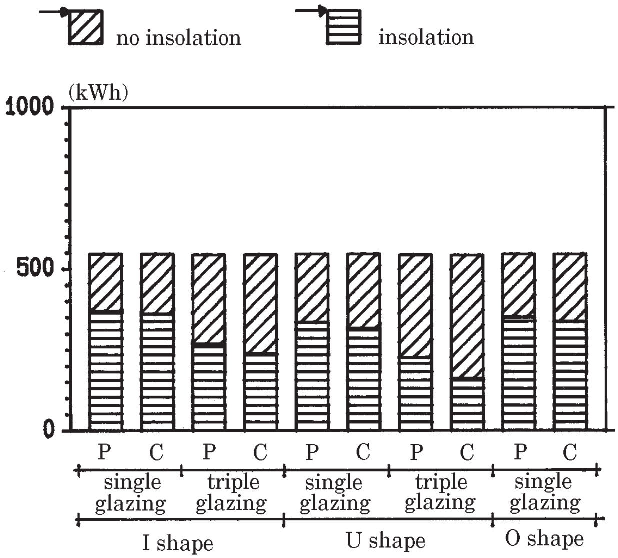


Figure 4.17 *Energy requirement in the building during the spring week. P = plasterboard, C = concrete (Wall, 1991b).*

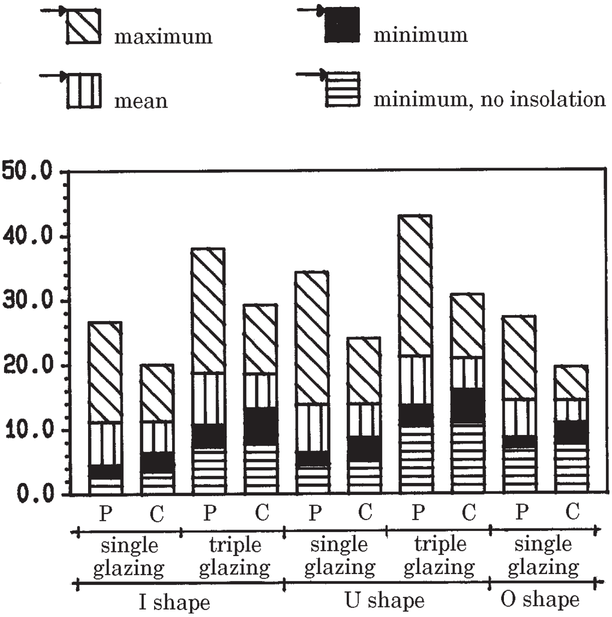


Figure 4.18 *Temperature in the courtyard during the spring week. P = plasterboard, C = concrete (Wall, 1991b).*

In order that the differences over a longer period may be seen, some cases have been selected for calculation for the heating season September-April in the Malmö climate, i.e. in actual fact January-April and September-December 1971. In calculations under steady-state conditions, the losses in these cases are the same. Calculations with DEROB-LTH have been carried out one month at a time, a total of eight months. Subdivision into months has been made in order to facilitate the computer runs and has no significance for the results. Table 4.1 in Subclause 4.1.1 shows the outside temperature and solar radiation during these eight months. September is the warmest month and January the coldest.

In these calculations also, the minimum temperature in the buildings is 20°C and the maximum temperature 25°C. A new limitation is that the temperature in the courtyard is not allowed to exceed 25°C.

In Figure 4.19 the monthly minimum temperatures in the courtyards with concrete walls are shown. The monthly minimum outside temperature has also been plotted. These minimum temperatures can be compared with the steady-state calculations of the minimum temperatures in the courtyards, shown in Figure 4.12. In both the steady-state calculations and the dynamic calculations, the triple glazed U shaped courtyard has the highest minimum temperature. However, according to the dynamic calculations in Figure 4.19, the triple glazed I shaped courtyard has a higher minimum temperature than the single glazed O shaped courtyard. The opposite was predicted in the steady-state calculations. This is due to the fact that triple glazing has a higher ability to retain the solar radiation than single glazing. On the whole, the single glazed courtyards have difficulty in keeping the temperature above 0°C. It is only the O shaped courtyard which just manages this.

Figure 4.20 sets out the monthly mean temperatures in the courtyards. The mean outside temperature has also been plotted. The temperature in the U shaped courtyard is at the same level as that in the single glazed O shaped courtyard in spite of the fact that the O shaped courtyard has a higher general temperature level according to steady-state calculations. At the same time, the energy that need be removed in the O shaped courtyard in order that the temperature should not exceed 25°C is the least of all cases. This is obviously determined by the way in which solar radiation has influenced the temperature in the glazed courtyards. The influence of solar radiation in the U shaped courtyard is greater than in the O shaped courtyard.

On the whole, the temperature in the triple glazed I shaped courtyard is higher in relative terms than predicted by the steady-state calculations. As pointed out before, this is due to the ability of the triple glazed roof to retain more of the incident solar radiation than the single glazed roof.

The energy required to maintain 20°C in the selected building is shown in Figure 4.21. From October to February, the energy need is highest in the O shaped courtyard. Since it is only the roof that is glazed, very little of the solar radiation enters the courtyard in the winter.

March is a little colder than February, but there is more insolation. In March the energy requirement in the triple glazed I and U shaped courtyards is lower than in February. In the single glazed O shaped courtyard there is a very slight drop; the sun is higher in March and more radiation enters the courtyard. On the other hand, the energy requirement increases in the single glazed I and U shaped courtyards which cannot utilise solar radiation so well. With single glazing, the influence of outside temperature is greater in these courtyards.

If the building is recalculated as an "SBN 80 building", with an indoor temperature of 20°C, losses increase by about 14 040 kWh over the whole eight month period. In such a case, the building alongside the triple glazed U shaped courtyard needs approx. 84-87% of the energy gain which a similar building alongside the single glazed O shaped courtyard needs. These are the extreme cases which have been compared.

During such a long period also, the temperature in e.g. the triple glazed U shaped courtyard is thus higher than in the single glazed O shaped courtyard. At the same time the energy required to maintain 20°C in the buildings in the triple glazed U shaped courtyard is lower than that required in the buildings adjacent to the single glazed O shaped courtyard. The conclusions after the weekly runs agree in this case also; a higher temperature in a glazed space need not therefore mean that the energy requirement will be higher.

In reality, a glazed roof is not horizontal and if e.g. one of the surrounding buildings is lower than the others, the O shaped courtyard will have better prospects of collecting solar radiation.

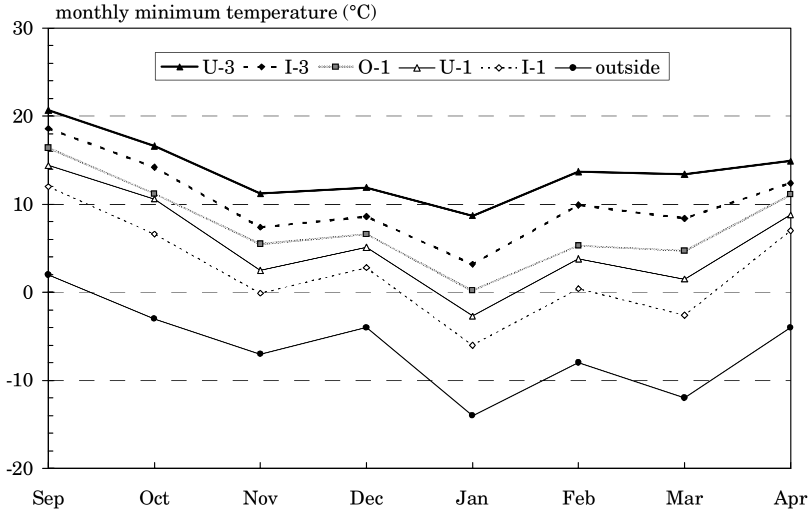


Figure 4.19 *Monthly minimum temperature for the different courtyards with concrete walls. I-1 = I shape single glazing, I-3 = I shape triple glazing, U-1 = U shape single glazing, and so on (Wall, 1991b).*

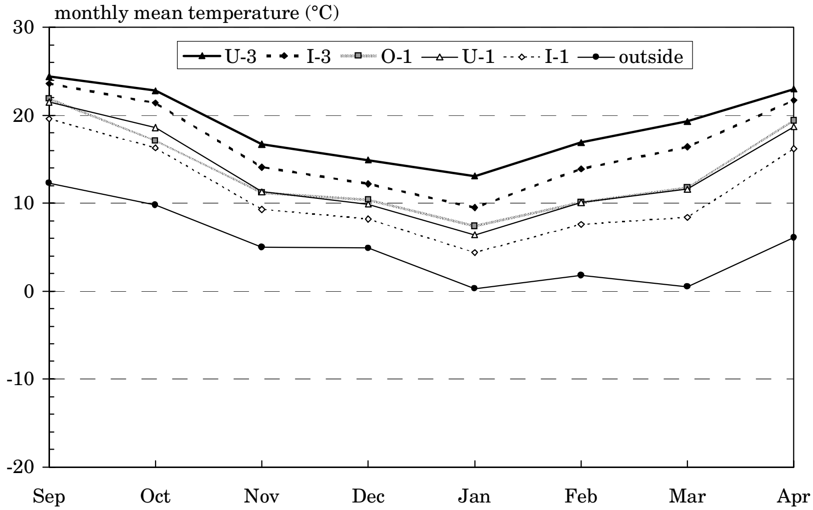


Figure 4.20 *Monthly mean temperature for the different courtyards with concrete walls. I-1 = I shape single glazing, I-3 = I shape triple glazing, U-1 = U shape single glazing, and so on (Wall, 1991b).*

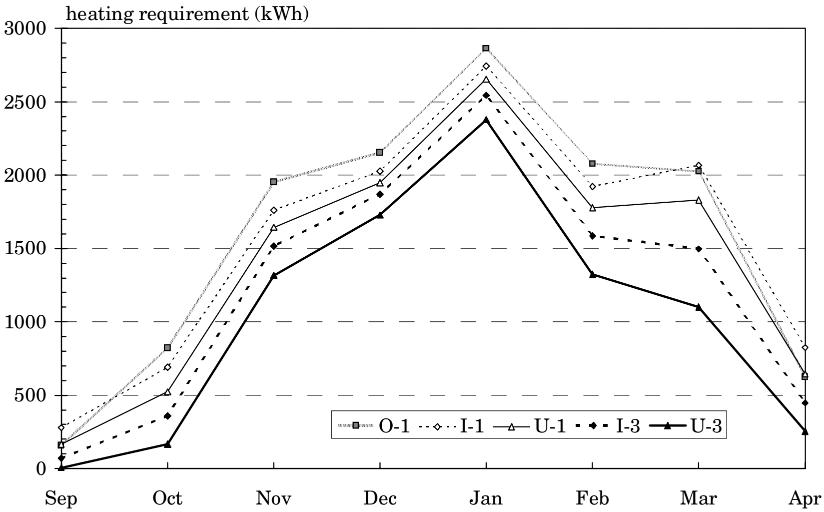


Figure 4.21 *Energy requirement for the selected building situated in the different courtyards with concrete walls. I-1 = I shape single glazing, I-3 = I shape triple glazing, U-1 = U shape single glazing, and so on (Wall, 1991b).*

4.3 The influence of the type of glazing

As seen in Section 4.2, the choice of the type of glazing can have a great influence on the temperature in the glazed space. The steady-state calculations presented in Figures 4.8 - 4.10 show that a choice of triple instead of double or single glazing will have a greater effect in raising the temperature level in the O shaped than in the U shaped courtyard, and the least effect in the I shaped courtyard. This depends on the factor *G* as was clearly seen in Figure 4.12. The temperature level, calculated under steady-state conditions, is an estimation of the minimum temperature in the glazed space.

The dynamic calculations with DEROB-LTH also show the influence of the type of glazing. Figure 4.22, for example, shows the minimum, mean and maximum temperatures in the I shaped courtyard during the winter week. The lowest bar represents the minimum temperature in the courtyard which would have occurred if there had been no sun at all. There is a large temperature difference between the single and triple glazed courtyard. Irrespective of the type of wall, the difference in mean temperature in the north-south direction is approx. 6.3°C and in the east-west direction 5.7°C between single and triple glazing. This really shows how important it is to "move" the insulation as far out in the structure as possible, i.e. to have a low value of the factor *G*.

Figure 4.23 shows the temperature in the I shaped courtyard during the spring week. The triple glazed courtyard is considerably warmer than the single glazed one, and in the normal course of events windows must naturally be opened and the sun kept out by sunshades. The mean temperature in the single glazed courtyard is approx. 11°C and in the triple glazed courtyard it is 19°C.

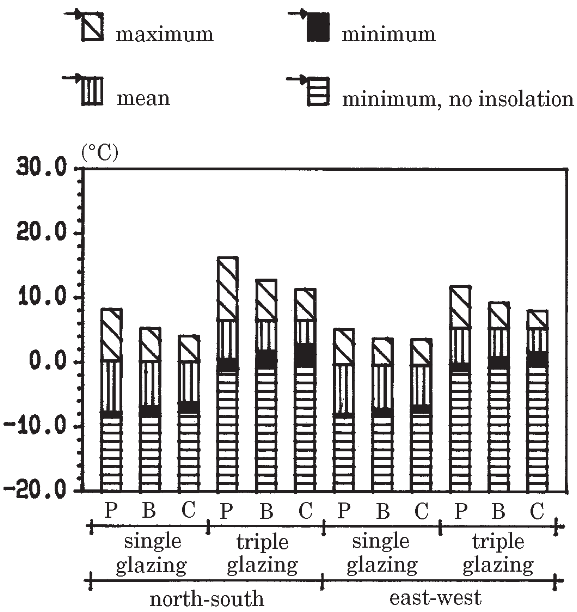


Figure 4.22 *Temperature in the I shaped courtyard during the winter week. P = plasterboard, B = brick, C = concrete (Wall, 1991b).*

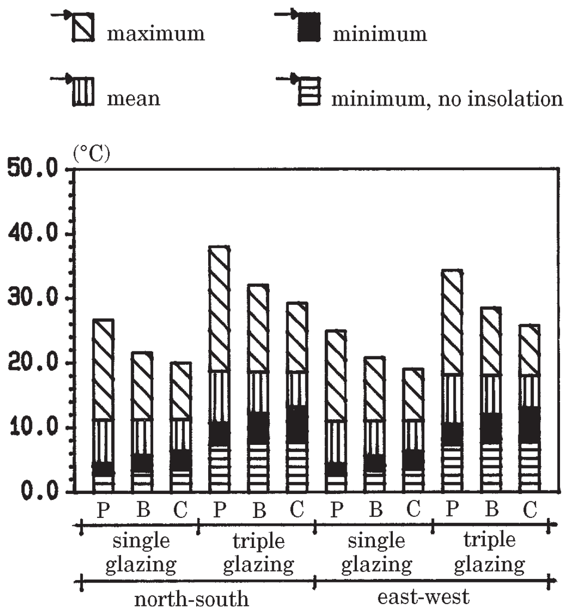


Figure 4.23 *Temperature in the I shaped courtyard during the spring week. P = plasterboard, B = brick, C = concrete (Wall, 1991b).*

The difference between single and triple glazing is also seen in Figure 4.24. This figure shows the hourly temperature in the I shaped courtyard during the spring week for the single and triple glazed courtyard with plasterboard walls. The outside temperature is also shown. The orientation of the courtyard is north-south, i.e. the glazed walls are oriented towards north and south. There is a larger difference between night and day temperatures in the triple glazed courtyard than in the single glazed courtyard. On sunny days, the maximum temperature in the triple glazed courtyard is at least 10°C higher. Note that if the courtyards had been ventilated, the difference between single and triple glazing would have been smaller.

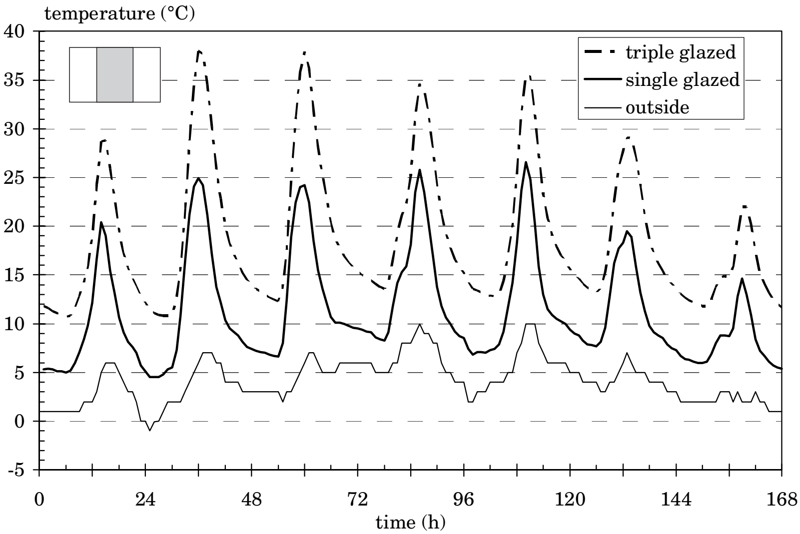


Figure 4.24 *Temperature in the north-south oriented single and triple glazed I shaped courtyards with plasterboard walls, spring week.*

4.4 The influence of the orientation of the building

The orientation of the glazed surfaces can influence the temperature in the glazed space. Adjoining buildings will have a shadowing effect on the glazed space. Since this parametric study is limited to simple geometries, only a few basic studies have been made in which the fabric losses calculated under steady-state conditions are the same irrespective of what the courtyard looks like. It is of course possible through unlimited variations in geometries to optimise the solar collection property of the glazed space. This is however not done in this study.

As an example, results concerning the U shaped courtyard are shown. Three orientations were studied, with the glazed gable to the south, west and east.

Figure 4.25 shows the energy required during the winter week to maintain 20°C in the three buildings for 18 basic cases. The higher bar shows the energy requirement without insolation and the lower bar that with insolation during the same week. The energy requirement for the buildings constructed entirely in accordance with the Swedish Building Code SBN 80 is obtained by adding a further 1 679 kWh losses. There is a slightly lower energy requirement with a southerly orientation but hardly any difference between west and east orientations.

Figure 4.26 sets out the minimum, mean and maximum temperatures in the courtyard during the same winter week. The bottom bar shows the minimum temperature for the same week without insolation. The mean temperature in the south oriented courtyard is about 2°C higher than in the west or east oriented courtyard. The orientation has a larger influence when the courtyard is triple glazed than when it is single glazed, especially with regard to the maximum temperature.

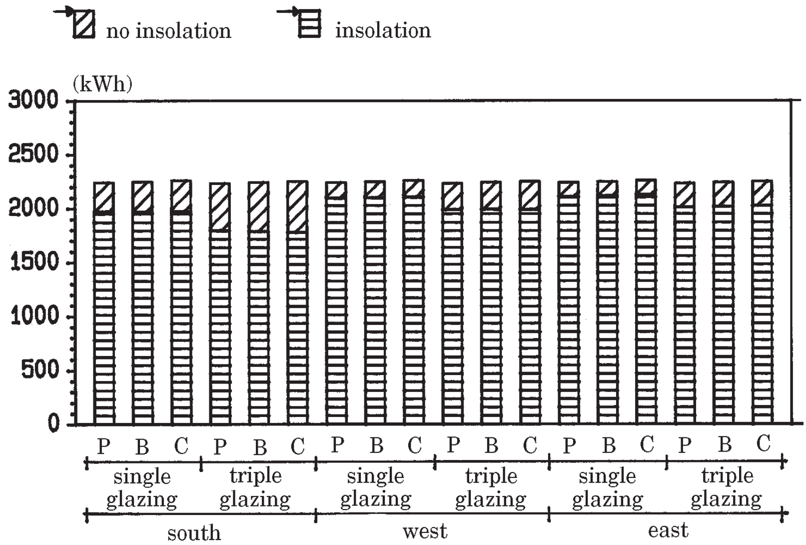


Figure 4.25 *Energy requirement during the winter week for the three buildings adjacent to the U shaped courtyard (Wall, 1991b).*

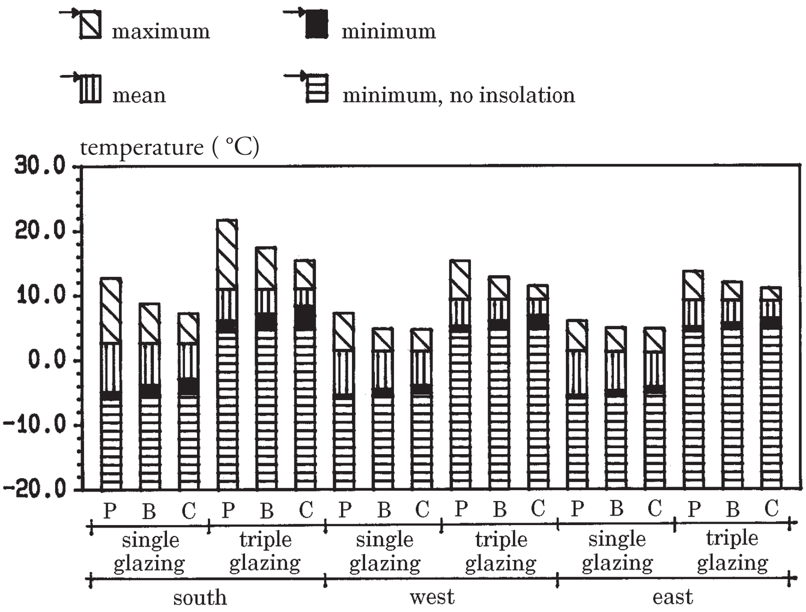


Figure 4.26 *Temperature in the U shaped courtyard during the winter week. P = plasterboard, B = brick, C = concrete (Wall, 1991b).*

The energy required to maintain 20°C in the buildings during the spring week is shown in Figure 4.27. For SBN 80 standards, 1 048 kWh is added. The maximum temperature permitted in the buildings is 25°C, higher temperatures are considered unacceptable. The higher bar represents a week without insolation, and the lower one a week with insolation. The orientation of the building is of very little importance during the spring week also. The type of glazing is of much greater importance.

Figure 4.28 shows the minimum, mean and maximum temperatures for the different cases during the spring week. The triple glazed courtyard of southerly orientation is warmest. As the solar radiation is more powerful than in the winter, the influence of the orientation, especially on the maximum temperature, is somewhat higher.

In Figure 4.29 the temperature variation during the spring week is shown for the single glazed U shaped courtyard with concrete walls towards the courtyard. The temperature with three different orientations is shown together with the outside temperature. During the nights, the temperature in the glazed space is about 6 - 8 °C higher than outside. In the middle of the day, the temperature in the east and west oriented courtyards is about 9 - 12°C higher than outside and in the south oriented courtyard about 11 - 17°C higher than outside.

In the triple glazed courtyard, the temperature level is higher, see Figure 4.30. The temperature in the triple glazed courtyard is above 15°C during the entire week. The temperature in the single glazed courtyard is below 15°C during most of the spring week, except in the middle of the day. The west and east oriented courtyards with triple glazing have approx. 14 - 17°C higher temperature in the middle of the day than outside. The temperature in the south oriented courtyard is about 18 - 23°C higher than outside in the daytime. As the courtyard is not ventilated, on the sunniest days the temperature with southerly orientation rises to approx. 30°C, which in reality is not acceptable.

The influence of the orientation is smaller for the I shaped courtyard, as can be seen in Figures 4.22 and 4.23. For the O shaped courtyard, the influence is negligible, at least when the geometry is as simple as in this study.

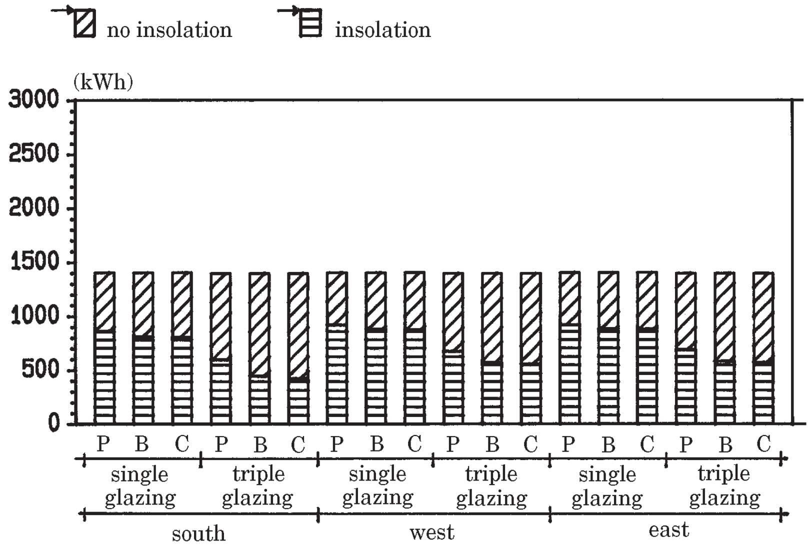


Figure 4.27 *Energy requirement during the spring week for the three buildings adjacent to the U shaped courtyard (Wall, 1991b).*

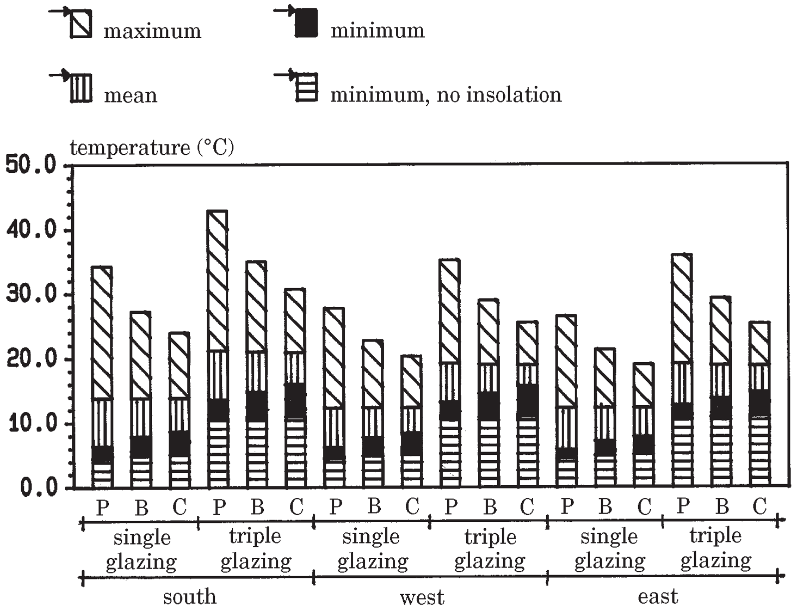


Figure 4.28 *Temperature in the U shaped courtyard during the spring week. P = plaster-board, B = brick, C = concrete (Wall, 1991b).*

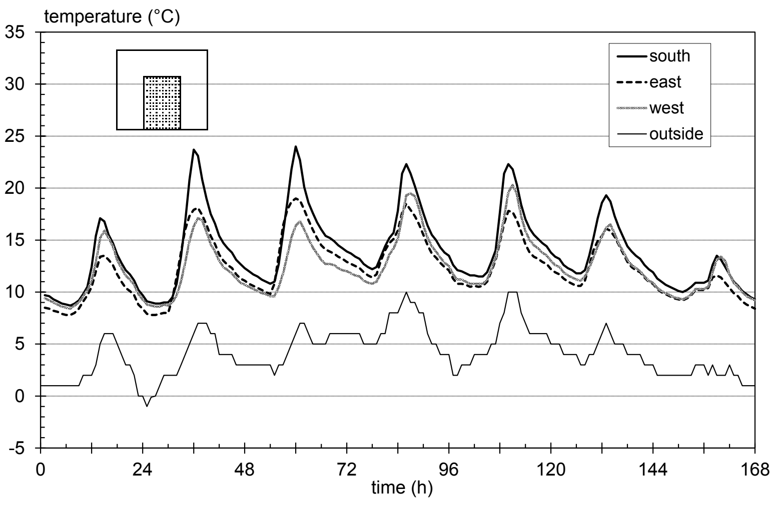


Figure 4.29 *Temperature in the U shaped single glazed courtyard with concrete walls at different orientations during the spring week.*

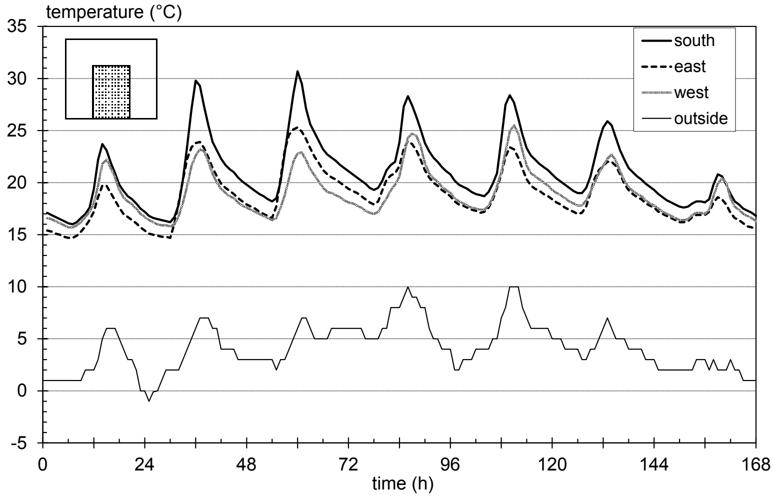


Figure 4.30 *Temperature in the U shaped triple glazed courtyard with concrete walls at different orientations during the spring week.*

4.5 The influence of thermal inertia

Building materials of high thermal inertia can be used in order to store energy from day to night and in this way reduce the energy need and increase thermal comfort. Thermal inertia damps out the temperature fluctuations and reduces the risk of excessive temperatures in the summer. This effect has been studied by changing the material in the walls between the courtyard and adjacent buildings. These walls consist either of plasterboard, brick or concrete with the necessary insulation.

It is important to bear in mind that the best way to make use of the thermal inertia is to let the glazed space have passive climatic control. If a constant temperature is required in the glazed space, then the thermal inertia will be of minor importance. This applies not only for glazed spaces, but ordinary buildings as well. But it is easier to accept temperature fluctuations in a glazed space than in an ordinary building.

As an example of the influence of thermal inertia, the temperature in the I shaped courtyard with different types of walls is shown. The courtyard is oriented towards north-south. Figure 4.31 shows the temperature during the winter week in the single glazed I shaped courtyard. The steady-state curve represents a simple manual calculation of the steady-state temperature, in which the solar radiation and the thermal inertia are not taken into account. This temperature is an estimation of the minimum temperature in the glazed space. The dynamic calculations show that the difference between the three types of walls is very small during the winter. Plasterboard walls, which have the smallest thermal inertia, give a somewhat higher temperature in the middle of the day and the lowest temperature at night. Concrete walls give the smallest temperature fluctuations. However, the mean temperature over the week is the same irrespective of the wall type. As can be seen, the steady-state calculation gives a good estimation of the minimum temperature during nights and even during cloudy days in the winter.

Figure 4.32 shows the corresponding temperatures in the I shaped triple glazed courtyard. The thermal inertia has a greater influence in the triple glazed courtyard, that is when the factor *G* is smaller. However, the minimum temperature is still very close to the steady-state calculation. Note also that the temperature level is significantly higher in the triple glazed than in the single glazed courtyard.

Figures 4.33 and 4.34 show the corresponding temperatures for the single and triple glazed I shaped courtyards during the spring week. The solar radiation is more powerful in the spring. There is therefore a larger difference between the wall types. In the triple glazed courtyard, the temperature is up to 10°C higher in the middle of the day when plasterboard walls are used instead of concrete walls. With low thermal inertia, as with plasterboard walls, the temperature drops very quickly when the sun goes down.

In the single glazed courtyard, the minimum temperature is approx. 2 - 3°C higher than in the steady-state calculation, depending on which type of wall is used. In the triple glazed courtyard the minimum temperature is 4 - 7°C higher than the minimum temperature estimated by manual calculation.

The smaller the value of *G* for the glazed space, the higher is the influence of thermal inertia. This means for example that the U shaped triple glazed courtyard can better utilise the thermal inertia than the I shaped triple glazed courtyard. During the winter, the thermal inertia has no appreciable significance. As soon as there are a few cloudy days, the temperature is largely the same irrespective of the thermal inertia.

As long as there are no requirements regarding the minimum or maximum temperatures, which would mean that the glazed space has to be heated or cooled, it is obvious that the thermal inertia can influence only the energy requirement in the adjacent buildings. The thermal inertia has however no significant influence on the energy requirements of the adjacent buildings.

However, if the U shaped courtyard is for instance heated to 20°C, calculations with DEROB-LTH show that the energy requirements for the glazed space are approx. 15% higher in the triple glazed courtyard with plasterboard walls than in the same courtyard with concrete walls. In the single glazed courtyard, energy requirements are only approx. 4% higher for walls with a low thermal inertia than with high thermal inertia. These calculations assume that the courtyard is unventilated.

If the U shaped courtyard is cooled to 20°C in the summer, the energy requirements for cooling are approx. 5% higher in the triple glazed courtyard with plasterboard walls than in the same courtyard with concrete walls. In the single glazed courtyard, cooling requirements are almost 12% higher when there are plasterboard walls instead of concrete walls between the glazed space and the adjacent buildings. These calculations also assume that the courtyard is unventilated.

This means that the thermal inertia has a greater influence on heating requirements in the *triple glazed* courtyard than in a single glazed one. However, thermal inertia has a greater influence on cooling requirements in a *single glazed* courtyard than in a triple glazed one.

With low thermal inertia it is possible to obtain higher temperatures in daytime; this can be beneficial in the winter. But at the same time the minimum temperature at night is lower and there is also a greater risk that excessive temperatures will occur in the summer.

In practice, the steady-state calculations describe with a good approximation the conditions which apply overnight. The estimation of the minimum temperature with steady-state calculations is quite good, especially for the single glazed courtyard with little thermal inertia. The estimation is very good in the winter irrespective of the courtyard type, which is the most important as the critical minimum temperatures occur during the winter.

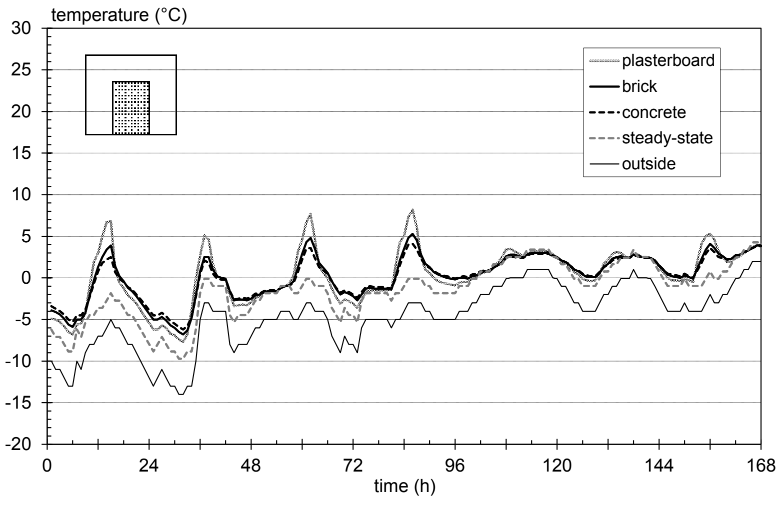


Figure 4.31 *Temperature in the single glazed I shaped courtyard of north-south orientation with different values of the thermal inertia, winter week. The steady-state minimum temperature and the outside temperature are also shown.*

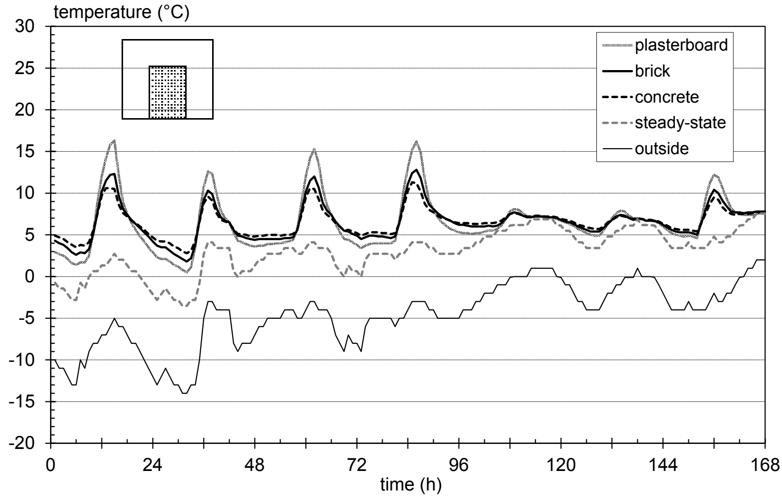


Figure 4.32 *Temperature in the triple glazed I shaped courtyard of north-south orientation with different values of the thermal inertia, winter week. The steady-state minimum temperature and the outside temperature are also shown.*

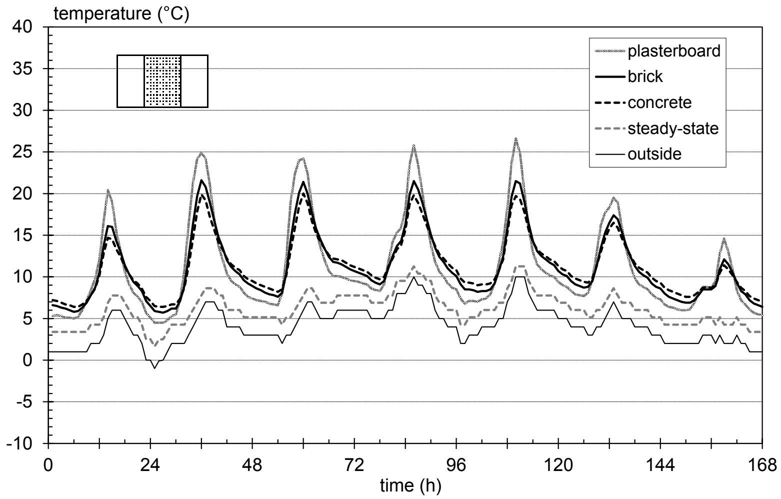


Figure 4.33 *Temperature in the single glazed I shaped courtyard of north-south orientation with different values of the thermal inertia, spring week. The steady-state minimum temperature and the outside temperature are also shown.*

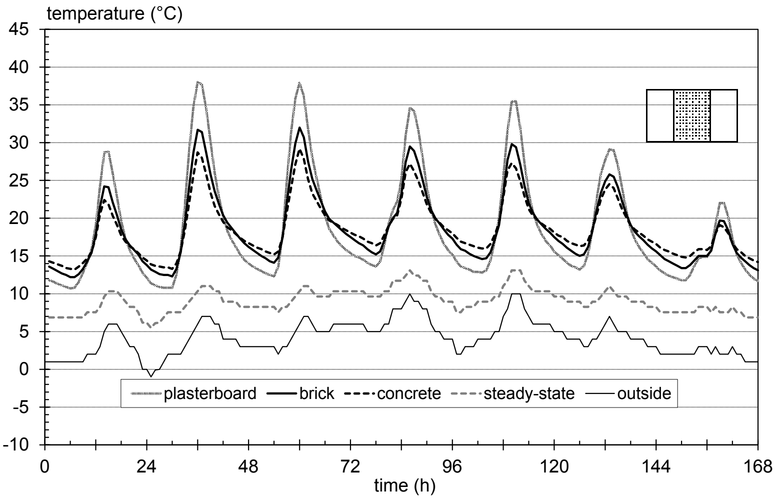


Figure 4.34 *Temperature in the triple glazed I shaped courtyard of north-south orientation with different values of the thermal inertia, spring week. The steady-state minimum temperature and the outside temperature are also shown.*

It can thus be seen that the heat storage capacity affects the range over which the temperature fluctuates during the day when the temperature is allowed to vary. It also has an effect on the power required for heating and cooling and, to a certain extent, on the energy requirement also. In non-steady temperature conditions, the response in inside temperature can be analysed via the concept of time constant as defined below.

$$\tau = \frac{M}{\sum U \cdot A} \qquad (4.3)$$

where

τ = time constant (h)
M = thermal inertia of the building (Wh/°C)
$\sum U \cdot A$ = specific losses of the building (W/°C)

The time constant is an expression for the time that elapses until the change in temperature indoors reaches e^{-1} of its final value for a sudden change in outdoor temperature. This can be written

$$\frac{T_i - T_{o,2}}{T_{o,1} - T_{o,2}} = e^{-1} \approx 0.37 \tag{4.4}$$

where

T_i = inside temperature (°C) (for a glazed space, this is denoted T_g)
$T_{o,1}$ = outside temperature prior to the drop (°C)
$T_{o,2}$ = outside temperature after the drop (°C)

It is assumed that the inside temperature T_i before temperature reduction is equal to the outside temperature $T_{o,1}$. All energy increments such as heating energy, heat gains due to occupants and solar radiation shall be put equal to zero in the calculation.

If calculation of the time constant is applied to a glazed space, the conditions are different. Since the time constant must be calculated when there are no energy gains, both the glazed space and the adjacent buildings will experience a drop in temperature when the outside temperature is instantaneously lowered. This gives a value of the time constant for the glazed space. It is obviously possible to compare this value with time constants for other glazed spaces, calculated in the same way, but in actual fact it bears no relationship to the way in which the glazed space functions in reality. After all, in actual conditions, a change in outside temperature gives rise to a temperature change in a glazed space with passive climatisation while, in principle, there is no change in temperature in the adjacent buildings. This implies that if the outside temperature suddenly drops, the temperature in the glazed space also decreases, but this drop in temperature is compensated to a certain extent by the increased energy increment from the adjacent buildings. In a real description of the way in which the thermal inertia of the glazed space exerts its influence, the glazed space cannot be treated separately since it is after all affected by the adjacent buildings. The question is, what exactly a time constant calculated according to Equation 4.4 says about a glazed space if the adjacent buildings are allowed in the calculation to have no heating.

If the time constant is instead calculated for the adjacent buildings heated to a constant temperature, the problem that now arises is that when there is a drop in temperature in the glazed space, the space is supplied with a progressively increasing amount of energy from the adjacent buildings until steady conditions prevail. When steady conditions have been attained, the temperature in the glazed space is not equal to the outside temperature but is somewhere between the outside temperature and the temperature in the adjacent buildings. The temperature which the glazed space ultimately has is determined by the ratio between the specific losses and gains of the glazed space, i.e. the factor *G* (see Section 4.2).

In order to study what this may imply for the glazed spaces of I, U and O shapes, calculations were made with DEROB-LTH. The walls abutting on adjacent buildings were either of plasterboard or concrete with the necessary insulation in accordance with Section 4.1. The outside temperature was first constant at 10°C for 30 days and was then reduced instantaneously to 0°C for the remainder of the time. Solar radiation or other energy gains were not included in the calculations. In the first calculation run there was no heating either in the glazed space or in the adjacent buildings. This meant that, once steady conditions had been attained, the temperature was 10°C both outside, in the glazed space and in the adjacent buildings. When the outside temperature was lowered to 0°C, the temperature in both the glazed space and the adjacent buildings decreased and gradually reached 0°C. In the second calculation run the temperature in the adjacent buildings was constant at 20°C, and this meant that both the initial and final temperature were higher in the glazed space than in the first calculation run.

An example of the calculations for the I shaped glazed courtyard with buildings on two sides is shown in Figure 4.35. The roof of the space is triple glazed and the walls abutting on the adjacent buildings are of plasterboard and insulation. The figure shows the last day of temperature build-up, after which the outside temperature is suddenly reduced from 10°C to 0°C. The lower curve shows the temperature in the glazed space when there is no heating in the adjacent buildings. The upper curve represents the temperature in the space when the adjacent buildings are heated to a constant 20°C. The temperature in the glazed space, which then starts at a higher level, finally drops to 6.0°C in this example. The time constant calculated as above was 17 hours for this glazed courtyard when there was no heating in the adjacent buildings.

In order that the time constant may be calculated with the adjacent buildings heated to 20°C, the time constant was defined as the time needed for the glazed space to decrease by 63% of the total temperature difference for the space, i.e. the difference between the temperature in the glazed space at the outside temperatures $T_{o,1}$ (10°C) and $T_{o,2}$ (0°C). This equation can be written

$$\frac{T_g - T_{g,2}}{T_{g,1} - T_{g,2}} = e^{-1} \tag{4.5}$$

where

T_g = temperature in the glazed space when the temperature has dropped by 63% (°C)
$T_{g,1}$ = temperature in the glazed space at the outside temperature $T_{o,1}$ (°C)
$T_{g,2}$ = temperature in the glazed space at the outside temperature $T_{o,2}$ (°C)

For the example in Figure 4.35, this time constant was found to be 7 hours. The two types of time constant for the different calculation cases are set out in Table 4.3.

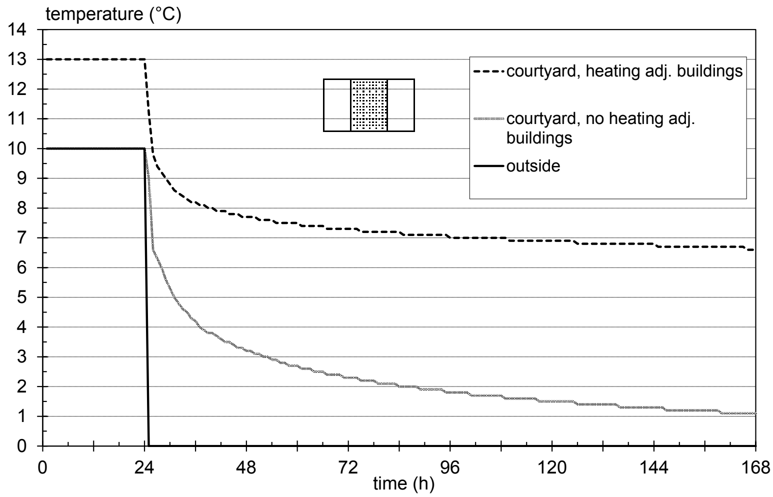


Figure 4.35 *Temperature in the triple glazed I shaped courtyard with plasterboard walls when the outside temperature instantaneously drops from 10°C to 0°C. The figure shows results from two calculations; one with heated adjacent buildings and one without any heating.*

Table 4.3 *Time constants for the three glazed courtyards.*
I = I shape, U = U shape, O = O shape.
1 = single glazing, 3 = triple glazing.
P = Plasterboard, C = Concrete.

case	time constant for the glazed space (h) adjacent buildings: no heating	 adjacent buildings: heating: T_i = 20°C
I-1-P	< 2	< 2
I-1-C	11.5	6.5
I-3-P	17	7
I-3-C	45	27
U-1-P	5.5	< 2
U-1-C	21	11
U-3-P	24	7
U-3-C	63	29
O-1-P	10	4
O-1-C	37	20
O-3-P	38	17
O-3-C	92	54

By calculating the time constant according to Equation 4.4 when no energy is supplied to the buildings, the time constant varies from under 2 hours to 92 hours. Walls with a high heat storage capacity give rise to a considerable increase in the time constant, but it is only if this higher heat storage capacity is combined with a double or triple glazed space which has a low value of the factor *G* that the time constant attains a value that can be denoted “normal” for a building. Otherwise the glazed space has little prospect of storing energy. If the time constant is calculated according to Equation 4.5, with the adjacent buildings heated which is the more realistic case, the time constants are entirely different and vary between ca 2 hours and 54 hours, as can be seen in Table 4.3.

4.6 The influence of airtightness and ventilation

Unintended ventilation in glazed spaces may have great significance for comfort and energy requirements. Large enclosures such as atria are used as circulation areas, receptions, cafeterias, restaurants, waiting rooms etc. When the atrium is used not only as a circulation area, increased requirements are placed on the climate inside the atrium. It is then no longer acceptable for the temperature to vary too much from day to night and during the year. Obviously, the question may be put whether this is a reasonable requirement. In cases where passive climatic control is applied, temperature is allowed to vary, but with proper building design it is nevertheless in most cases possible to achieve a reasonable temperature level even during the winter months as long as people do not stay for longer periods in the glazed space.

Irrespective of whether temperature is maintained at the highest possible level during the winter by means of passive climatic control, or whether it is necessary to supply both heating during the winter and cooling during the summer, it is essential that there should be little unintended ventilation. Excessive unintended ventilation increases energy use and has an adverse effect on indoor climate. The heating requirements to obtain indoor temperatures in an atrium can easily be doubled with a leaky atrium instead of an airtight one. The desired degree of ventilation should be achieved by opening vents and/or by mechanical ventilation, and can thus be intentionally altered during different parts of the day and the year.

The influence of ventilation or air leakage on the temperature varies greatly for different types of glazed spaces. In order to exemplify this, steady-state calculations were made for the U shaped single and triple glazed courtyards for different air change rates; see Figure 4.36. The outside temperature is -20°C. It can be seen that the temperature changes along the specific loss/gain curve when the air change rate rises from 0 to 1.5 ach in the two courtyards. In the triple glazed courtyard the effect is drastic, with a total temperature drop of 8°C. On the other hand, the drop for single glazing is only 2.4°C. This is due to the fact that fabric losses to the outside are already so high that the percentage change is not as large as in the case of the triple glazed courtyard.

The effect of ventilation on the temperature in the courtyard is also shown by dynamic calculations, see Figures 4.37 and 4.38. These set out the temperature in the single and triple glazed U shaped courtyard respectively with variable ventilation during the winter week. The outside temperature has also been plotted. The courtyard is oriented towards the south and has concrete walls. In the single glazed case the mean temperature drops by 2.6°C during the week when the ventilation increases from 0 to 1.5 ach, while in the triple glazed case there is a steep decrease of 7.4°C.

In the summer, the glazed spaces can be very hot. The triple glazed courtyards become warmer than the single glazed ones. In this parametric study the U shaped triple glazed courtyard is the warmest. If the courtyard has low thermal inertia, the maximum temperature is of course higher than with high thermal inertia. As seen in Figure 4.36 it is easier to ventilate a triple than a single glazed glazed courtyard which means that with efficient ventilation there will be no large difference in summer temperatures between single glazing and triple glazing. However, it is very difficult to maintain comfortable temperatures in a glazed space by only ventilation; see Figure 4.39. This figure sets out the temperature during the summer week in the triple glazed U shaped courtyard with plasterboard walls. The top curve refers to an unventilated courtyard, and the curves below to an air change rate of 2 ach and 10 ach, respectively. The courtyard is completely unshaded. The unventilated courtyard has a maximum temperature of approx. 69°C! With a ventilation of 2 ach, the maximum temperature is reduced to 49°C. With an air change rate of 10 ach, the maximum temperature is still too high to be acceptable, namely 34°C.

The mean outside temperature during this summer week is 20°C and the maximum temperature is 26°C. Naturally, it is not possible in the middle of the day to achieve by ventilation a lower temperature than that outside. The influence of solar radiation is very strong. It is thus very difficult to rely only on ventilation in order to reduce the temperature during the summer.

If the temperature at night is low, then it is possible by efficient ventilation early in the morning to have a somewhat lower temperature than outside for a short while, due to the thermal inertia.

With a mechanical ventilation system the supply air can of course be cooled by e.g. a heat pump. It is however recommended that ventilation should chiefly be based on direct use of outside air and that this should be combined with the use of solar curtains. Otherwise the energy requirement for cooling can be very high.

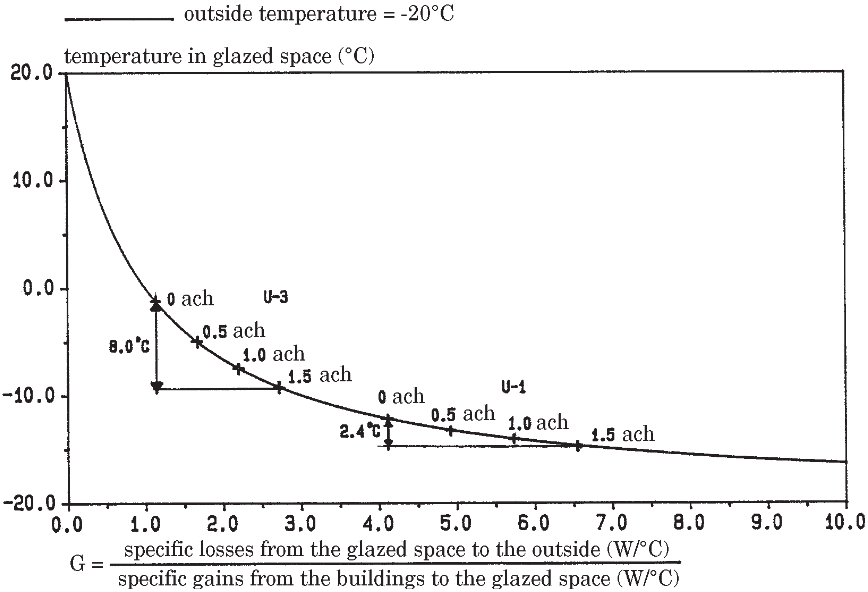


Figure 4.36 *Temperature in the single and triple glazed U shaped courtyard for different air change rates. Steady-state calculations (Wall, 1991b).*

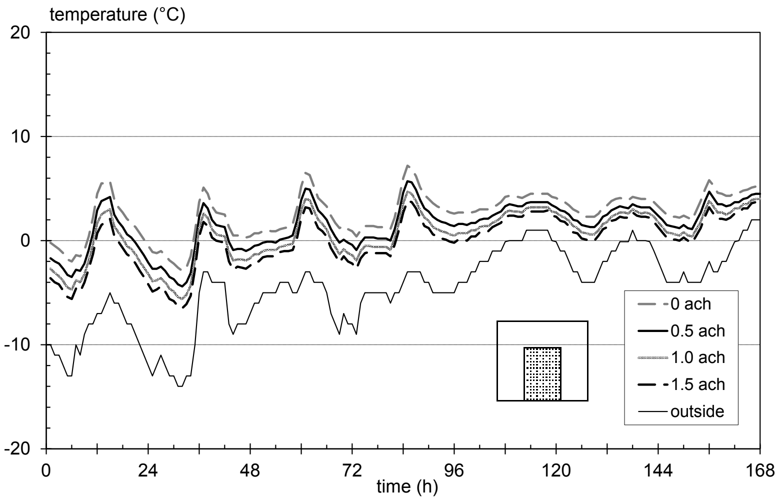


Figure 4.37 *Temperature in the single glazed U shaped courtyard with concrete walls at different air change rates during the winter week. Southerly orientation (Wall, 1991b).*

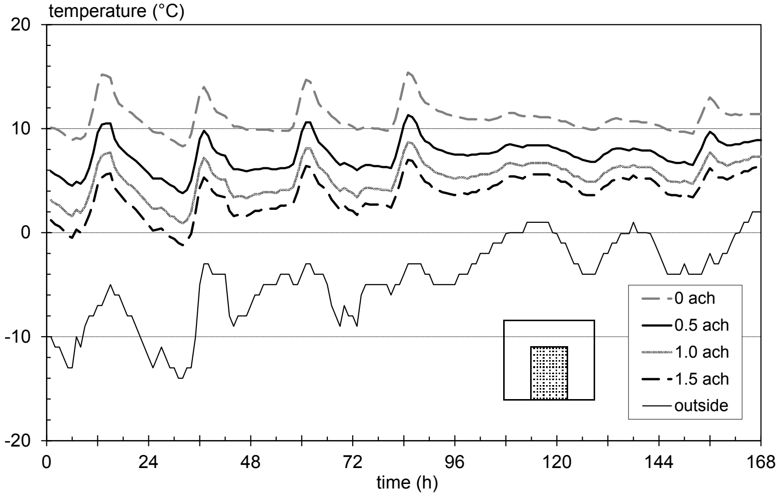


Figure 4.38 *Temperature in the triple glazed U shaped courtyard with concrete walls at different air change rates during the winter week. Southerly orientation (Wall, 1991b).*

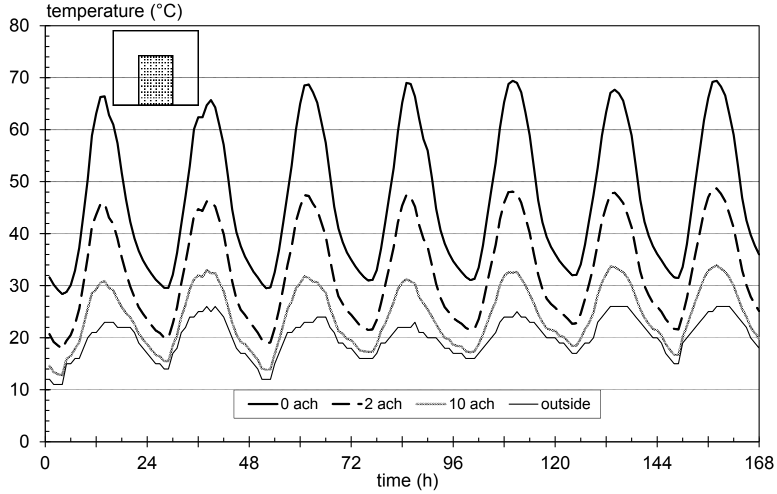


Figure 4.39 *Temperature in the triple glazed U shaped courtyard with plasterboard walls at different air change rates during the summer week. Southerly orientation.*

4.7 The influence of sunshades

Sunshades can be used in order to reduce the heat gain from solar radiation. The most effective way to reduce solar gain is to have exterior shadings, thus preventing the solar radiation from being transmitted into the glazed space. Exterior shadings are however exposed to the outside climate and must be able to resist wind, solar radiation, rain and snow.

Sunshades can also be placed between the panes of glass in the window or on the inside of the window or glazed facade/roof. A larger amount of solar radiation will then be transmitted into the glazed space. The ability of these types of shadings to reflect incoming solar radiation directly back to the outside will determine their efficiency. The rest of the radiation will be absorbed and act as a heat source in the glazed space. One advantage with internal shadings is that they are protected from the outside climate.

In order to shade large glazed facades, it is not possible to use exterior roof overhangs. The overhang will only shade the upper part of a high facade. In this case it is more efficient to use vertical shading devices or to plant broad-leaved trees outside the glazed facade. These will provide shade in the summer when it is needed, but not so much in winter when the leaves are gone.

A glazed roof is exposed to powerful solar radiation during the summer when the solar altitude is high. One solution is interior shading which retains the solar radiation at a high level in the glazed space. In combination with opened vents in the roof and at low level in the glazed space, the heat will be transported out through the roof vents before it reaches occupied zones.

As can be seen in Section 4.6, the use of ventilation alone in order to reduce the temperature in the glazed space is not efficient enough. In Figure 4.39, the influence of ventilation was shown for the triple glazed U shaped courtyard with plasterboard walls during the summer week. In Figure 4.40, these results are shown together with a calculated temperature for the case when the glazed space was ventilated at 2 ach (for 24 hours) and the roof was at the same time shaded between 0600 and 1800 hours. The glazed gable was still unshaded. The shading device was exterior and the transmission of solar radiation was zero. This represents the theoretically highest effect of sunshades. The maximum temperature is then approx. 31°C during the week and can be compared with the same glazed space ventilated at 2 ach but without any sunshades, when the maximum temperature is 49°C. It is also slightly better than ventilation alone at 10 ach (34°C). This shows that the combination of ventilation and sunshades is efficient. However, the large glazed facade towards the south still transmits a lot of solar radiation and causes the glazed space to be too hot in the middle of the day. As the outside temperature at the same time is 26°C, it is hard to get closer to this without an active cooling system.

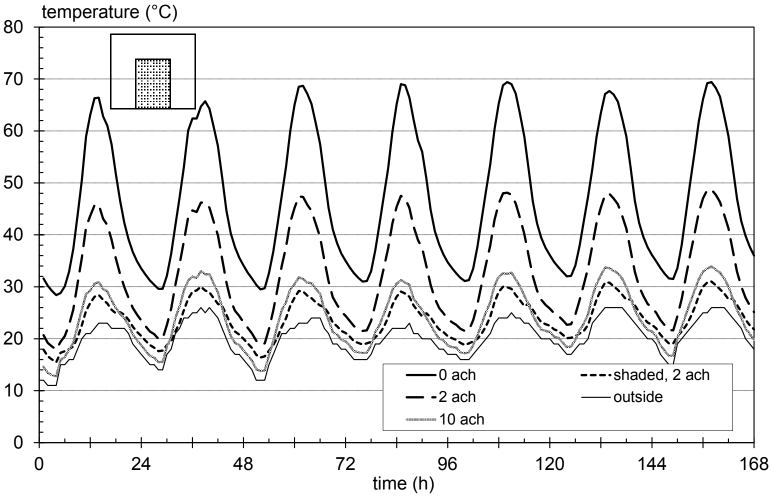


Figure 4.40 *Ventilation and sunshades used in order to reduce the temperature in the triple glazed U shaped courtyard with plasterboard walls during the summer week. Southerly orientation.*

4.8 The effect of using the glazed space as part of the ventilation system

In principle, three types of ventilation strategies can be used in glazed spaces and adjacent buildings. One way is simply to ventilate the glazed space and the adjacent buildings separately. In this case the glazed space and the buildings are independent of each other and can have different ventilation strategies. Another type is to use the glazed space as a preheater which means that the adjacent buildings take the supply air from the glazed space. As the temperature in the glazed space is higher than outside, the energy requirement for heating the supply air to indoor temperature will be lower than when the air is taken directly from the outside. With the third type of ventilation strategy, the exhaust air from the buildings is used as inlet air to the glazed space, thus heating the space during the winter.

This section describes the advantages and disadvantages of different combined systems in comparison with separate ventilation systems in the glazed space and the adjacent buildings. The use of heat exchangers in order to reduce the ventilation losses is also studied.

The calculations are based on the simple calculation method described in Chapter 3.

4.8.1 Basic information about the study

The U shaped glazed courtyard is chosen as an example in order to show the influence of using the glazed space as part of the ventilation system; see Figure 4.41. The example shows calculations for both a single glazed and a triple glazed courtyard. The glazed gable is oriented towards south.

The volume of the courtyard is 1 458 m³ and the volume of the surrounding buildings is 3 717 m³. The air flow is assumed to be 1 858 m³/h which is equal to 0.5 ach in the adjacent buildings. This air flow is equivalent to a ventilation of 1.3 ach in the glazed courtyard.

In order to simplify the calculation cases, unintended air leakage is not taken into account. In addition, energy requirements for fans are not included in the calculations. In some cases a heat exchanger, with the energy efficiency 60%, is used.

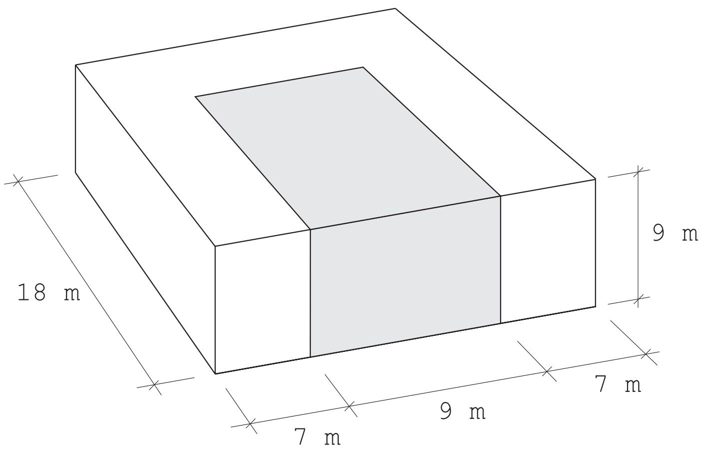


Figure 4.41 The U shaped courtyard.

Climatic data used are described in Wall (1994b). In this ventilation study, climatic data from Lund 1988 were chosen. Lund is situated in the south of Sweden at 55.72°N and 13.22°E. The outside temperature in Lund during 1988 can be seen in Table 3.2.

4.8.2 Description of the cases

The study is divided into 7 different cases defined as below.

Case 1

In Case 1, the air in the glazed space acts as supply air to the adjacent buildings. No heat exchanger is used. The direction of the air flows is shown in Figure 4.42a.

This system will in principle give rise to both positive and negative effects. As mentioned earlier, the advantage of this system is that energy requirements for heating the supply air to the buildings will be less than if the air is taken directly from the outside. There are also disadvantages. One is that the temperature level in the glazed space during the winter will be reduced since an unnecessarily high air flow will be taken from the outside. Another disadvantage is that the fabric losses from the adjacent buildings to the glazed space will increase, increasing the energy needed to heat the buildings.

Case 2

This case is equal to Case 1, but a heat exchanger is used to transfer heat from the exhaust air from the buildings to the outside air supplied to the glazed space; see Figure 4.42b. This will reduce the ventilation losses in the glazed space and a higher temperature level will be achieved. The fabric losses from the adjacent buildings to the glazed space will thereby be reduced.

Case 3

The supply air to the buildings is taken from the glazed space as in Cases 1 and 2. However, the heat from the exhaust air from the buildings is transferred to the supply air to the buildings and not to the supply air to the glazed space as in Case 2; see Figure 4.42c. This will minimise the ventilation losses of the adjacent buildings.

Case 4

In this case the exhaust air from the buildings is used as supply air to the glazed space; see Figure 4.42d. The supply air to the buildings is taken directly from the outside. No heat exchanger is used. In this way, when the exhaust air from the buildings acts as supply air to the courtyard, a higher temperature level is obtained.

Case 5

As in Case 4, the glazed space is heated by the exhaust air from the buildings; see Figure 4.42e. The difference is that, by using a heat exchanger, the exhaust air from the courtyard is preheating the outside air going into the buildings. This will reduce the ventilation losses of the buildings, in comparison with Case 4.

Case 2 and case 5 are also similar. In both cases, the exhaust air from the buildings is used to heat the glazed space. In Case 2, a heat exchanger is used and in Case 5 the exhaust air is used directly as supply air to the glazed space. The supply air to the buildings is taken from the courtyard in Case 2. In Case 5 the supply air is taken from the outside but is preheated by the exhaust air from the courtyard.

Case 6

In this case, the buildings and the glazed space have separate ventilation systems; see Figure 4.42f. The buildings have a ventilation rate of 0.5 ach and a heat exchanger is used. The glazed space is ventilated separately at 0.3 ach (no heat exchanger). This differs from the above cases in which the courtyard has an air flow corresponding to 1.3 ach.

The only way the courtyard and the adjacent buildings interact thermally in this case is that the courtyard is used to reduce the fabric losses of the buildings and at the same time the temperature in the courtyard is higher than outside.

Case 7

This case is the same as Case 6 but no heat exchanger is used; see Figure 4.42g. Case 7 is used as a reference when the results are compared. It can be described as a kind of “worst case“, and in Cases 1-6 different strategies are tested in order to improve this situation.

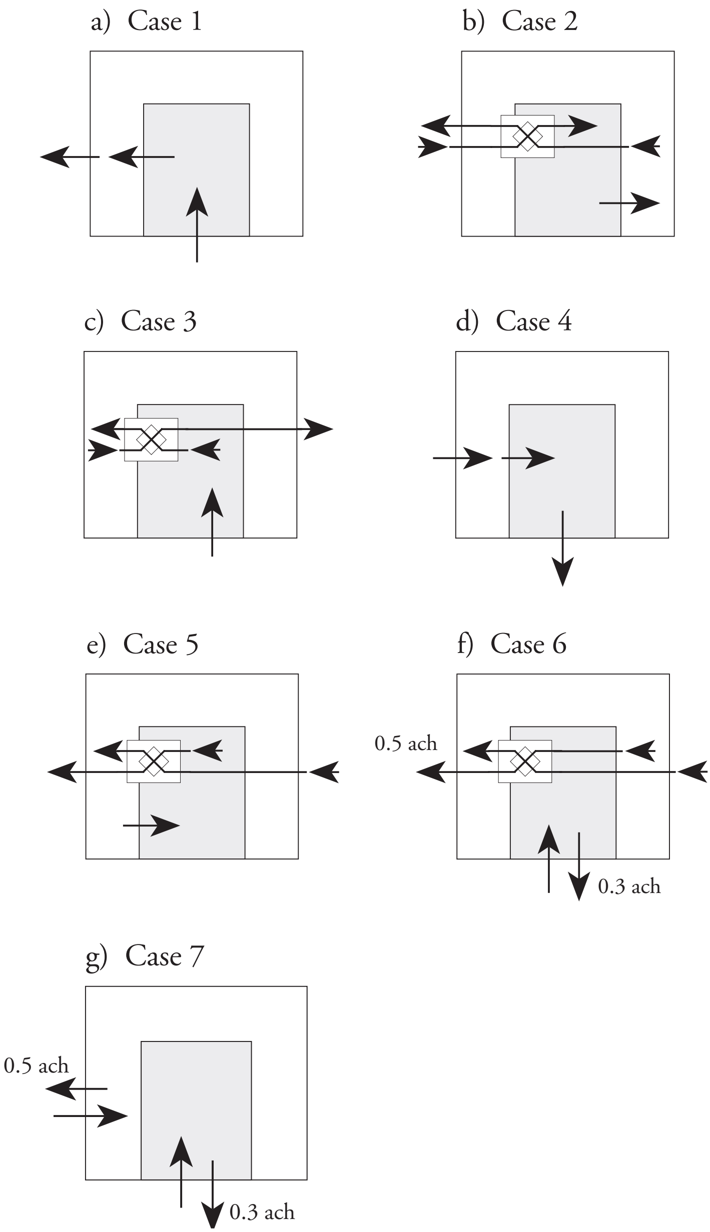


Figure 4.42 a-g Ventilation systems for the different cases.

4.8.3 Results for the U shaped building type

The manual calculation method used is based on an energy balance drawn up for the glazed space, in which its losses Q_{from} and gains Q_{to} are equal. Generally,

$$Q^t_{from} + Q^v_{from} = Q^t_{to} + Q^v_{to} + S \cdot P_{sun} \tag{4.6}$$

where

Q^t_{from} = fabric losses of the glazed space (W),
Q^v_{from} = ventilation losses of the glazed space (W),
Q^t_{to} = transmission gain from the adjacent buildings to the glazed space (W),
Q^v_{to} = ventilation gain from the adjacent buildings to the glazed space (W),
S = solar collection property of the glazed space (-), and
P_{sun} = monthly mean of solar radiation transmitted to the glazed space (W).

Equation 4.6 describes the energy balance for a glazed space with passive climatic control, i.e. no active heating or cooling system is used.

The solar collection property *S* is 0.65 for the single glazed U shaped courtyard and 0.70 for the triple glazed one.

The fabric losses and ventilation losses are calculated according to Equations 3.1, 3.2, 3.4 and 3.5.

The influence of the energy stored in the building components of the glazed space is ignored with this calculation method. However, since this is a parametric study which compares different cases, the method is well suited for this purpose.

Depending on ventilation strategy in the glazed space and adjacent buildings and on the thermal properties to be estimated, one or more terms in the energy balance (Equation 4.6) can be omitted.

The specific heat losses for the different cases, divided into transmission and ventilation, are shown in Tables 4.4 and 4.5 for the single glazed and triple glazed courtyard respectively. For the buildings, only the specific heat losses of the facades between the buildings and the glazed space are shown. This is due to the fact that this is the only part that will change between the different cases.

Table 4.4 Specific losses for the U shaped single glazed courtyard.

case	specific losses (W/°C)			
	glazed space transmission	glazed space ventilation	buildings to glazed space transmission	buildings ventilation
1 - 5	1 247.4	613.3	299.7	613.3
6 - 7	1 247.4	144.3	299.7	613.3

Table 4.5 Specific losses for the U shaped triple glazed courtyard.

case	specific losses (W/°C)			
	glazed space transmission	glazed space ventilation	buildings to glazed space transmission	buildings ventilation
1 - 5	518.4	613.3	453.6	613.3
6 - 7	518.4	144.3	453.6	613.3

By using Equations 3.1, 3.2, 3.4 and 3.5 and data from Table 4.4, the fabric and ventilation losses and gains for the U shaped single glazed courtyard, in Case 1, are obtained as:

$$Q^t_{from} = \sum_{from} U \cdot A \cdot (T_g - T_o) = 1247.4\,(T_g - T_o)\ \text{(W)}$$

$$Q^v_{from} = V_g \cdot n_g \cdot \rho \cdot c_p \cdot (T_g - T_o) = 613.3\,(T_g - T_o)\ \text{(W)}$$

$$Q^t_{to} = \sum_{to} U \cdot A \cdot (T_i - T_g) = 299.7\,(T_i - T_g)\ \text{(W)}$$

$$Q^v_{to} = V_i \cdot n_i \cdot \rho \cdot c_p \cdot (T_i - T_g) = 0\ \text{(W)}$$

In order to calculate the temperature in the single glazed courtyard for Case 1, the following energy balance is used:

$$Q^t_{from} + Q^v_{from} = Q^t_{to} + S \cdot P_{sun} \qquad (4.7)$$

which means

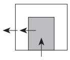
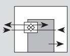
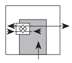
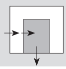
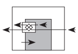
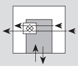
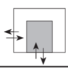
$$1247.4\,(T_g - T_o) + 613.3\,(T_g - T_o) = 299.7\,(T_i - T_g) + S \cdot P_{sun}$$
$$1860.7\,(T_g - T_o) = 299.7\,(T_i - T_g) + S \cdot P_{sun}$$

The temperature in adjacent buildings, T_i, is set to 20°C in all cases. The outside temperature for Lund 1988 is taken from Wall (1994b). In order to calculate the mean temperature in the glazed space, the solar gain, i.e. the absorbed solar radiation ($S \cdot P_{sun}$), is calculated according to Wall (1994b). One calculation is made for each month of the year.

In order to estimate the minimum temperature in the glazed space, the solar radiation is excluded in the energy balance (Equation 4.7), i.e. $P_{sun} = 0$.

In the same way, temperatures for Cases 2 - 7 are calculated. The energy balance is specific to each case, depending on which ventilation system is used. Table 4.6 shows the calculated minimum and mean temperatures in the single and triple glazed courtyards for the different cases.

Table 4.6 Minimum and mean temperature in the U shaped single and triple glazed courtyards during the coldest month, 1988 in Lund.

case	single glazed U shaped courtyard		triple glazed U shaped courtyard	
coldest month	min temp coldest month (°C)	mean temp coldest month (°C)	min temp coldest month (°C)	mean temp (°C)
1 	-5.1	5.8	-0.8	8.4
2 	-2.1	8.7	3.3	12.4
3 	-5.1	5.8	-0.8	8.4
4 	3.2	10.7	10.4	15.1
5 	3.2	10.7	10.4	15.1
6 	-3.9	6.6	2.8	10.8
7 	-3.9	6.6	2.8	10.8

In Table 4.6, the temperatures are shown for the coldest month during 1988. The highest temperatures are obtained in Cases 4 and 5 in which the exhaust air from the buildings is used as supply air to the courtyards. The mean temperature in the single glazed courtyard during the coldest month is then approx. 5°C higher than in Cases 1 and 3 in which the supply air to the courtyard is taken directly from outside. For the triple glazed courtyard, the mean temperature during the coldest month is almost 7°C higher in Cases 4 and 5 than in Cases 1 and 3.

The next step is to calculate the fabric and ventilation losses of the buildings and also the ventilation losses for the glazed space.

For the single glazed U shaped courtyard, the fabric losses between the buildings and the glazed space are in Case 1 given by

$$E_{to}^{t} = 299.7\,(T_i - T_g) \cdot h \,/\, 10^6 \quad \text{(MWh)} \tag{4.8}$$

where

T_i = 20°C and
h = the number of hours in the month.

In Equation 4.8, the temperature in the glazed space is the calculated mean temperature for each month.

In Case 1, the total ventilation losses of the adjacent buildings, single glazed courtyard, are given as

$$E_{b}^{v} = 613.3\,(T_i - T_g) \cdot h \,/\, 10^6 \quad \text{(MWh)} \tag{4.9}$$

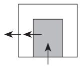
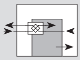
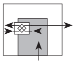
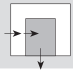
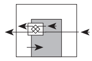
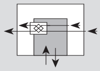
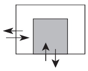
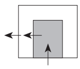
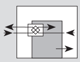
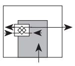
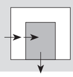
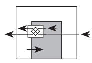
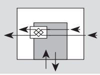
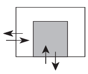
The total ventilation losses in Case 1 for the single glazed courtyard are given as

$$E_{g}^{v} = 613.3\,(T_g - T_o) \cdot h \,/\, 10^6 \quad \text{(MWh)} \tag{4.10}$$

Also in these equations, it is the monthly mean temperatures that should be used.

In a similar way, the fabric and ventilation losses can be calculated for Cases 2 - 7. These energy losses during the heating season January-April and September-December 1988 are shown in Table 4.7. The fabric losses of the buildings which are presented refer only to the facades between the buildings and the glazed space. Table 4.7 contains results for both the single glazed and the triple glazed courtyard and should be compared with the temperatures in Table 4.6.

Table 4.7 *Energy losses and gains in the single and triple glazed U shaped courtyards for the different cases.*

case	U shaped single glazed courtyard buildings fabric losses (MWh)	 buildings vent. losses (MWh)	 glazed space vent. losses (MWh)
1 	17.0	34.8	17.3
2 	12.7	25.9	0
3 	17.0	13.9	17.3
4 	9.8	55.1	0
5 	9.8	33.5	0
6 	14.7	22.0	15.2
7 	14.7	55.1	15.2
case	U shaped triple glazed courtyard buildings fabric losses (MWh)	 buildings vent. losses (MWh)	 glazed space vent. losses (MWh)
1 	19.1	25.8	26.3
2 	10.9	14.7	0
3 	19.1	10.3	26.3
4 	5.7	55.1	0
5 	5.7	24.2	0
6 	12.3	22.0	8.8
7 	12.3	55.1	8.8

In cases 1, 2 and 3 the glazed space is used as a preheater for the adjacent buildings. In cases 1 and 3 all the supply air to the courtyard is taken directly from the outside without using a heat exchanger, which means that the temperature in the glazed space will be the same in these cases. Consequently, the fabric losses of the buildings are the same. The only thing that differs between Cases 1 and 3 is that, in Case 3, the ventilation losses of the buildings are very small due to the heat exchanger which takes heat from the exhaust air from the buildings in order to heat the supply air. The supply air to the buildings is thus preheated both by the exhaust air from the buildings and by the glazed courtyard.

The efficiency of using the glazed space as a preheater in Case 1 can be shown by comparing the ventilation losses of the buildings in Case 1 with those in Case 7. The ventilation losses will be reduced to 34.8 MWh / 55.1 MWh, approx. 63% for the single glazed courtyard and 25.8 MWh / 55.1 MWh, approx. 47% for the triple glazed space. This means that the preheating efficiency of the single glazed courtyard is 37% and the efficiency of the triple glazed courtyard is 53%. In Case 3, the ventilation losses of the buildings will be reduced by 75% for the single glazed courtyard and by 81% for the triple glazed space. However, the ventilation losses in the glazed space are higher in Cases 1 and 3 than in Case 2, and the temperature in the glazed space is therefore lower.

By using the exhaust air from the buildings in combination with a heat exchanger in order to obtain a higher temperature level in the glazed space, as in Case 2, the mean temperature will rise by about 3°C in the single glazed courtyard and by about 4°C in the triple glazed one, compared with Case 1. This causes the fabric losses between the buildings and the glazed space to be reduced by 4.3 MWh in the single glazed courtyard and by 8.2 MWh in the triple glazed one.

If the main goal is to secure a high temperature level in the glazed space during the winter, the exhaust air from the buildings can be used as supply air to the glazed space as in Cases 4 and 5. The mean temperature during the coldest month will then be approx. 5°C higher than in Case 1 in the single glazed courtyard and almost 7°C higher in the triple glazed one. In this way the fabric losses of the buildings will be very small. In Case 5, the ventilation losses of the buildings are reduced by the use of a heat exchanger.

In Cases 2 and 5, the exhaust air from the buildings is used to heat the glazed space. In Case 2, a heat exchanger is used and in Case 5 the exhaust air is used directly as supply air to the glazed space. This makes the temperature of the glazed space in Case 5 higher than in Case 2. However, in Case 5 the ventilation losses of the buildings will be higher because the outside air acts as supply air to the buildings (even though it is preheated).

In Cases 6 and 7, the buildings and the courtyard are ventilated separately. In these cases the ventilation in the courtyard is equal to only 0.3 ach. The buildings still have a ventilation of 0.5 ach, which in Case 6 is combined with a heat exchanger. The reduced ventilation in the glazed space will result in a higher temperature level than in Cases 1 and 3 which during the winter have an unnecessarily high ventilation of 1.3 ach.

4.8.4 Results for the I shaped and O shaped building types

The calculations described above have also been made for the I shaped single glazed courtyard with glazed gables facing south and north, and also for the O shaped single glazed courtyard.

For these two building types also, the air flows in the adjacent buildings are equal to 0.5 ach. This means that the courtyard in the I shaped type of building has an air flow corresponding to 0.8 ach. In the O shape, the air flow in the courtyard is equal to 2.2 ach due to much larger surrounding buildings.

Table 4.8 shows the minimum and mean temperatures in the single glazed I shaped and O shaped courtyards. The temperatures are shown for the coldest month during 1988 in Lund. As can be seen, the temperature in the O shaped courtyard is considerably higher than in the I shaped courtyard in the cases when the ventilation losses of the courtyard are low. However, in Case 1 which has high ventilation losses, the temperatures are significantly reduced especially in the O shaped courtyard.

In Table 4.9 the fabric and ventilation losses of the I shaped and O shaped building types are shown in the same way as for the U shaped building type in Table 4.7. The energy losses in the O shaped building type are of course much larger than in the I shaped building type, due to larger buildings and larger air flows in the O shaped building.

Table 4.8 *Minimum and mean temperature in the single glazed I shaped and O shaped courtyards during the coldest month, 1988 in Lund.*

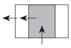
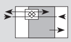
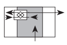
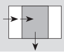
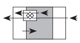
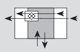
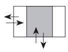
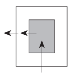
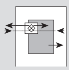
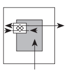
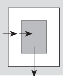
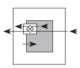
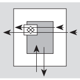
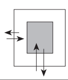
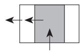
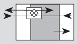
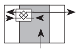
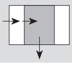
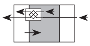
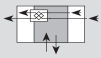
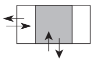
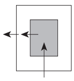
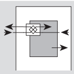
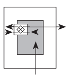
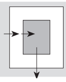
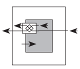
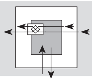
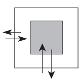
case	single glazed I shaped courtyard min temp coldest month (°C)	single glazed I shaped courtyard mean temp coldest month (°C)
1 	-6.2	5.2
2 	-4.1	7.3
3 	-6.2	5.2
4 	-0.4	8.6
5 	-0.4	8.6
6 	-5.7	5.5
7 	-5.7	5.5
case	**single glazed O shaped courtyard min temp coldest month (°C)**	**single glazed O shaped courtyard mean temp coldest month (°C)**
1 	-3.8	6.0
2 	0.8	10.6
3 	-3.8	6.0
4 	8.9	13.7
5 	8.9	13.7
6 	-0.7	8.1
7 	-0.7	8.1

Table 4.9 *Energy losses and gains in the single glazed I shaped and O shaped courtyards for the different cases.*

case		I shaped single glazed courtyard buildings fabric losses (MWh)	buildings vent. losses (MWh)	glazed space vent. losses (MWh)
1		11.5	22.0	9.8
2		9.5	18.3	0
3		11.5	8.8	9.8
4		8.2	33.6	0
5		8.2	22.7	0
6		10.9	13.4	4.2
7		10.9	33.6	4.2

case		O shaped single glazed courtyard buildings fabric losses (MWh)	buildings vent. losses (MWh)	glazed space vent. losses (MWh)
1		25.8	63.3	31.0
2		15.8	38.1	0
3		25.8	24.9	9.8
4		9.6	93.3	0
5		9.6	50.3	0
6		18.6	37.3	6.0
7		18.6	93.3	6.0

4.8.5 Discussion and conclusions

In order to draw some general conclusions, all three building types studied should be compared.

In Table 4.10, the minimum temperatures in the glazed courtyards are shown for the different cases. The minimum outside temperature in Lund during the year was -9.1°C. In Cases 1 and 3, the supply air to the glazed courtyard is taken directly from the outside. The temperature in the glazed space is therefore significantly lower than in Cases 4 and 5 in which the supply air is taken from adjacent buildings. If the single glazed courtyards are compared, it can be seen that taking the supply air to the courtyard directly from the outside will lower the temperature more in the U shape than in the I shape and most in the O shaped courtyard, compared with the cases when the supply air is taken from adjacent buildings.

In Table 4.11, the mean temperatures in the glazed courtyards are shown for the same cases. With reference to the temperature levels in the glazed courtyards, it is seen that the best ventilation system is the one in which the exhaust air from the buildings is used as supply air to the courtyard. This is true for all three types of glazed courtyards.

In order to compare the total fabric losses and ventilation losses for the different cases, Case 7 for the single glazed courtyard is used as a reference for each building type separately. The total fabric losses are then calculated including the fabric losses from the buildings to the outside. The total fabric losses of the buildings are estimated by using the insulation standard according to Swedish Building Regulations, BBR 94. The total fabric losses and ventilation losses for Case 7 are 100% which means 66 MWh for the single glazed I shape, 104 MWh for the single glazed U shape and 160 MWh for the single glazed O shape.

In Table 4.12 the energy losses for each case are shown in relation to the reference values. The triple glazed U shaped courtyard has a higher energy efficiency than the single glazed U shaped courtyard. Case 2 for the triple glazed U shaped courtyard uses only 58% of the energy in the reference case (single glazed U shaped courtyard). Table 4.12 also shows that for the triple glazed U shaped courtyard Case 2 results in lower energy losses in the adjacent buildings than Case 3. However, for the single glazed U shaped courtyard the opposite applies. This indicates that in a triple glazed courtyard it is slightly better to use the energy from the exhaust air from the buildings to heat the supply air to the courtyard than to use it for heating the supply air to the buildings directly. However, in a single glazed courtyard it is more energy efficient to use the energy from the exhaust air from the buildings directly for heating the supply air to the buildings.

A comparison of the energy losses for the buildings adjacent to the single glazed courtyards in Table 4.12 shows that the most energy efficient ventilation system, as far as the adjacent buildings are concerned, is the one in Case 3 which produces the greatest possible reduction in the total losses for the buildings.

However, when not only the energy losses for the buildings but also the temperatures in the glazed courtyards shown in Tables 4.10 and 4.11 are compared, the best ventilation system is the one in Case 5, independent of the type of glazed space. In Case 5 the exhaust air from the buildings is taken directly to the courtyard and the exhaust air from the glazed space is heat exchanged with the supply air to the buildings. This results in relatively high temperature levels in the glazed spaces and at the same time low total energy losses in adjacent buildings.

Heat exchangers should not be used during the summer. If they are used, the resulting temperatures may be very high. If a ventilation system with a heat exchanger is used in the winter, it must be possible for this to be disconnected during the summer. In office buildings, the ventilation system is also often used as an active cooling system for the glazed space in the summer.

Whether or not a heat exchanger should be used is a choice that affects not only the energy aspect but also the required air quality. In Cases 1, 2 and 3 it is assumed that the air from the glazed space is acceptable as supply air to the buildings. In Cases 4 and 5 it is assumed that the exhaust air from the buildings can be used as supply air to the glazed courtyard. This may not always be a good solution as regards air quality. The decision depends on how the buildings and the glazed space are used. Using a heat exchanger to take heat from the exhaust air and using the outside air as supply air may be a better choice.

Table 4.10 *Minimum temperature in the glazed courtyards during the coldest month, 1988 in Lund.*
I-1 = I shaped single glazed courtyard
U-1 = U shaped single glazed courtyard
U-3 = U shaped triple glazed courtyard
O-1 = O shaped single glazed courtyard

case	shape I-1 (°C)	 U-1 (°C)	 U-3 (°C)	 O-1 (°C)
1	-6.2	-5.1	-0.8	-3.8
2	-4.1	-2.1	3.3	0.8
3	-6.2	-5.1	-0.8	-3.8
4	-0.4	3.2	10.4	8.9
5	-0.4	3.2	10.4	8.9
6	-5.7	-3.9	2.8	-0.7
7	-5.7	-3.9	2.8	-0.7

Table 4.11 *Mean temperature in the glazed courtyards during the coldest month, 1988 in Lund.*
I-1 = I shaped single glazed courtyard
U-1 = U shaped single glazed courtyard
U-3 = U shaped triple glazed courtyard
O-1 = O shaped single glazed courtyard

case	shape I-1 (°C)	U-1 (°C)	U-3 (°C)	O-1 (°C)
1	5.2	5.8	8.4	6.0
2	7.3	8.7	12.4	10.6
3	5.2	5.8	8.4	6.0
4	8.6	10.7	15.1	13.7
5	8.6	10.7	15.1	13.7
6	5.5	6.6	10.8	8.1
7	5.5	6.6	10.8	8.1

Table 4.12 *The sum of fabric losses and ventilation losses of the buildings in relation to the reference. The figures are based on the total fabric and ventilation losses of the buildings with an insulation standard according to the Swedish Building Regulations BBR 94.*
I-1 = I shaped single glazed courtyard
U-1 = U shaped single glazed courtyard
U-3 = U shaped triple glazed courtyard
O-1 = O shaped single glazed courtyard

case	shape I-1 (%)	U-1 (%)	U-3 (%)	O-1 (%)
1	83	83	76	86
2	75	70	58	64
3	63	63	61	62
4	96	95	91	94
5	80	75	62	67
6	69	68	66	65
7	100	100	98	100

4.9 Auxiliary heating and cooling

If the temperature in the glazed space obtained by passive climatic control is not acceptable, then it may be necessary to heat or cool the glazed space. The energy requirements for heating and cooling can be considerable depending on the type of glazed space.

This section presents heating and cooling requirements for the U shaped single and triple glazed courtyards. These courtyards are the same as those used in Section 4.8.

The study is based on the calculation method described in Chapter 3.

4.9.1 Heating requirements

Depending on the type of activities which are planned for in the glazed space, a certain temperature level has to be accomplished. If this temperature level is higher than what is possible to maintain by passive climatic control, heat must be supplied.

Heating requirements are calculated for the single and triple glazed U shaped courtyards during 1988 in Lund. The courtyards are not ventilated and have no air infiltration. Thus, the buildings and the courtyard have no combined ventilation system. The specific losses for the single and triple glazed courtyards are shown in Table 4.13.

Table 4.13 Specific losses for the single and triple glazed U shaped courtyards.

U shaped courtyard	specific losses glazed space transmission (W/°C)	glazed space ventilation (W/°C)	buildings to glazed space transmission (W/°C)
single glazed	1 247.4	0	299.7
triple glazed	518.4	0	453.6

In order to calculate the energy requirements for heating the glazed space, the following energy balance is used:

$$Q_{from}^{t} = Q_{to}^{t} + S \cdot P_{sun} + P_{heat} \qquad (4.11)$$

This means for the single glazed courtyard

$$1247.4\,(T_g - T_o) = 299.7\,(T_i - T_g) + S \cdot P_{sun} + P_{heat} \qquad (4.12)$$

and for the triple glazed courtyard

$$518.4\,(T_g - T_o) = 453.6\,(T_i - T_g) + S \cdot P_{sun} + P_{heat} \qquad (4.13)$$

The temperature T_i in the buildings is set to 20°C. The temperature in the glazed courtyard T_g is the required temperature. The solar gains are calculated according to Wall (1994b) using data from Lund 1988. The outside temperature is shown in Table 3.2.

The power needed to obtain a certain temperature in the glazed courtyard (P_{heat}) is calculated from Equations 4.12 and 4.13. The energy requirement is then calculated from

$$E_{heat} = P_{heat} \cdot h / 10^6 \quad \text{(MWh)} \qquad (4.14)$$

The total energy required to heat the glazed courtyard to a certain temperature level is presented in Figure 4.43. The energy requirements for both the single glazed and the triple glazed courtyard are shown. As the triple glazed courtyard has a higher temperature than the single glazed one with passive climatic control, auxiliary heat in the triple glazed courtyard is required during a shorter time of the year. If the courtyard is to be heated to 20°C, auxiliary heating is required during January - March and November - December in the triple glazed courtyard. In the single glazed courtyard, heating is required during January - April and October - December. In order to maintain a minimum temperature of 20°C in the glazed space, approx. 70 MWh is needed in the single glazed courtyard and 20 MWh in the triple glazed one. This is equivalent to 435 kWh per m² floor area and year in the single glazed courtyard during the year, and to 122 kWh per m² floor area and year in the triple glazed courtyard. Note that the calculated energy requirements are based on the assumption that there are no ventilation losses. In practice, the courtyard will at least have energy losses due to infiltration (air leakage).

If the glazed space is heated, energy requirements for heating adjacent buildings will be reduced due to reduced fabric losses between the buildings and the glazed space. The reduction in fabric losses can be calculated for the single glazed courtyard from

$$E^{t}_{to,red} = 299.7\,(T_{g,heated} - T_g) \cdot h / 10^6 \quad \text{(MWh)} \qquad (4.15)$$

and for the triple glazed courtyard from

$$E^{t}_{to,red} = 453.6\,(T_{g,heated} - T_g) \cdot h / 10^6 \quad \text{(MWh)} \qquad (4.16)$$

where

$T_{g,heated}$ = the required temperature in the glazed courtyard (°C)
T_g = the temperature in the unheated courtyard (°C)

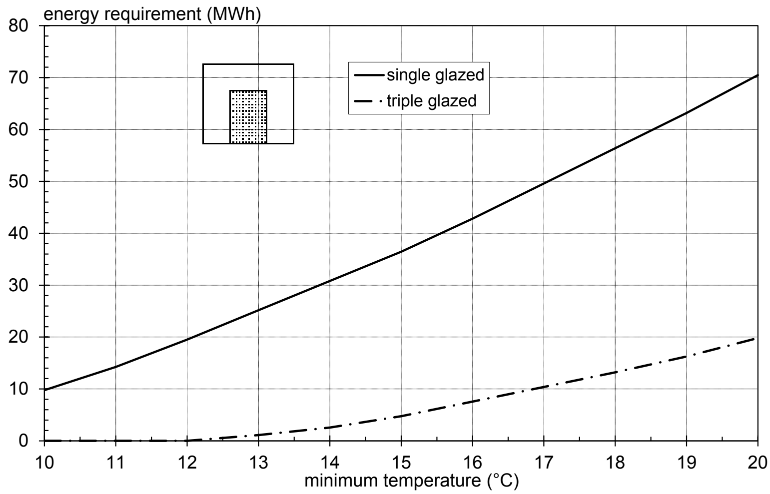


Figure 4.43 *Energy requirement to maintain a certain minimum temperature in the glazed courtyard for single and triple glazing. Lund, 1988. There is no ventilation in the courtyard.*

Figure 4.44 sets out the energy requirements for heating the single glazed courtyard to a certain minimum temperature. The *reduction* in energy requirement in the surrounding buildings when the courtyard is heated to a certain temperature is also presented, calculated from Equation 4.15. The total heating requirement in the glazed space, less the reduced heating demand in adjacent buildings, gives the net energy requirement. This net energy requirement is also presented in Figure 4.44. The reduction in heating requirement in the adjacent buildings is far from compensating for the requirements in the glazed courtyard. The net energy required to keep the temperature to a minimum of 20°C in the single glazed courtyard is approx. 57 MWh, equivalent to 351 kWh/m² and year.

In Figure 4.45 the corresponding results are shown for the triple glazed courtyard. The reduction in energy requirement in the surrounding buildings is calculated from Equation 4.16. The heating requirements are much lower than in the single glazed courtyard. When the reduction in heating requirement in adjacent buildings is taken into account, the net energy demand to keep the temperature to a minimum of 20°C in the glazed space is approx. 10 MWh or 65 kWh/m² and year.

The energy requirement for heating is thus greatly influenced by the design of the glazed space and adjacent buildings. If the glazed space is to be heated, it is essential to have highly insulated glazed surfaces towards the outside and a minimum of ventilation losses.

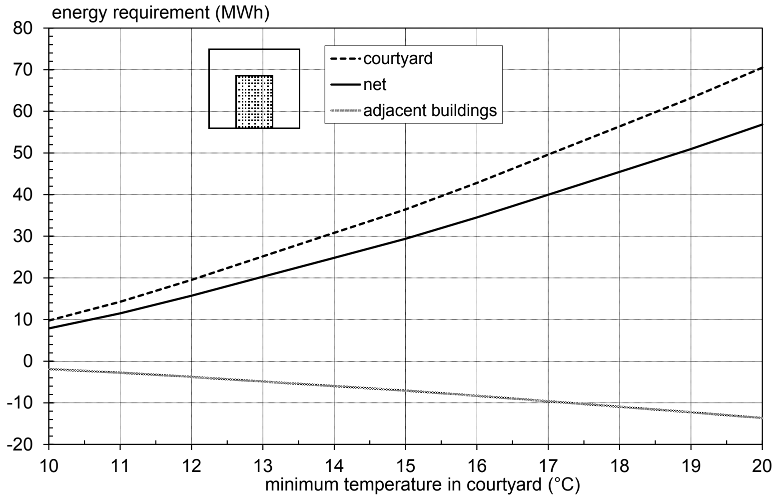


Figure 4.44 *Total energy required to maintain a certain minimum temperature in the courtyard with single glazing, the reduction in energy requirement in the adjacent buildings and the net energy requirement. There is no ventilation in the courtyard. The energy requirement in the adjacent buildings is defined as equal to zero when there is no heating in the courtyard. Lund, 1988.*

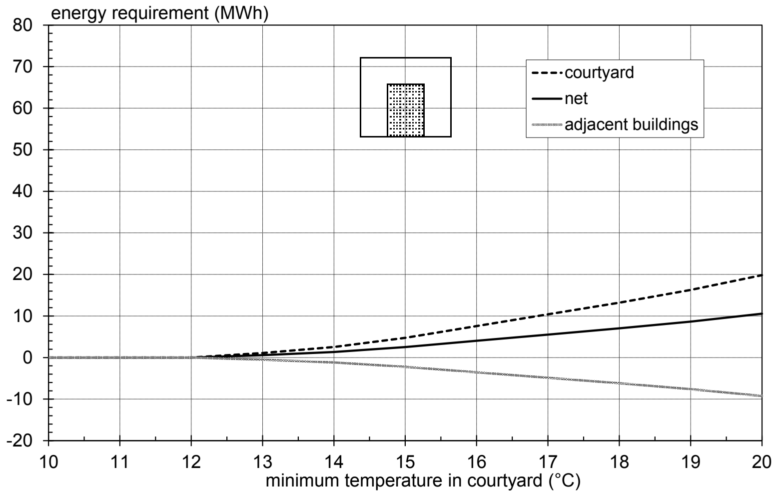


Figure 4.45 *Total energy required to maintain a certain minimum temperature in the courtyard with triple glazing, the reduction in energy requirement in the adjacent buildings and the net energy requirement. There is no ventilation in the courtyard. The energy requirement in the adjacent buildings is defined as equal to zero when there is no heating in the courtyard. Lund, 1988.*

4.9.2 Cooling requirements

In the summer, solar radiation has a strong influence on the temperature in a glazed space. It is hoped that passive climatic control, using sunshades and opening vents, is the first action taken to lower the temperature. This has been discussed in Sections 4.6 and 4.7. If these measures are not sufficient, an active cooling system can be used to cool the supply air.

In this section, an active cooling system is studied. The energy requirements for cooling the U shaped single and triple glazed courtyards are calculated. The calculation method used is described in Chapter 3.

The specific losses are presented in Table 4.14 for the single and triple glazed courtyards. The ventilation losses are equivalent to 0 ach and 2 ach respectively.

Table 4.14 Specific losses for the single and triple glazed U shaped courtyard.

U shaped courtyard	specific losses: glazed space transmission (W/°C)	glazed space ventilation (W/°C) 0 ach	glazed space ventilation (W/°C) 2 ach	buildings to glazed space transmission (W/°C)
single glazed	1 247.4	0	962.3	299.7
triple glazed	518.4	0	962.3	453.6

The energy requirement for cooling the glazed courtyard is calculated from the energy balance

$$Q^t_{from} + P_{cool} = Q^t_{to} + S \cdot P_{sun} \tag{4.17}$$

The fabric losses from the buildings to the glazed space, Q^t_{to}, are set to zero. During the summer the temperature in adjacent buildings can be lower than in the glazed courtyard which means that the buildings may have a small cooling effect on the glazed space. This is however not taken into account. The energy balances are therefore written as follows:

For the single glazed courtyard, without ventilation:

$$1247.4\,(T_g - T_o) + P_{cool} = S \cdot P_{sun} \tag{4.18}$$

For the single glazed courtyard, with a ventilation of 2 ach:

$$1247.4\,(T_g - T_o) + 962.3\,(T_g - T_o) + P_{cool} = S \cdot P_{sun}$$
$$2209.7\,(T_g - T_o) + P_{cool} = S \cdot P_{sun} \tag{4.19}$$

For the triple glazed courtyard, without ventilation:

$$518.4\,(T_g - T_o) + P_{cool} = S \cdot P_{sun} \tag{4.20}$$

For the triple glazed courtyard, with a ventilation of 2 ach:

$$518.4\,(T_g - T_o) + 962.3\,(T_g - T_o) + P_{cool} = S \cdot P_{sun}$$
$$1480.7\,(T_g - T_o) + P_{cool} = S \cdot P_{sun} \tag{4.21}$$

where

P_{cool} = The required cooling power to obtain a certain temperature (T_g) in the glazed courtyard (W).

Note that the ventilation losses equivalent to 2 ach are smaller than the fabric losses in the single glazed courtyard but almost twice as large as the fabric losses in the triple glazed courtyard.

The power needed to obtain a certain temperature in the glazed courtyard (P_{cool}) is calculated from Equations 4.18 - 4.21. The energy requirement is then calculated from

$$E_{cool} = P_{cool} \cdot h / 10^6 \quad \text{(MWh)} \tag{4.22}$$

In Figure 4.46, cooling requirements are shown, based on Equations 4.18-4.22. The triple glazed courtyard has a higher energy requirement for cooling than the single glazed one, but if the courtyards are ventilated, the cooling demand will not differ much. The energy requirements for cooling the glazed space to 20°C, if it is not ventilated, are 368 kWh/m² and year for the triple glazed courtyard and 336 kWh/m² and year for the single glazed one. With a ventilation of 2 ach, the cooling requirements are 227 kWh/m² and year for the triple glazed space and 237 kWh/m² and year for the single glazed space. Note that the courtyards are not shaded in any way.

Ventilation of the courtyard has not always a cooling effect. If the glazed space is cooled and the required temperature is lower than the outside temperature, vents should not be opened.

If a temperature of 25°C is accepted in the glazed space, the cooling requirements are reduced significantly. With a ventilation of 2 ach, the cooling requirement in the single glazed courtyard will then be 46 kWh/m² and year, and in the triple glazed courtyard it will be 88 kWh/m² and year.

These simple estimates are based on the mean temperature of the glazed space. The required power for the cooling system can be very high unless the temperature is allowed to be higher than 20 - 25°C during one single hour.

Energy requirements for cooling can thus be considerable. If the demand on the temperature level is lowered, the energy requirements can be reduced significantly. It is still advisable to use sunshades and to open vents as far as possible. However, opening the vents during daytime in the summer is not an efficient measure, since the outside temperature can be in the range of 25 - 30°C.

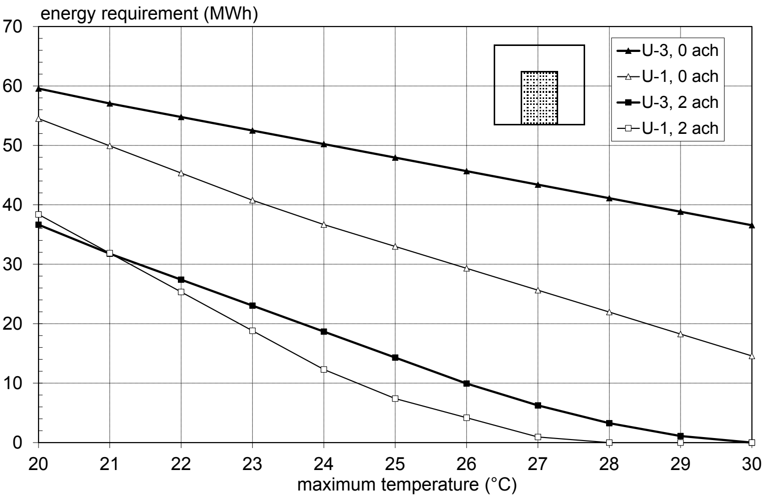


Figure 4.46 *Energy requirements for cooling to maintain a certain maximum temperature in the glazed courtyard for single and triple glazing. The courtyard is either ventilated with 2 ach or not ventilated at all. Lund, 1988.*

4.10 The influence of solar radiation

Obviously, solar radiation is an important heat gain in glazed spaces. The influence of solar radiation on temperatures and energy requirements has been evident in earlier sections of this chapter. In addition to those results, by utilising one of the advantages of a simulation program, this influence can be shown in a very clear and simple way. This is accomplished by calculations with DEROB-LTH in which climatic data of solar radiation is set to zero in comparison with calculations with solar radiation. The building models used, and also the climatic data, are described in Section 4.1.

In Figure 4.47, the temperature in the I shaped single glazed courtyard during the spring week is plotted. The buildings have plasterboard walls abutting on the courtyard. The orientation of the courtyard is north-south. The bottom curve shows the temperature without any influence of solar radiation. Figure 4.48, shows the corresponding results for the triple glazed courtyard. If the curves relating to the case without insolation are compared, it is seen that the temperature varies more in the single than in the triple glazed courtyard. This can be expressed by saying that in the triple glazed case the courtyard is situated further inside the climatic envelope. The character of the courtyard temperature therefore approaches the indoor temperature (warmer and smaller fluctuations); see also Figure 4.13. It can also be seen that solar radiation has a greater influence on the temperature in the triple glazed courtyard than in the single glazed courtyard. This fact is true for all types of glazed space. Of course, the type of glazed space also influences the utilisation of solar radiation.

During the winter, solar radiation often has a small inflence on the temperature, since the days are short and the intensity of radiation low. This is seen in particular in atrium buildings where only the roof is glazed. The temperature in the O shaped single glazed courtyard with concrete walls during the winter week is shown in Figure 4.49. The contribution due to the sun is very small. The minimum temperature is on the other hand reasonably high considering that the outside temperature drops to -14°C. Other examples can be seen in Wall (1991b).

The main conclusion is that solar radiation is very important for glazed spaces and it can be utilised in more or less efficient ways. Consequently, care should be take to ensure that the solar gains are calculated accurately when temperatures and energy requirements are to be estimated during the design stage.

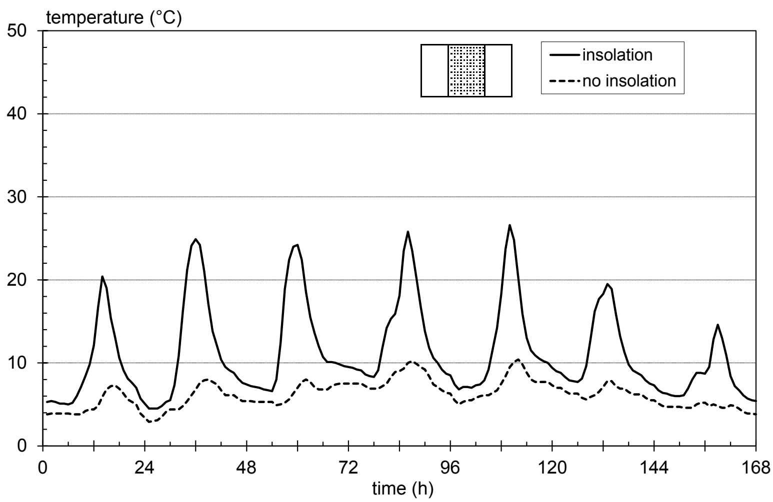


Figure 4.47 Temperature in the single glazed I shaped courtyard of north-south orientation with plasterboard walls, spring week (Wall, 1991b).

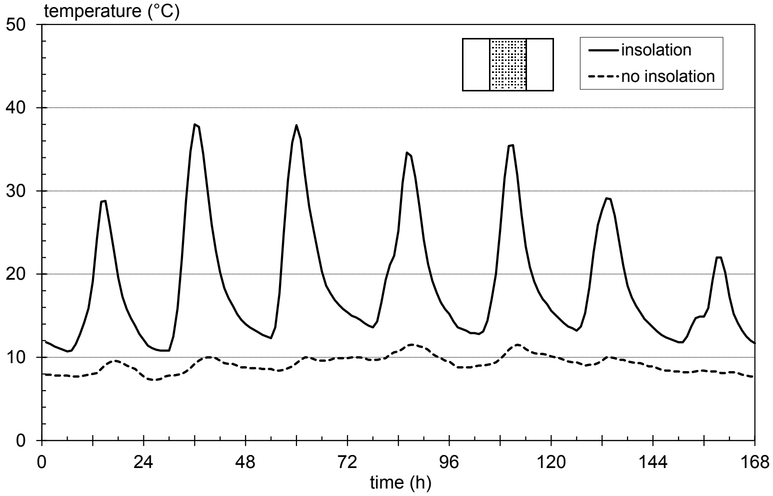


Figure 4.48 *Temperature in the triple glazed I shaped courtyard of north-south orientation with plasterboard walls, spring week (Wall, 1991b).*

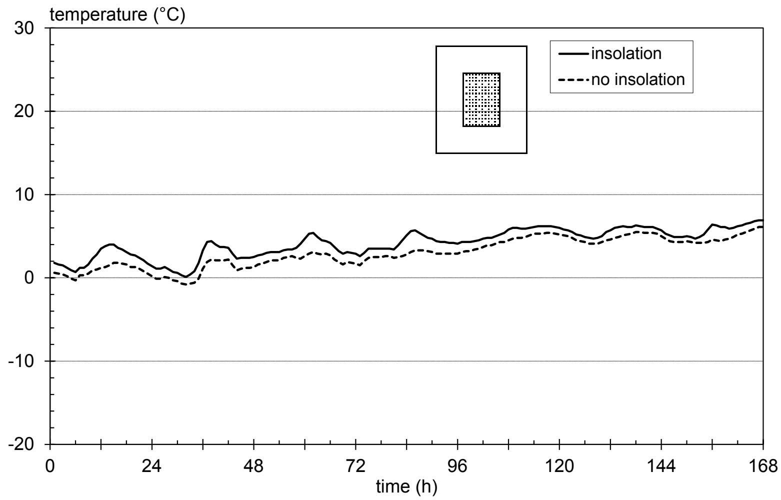


Figure 4.49 *Temperature in the single glazed O shaped courtyard of north-south orientation with concrete walls, winter week (Wall, 1991b).*

4.11 Distribution of solar radiation in glazed spaces and adjacent buildings A comparison of simulation programs

Energy simulation programs are commonly used to calculate the climate and energy requirements in glazed spaces and adjacent buildings. These programs have usually been developed to study buildings with ordinary window sizes. When used to estimate the influence of solar radiation within glazed spaces, the accuracy of these programs varies greatly depending on the calculation method.
Comparisons of four simulation programs were carried out for a sunspace with an adjacent room. The distribution of solar radiation to different surfaces was compared. In addition, the distribution of solar radiation between the glazed space and the adjacent room as well as the proportion of short wave radiation lost to the outside were studied.

The programs show very large differences in the calculation of the distribution of solar radiation. The more simple calculation methods overestimate the utilisation of solar radiation. This means for example that the temperature in the glazed space will be overestimated and the energy requirements for heating will be underestimated. Energy requirements for cooling the glazed space in summer will also be overestimated.

The investigation shows that simulations of atrium buildings or other types of glazed spaces must be based on a geometrical description of the buildings, with transmission through windows, reflection and absorption taken into account. In addition, energy simulation programs which assume that all transmitted solar radiation is utilised should only be used for buildings with windows of ordinary size.

This study is also presented in Wall (1996).

4.11.1 Introduction

Glazed spaces ranging from small glazed verandas to large atrium buildings have become a common feature in architecture. When designing such spaces, programs are often used to estimate temperatures and energy requirements for both the glazed space and adjacent buildings. Since a glazed space is greatly affected by aspects of the outside climate such as insolation and temperature, it is important that the calculation program should take this into account in detail.

Traditionally, the distribution of solar radiation inside a building has not been of major interest in energy simulation programs since most of the transmitted radiation in a building with ordinary sized windows is absorbed. The transmitted solar radiation is then a good approximation of the solar gain. However, such energy simulation programs, designed for buildings with ordinary window sizes, are also commonly used for the energy calculation of glazed spaces, which exhibit quite different characteristics.

Several studies have been carried out to validate and improve energy calculation programs by comparisons between them (Judkoff & Neymark, 1995) or between simulation programs and building measurements (Lomas, Eppel, Martin & Bloomfield, 1994). However, comparisons of programs for the calculation of solar radiation are limited to incident radiation and that transmitted through windows. As a result, these types of studies have not dealt with comparisons of the distribution of solar radiation inside the building, nor have they compared the distribution between the glazed space and adjacent buildings.

Studies of glazed spaces necessitate a detailed calculation of the distribution of solar radiation by the energy simulation program used. While the proportion of transmitted radiation which is retained in a building with ordinary sized windows is about 95 - 100%, for a glazed space this proportion may vary between 30 and 85% (Wall, 1994b; Wall, 1995). If this difference in behaviour is not taken into account, the design of the building will be based on the wrong assumptions, which may result in a poor climate in the glazed space and unnecessarily high energy requirements.

This section presents a comparison of four simulation programs for a glazed space with a room behind. Comparisons of the distribution of solar radiation between the glazed space and the adjacent room as well as the proportion of short wave radiation lost to the outside were studied. In addition, an estimate was made of the influence of the choice of calculation method on the assessment of temperatures and energy requirements for both heating and cooling. The first part of this study was made within the International Energy Agency [IEA], Solar Heating & Cooling Programme, Task12 A3; Building Energy Analysis and Design Tools for Solar Applications, Atrium Model Development.

4.11.2 Description of the building

The building studied consisted of a room and a glazed space, see Figure 4.50. The room had two large windows facing the glazed space to the south. The glazed space, consisting of three single glazed walls and a single glazed roof, was 24 m^2. The room behind was 48 m^2 and the double glazed windows between the room and the glazed space were each 6 m^2.

Physical properties included as input data are shown in Table 4.15. Absorptance, transmittance and reflectance were included to calculate the distribution of solar radiation. The absorptance of opaque surfaces was set to either 0.20 (light) or 0.80 (dark). In the last part of the study, the influence on temperature and energy requirements was estimated by using the U-values shown in Table 4.15. The air leakage of the glazed space was set to 0.5 ach.

In this section, data are presented for the above building. The study of the distribution of solar radiation contains other configurations for the sunspace and is presented in a report (IEA Task12A3, 1996). That study was, however, limited to comparisons of the distribution of solar radiation.

Descriptions of the calculation methods for solar radiation in the four tested simulation programs: DEROB-LTH, SUNREP (TRNSYS), FRES and tsbi3, are found in Chapter 2.

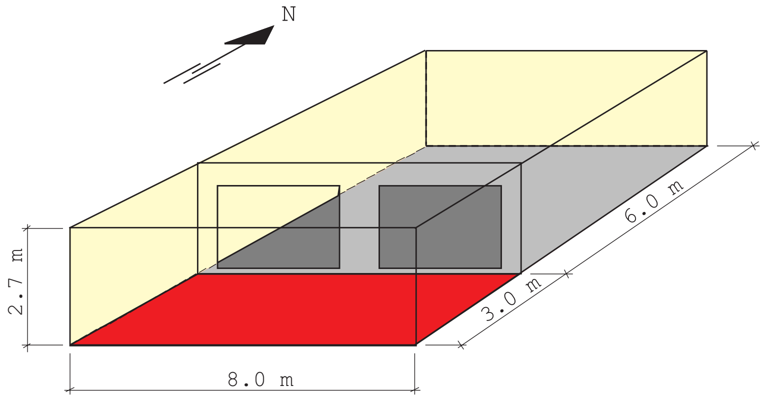


Figure 4.50 *The room with a sunspace (IEA Task12A3, 1996).*

Table 4.15 *Physical properties used as input data.*

surface	U value (W/m²°C)	absorp-tance (-)	transmit-tance (-)	reflec-tance (-)
windows	2.9	0.06/pane	0.86/pane	0.08/pane
glazed surfaces, sunspace	5.8	0.06	0.86	0.08
wall, room/sunspace	0.20	0.20/0.80	-	0.80/0.20
floor, sunspace	4.2	0.20/0.80	-	0.80/0.20
all opaque surfaces, room		0.20/0.80	-	0.80/0.20
ground		0.80	-	0.20

4.11.3 Description of the output data studied

In order to evaluate the simulation programs for the calculation of solar gains, these programs were used to determine hourly values of solar radiation in the following way:

$P_{tot,gl}$ total incident short wave radiation on the outside of the sunspace (W)
$P_{trans,gl}$ total short wave radiation transmitted to the sunspace (W)
$P_{net,gl}$ the part of $P_{trans,gl}$ that remains in the sunspace (%)
P_{tot} total incident short wave radiation on the outside of the windows of the room (W)
P_{trans} total short wave radiation transmitted to the room (W)
P_{net} the part of P_{trans} that remains in the room (%)

The distribution of solar radiation to different inner surfaces was also calculated. Results from those calculations are presented in IEA Task12A3 (1996).

4.11.4 Description of climatic data

Climatic data from Copenhagen, Denmark were used. Copenhagen is situated at latitude 56.0°N. Data were taken from the Danish Test Reference Year (TRY). Two days were chosen as examples for this paper. The 22nd of December was a clear winter day, see Figure 4.51. The mean temperature during this day was -2.6°C. The 7th of June was also a clear day, see Figure 4.52. The mean temperature then was 19.0°C.

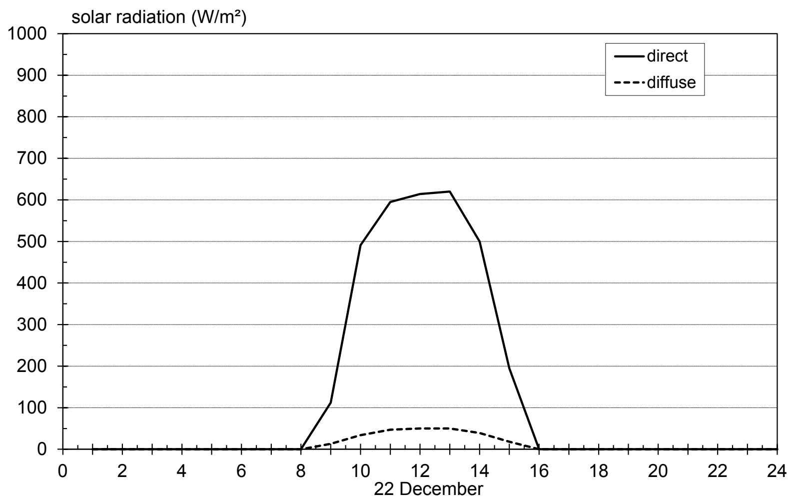


Figure 4.51 *Direct solar radiation at normal incidence and diffuse solar radiation on a horizontal surface. A clear winter day (IEA Task12A3, 1996).*

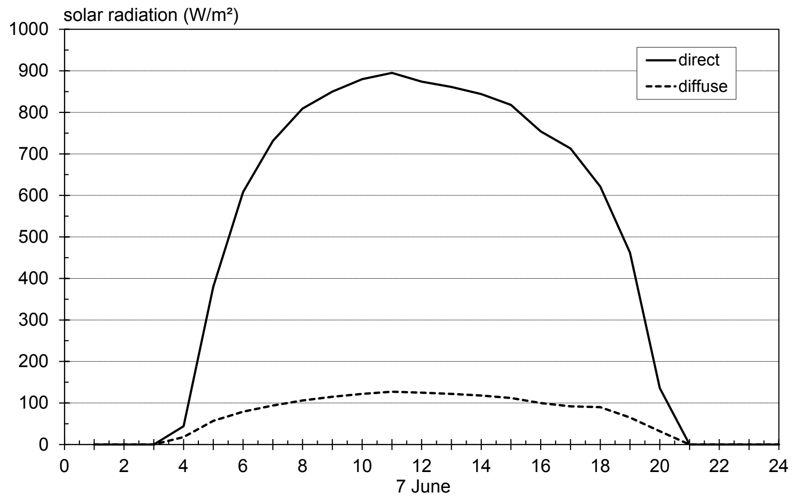


Figure 4.52 *Direct solar radiation at normal incidence and diffuse solar radiation on a horizontal surface. A clear summer day (IEA Task12A3, 1996).*

4.11.5 Evaluation method

To determine whether different methods for the calculation of solar gains resulted in differences in the estimation of temperatures and energy requirements, steady-state calculations of the temperature in the glazed space and energy requirements for heating and cooling were made.

In order to calculate the temperature in the glazed space, the following energy balance was used:

$$Q^{t}_{from} + Q^{v}_{from} = Q^{t}_{to} + P_{abs} \tag{4.23}$$

where

Q^{t}_{from} = fabric losses of the glazed space (W),

Q^{v}_{from} = ventilation losses of the glazed space (W),

Q^{t}_{to} = transmission gain from the adjacent buildings to the glazed space (W) and

P_{abs} = mean power of solar radiation absorbed in the glazed space (W).

By using the thermal properties in Table 4.15 and with an air leakage of 0.5 ach, the following equation is obtained:

$$457.9\,(T_g - T_o) + 10.7\,(T_g - T_o) = 36.7\,(T_i - T_g) + P_{abs}$$
$$468.6\,(T_g - T_o) = 36.7\,(T_i - T_g) + P_{abs} \qquad (4.24)$$

where

T_g = mean temperature in the glazed space (°C)
T_o = mean outside temperature (°C)
T_i = mean temperature in adjacent room (°C)

The mean outside temperature was -2.6°C during the winter day and 19.0°C during the summer day. The temperature in the adjacent room was set to 20°C.

According to Equation 4.24, the temperature in the sunspace during the winter day is given by

$$T_g = -0.96 + P_{abs} / 505.3 \qquad (4.25)$$

and during the summer day

$$T_g = 19.06 + P_{abs} / 505.3 \qquad (4.26)$$

Energy requirements for heating the glazed space during the winter day were calculated by the following energy balance:

$$Q^t_{from} = Q^t_{to} + P_{abs} + P_{heat}, \qquad (4.27)$$

which means

$$468.6\,(T_g - T_o) = 36.7\,(T_i - T_g) + P_{abs} + P_{heat} \qquad (4.28)$$

The mean power P_{heat} required to obtain a certain temperature in the sunspace is calculated from Equation 4.28. The energy requirement E_{heat} is then calculated from

$$E_{heat} = P_{heat} \cdot 24 / 1000 \quad \text{(kWh)} \qquad (4.29)$$

The energy requirement for cooling the sunspace during the summer day was calculated from the energy balance

$$Q^t_{from} + P_{cool} = P_{abs}, \qquad (4.30)$$

which means

$$468.6\,(T_g - T_o) + P_{cool} = P_{abs} \tag{4.31}$$

The fabric losses between the sunspace and adjacent room are not taken into account in this case. The mean power P_{cool} required to obtain a certain temperature in the sunspace is thus calculated from Equation 4.31. The energy required is then calculated from

$$E_{cool} = P_{cool} \cdot 24 / 1000 \qquad \text{(kWh).} \tag{4.32}$$

4.11.6 Results

The calculations of the distribution of solar radiation were made by experts on each program. The results from blind calculations were then compared. In addition, to study the effect of using different methods for the calculation of solar gains, steady-state calculations of the temperature in the glazed space and of energy requirements for both heating and cooling were made using the solar gains calculated by the four programs.

Calculations produced by the four programs, presented as solar energy balances, are shown for the winter day. See Figure 4.53. Solar radiation transmitted into the sunspace is defined as 100%. In this way, the comparisons are not influenced by the methods used for calculation of incident and transmitted radiation. Only the methods used to distribute the solar radiation are compared. In Figure 4.53, the transmitted short wave radiation is shown divided into three parts; that absorbed in the sunspace, that absorbed in the adjacent room and that lost to the outside.

Figure 4.53 shows the results for two different absorptivities of the surfaces; the input was either 0.80 or 0.20. With dark surfaces the proportion of the transmitted radiation absorbed in the sunspace is between 45% and 60%, depending on which program is used. With light surfaces this proportion is between 20% and 58%, which means that the discrepancies are even larger. The two programs DEROB-LTH and TRNSYS/SUNREP, which use a geometrical description of the building to calculate the distribution, estimate a much larger part of the radiation to be lost to the outside than do the other two programs.

There are also important differences between the four programs as regards the calculation of absorbed solar energy during the winter day. See Table 4.16. The absorbed radiation is the solar gain used in the energy balance in order to calculate temperatures and energy requirements. Table 4.16 provides a comparison of the methods used to distribute the solar radiation in combination with those used to calculate incident and transmitted radiation. From this table it can be seen that with dark surfaces a higher amount of absorbed solar radiation is calculated by all four programs than with light surfaces. However, the influence of absorptivity differs greatly between the programs. FRES shows the absorptivity factor to have almost no influence and DEROB-LTH shows the largest influence. The absolute figures of absorbed solar energy differ the most when the surfaces have a low absorptivity factor. With this low absorptivity factor, DEROB-LTH calculates the absorbed radiation to be 14.7 kWh and FRES calculates the radiation to be 42.4 kWh, which is a solar energy gain almost 3 times as high.

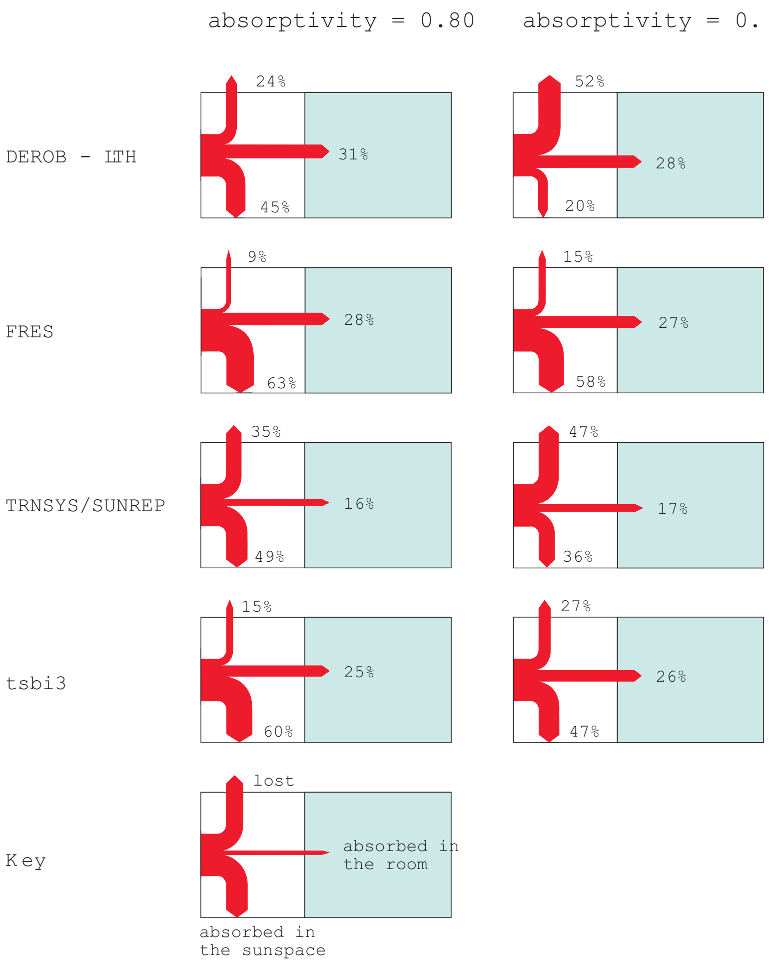


Figure 4.53 *Solar energy balance for the winter day. Solar radiation transmitted into the sunspace is defined as 100% (IEA Task12A3, 1996).*

Table 4.16 Absorbed solar radiation in the sunspace during the 22nd of December (IEA Task12A3, 1996).

computer program	absorbed solar radiation (kWh) a = 0.80	absorbed solar radiation (kWh) a = 0.20
DEROB-LTH	32.7	14.7
FRES	46.2	42.4
SUNREP/TRNSYS	29.8	21.9
tsbi3	42.3	33.7

Very large differences in the calculated solar distribution are found when the solar energy balance for the summer day, calculated by the four programs, is compared. See Figure 4.54. There are large variations in the estimates of the transmitted radiation absorbed in the glazed space. For example, with light surfaces, 21% of the radiation is absorbed in the sunspace and 68% is lost to the outside according to DEROB-LTH. Almost the opposite is the estimate according to FRES; 76% absorbed in the sunspace and 16% lost to the outside. DEROB-LTH and TRNSYS/SUNREP have results in good agreement regarding the calculations with high absorptivity, but are not consistent regarding the calculation with low absorptivity. FRES and tsbi3 calculate the highest utilisation of solar radiation for both the summer and the winter day.

Consistently, very large differences are found in the calculated absorbed solar energy in the sunspace during the summer day, depending on which program is used. See Table 4.17. As can be seen, the solar gains are very large compared with the winter day. With dark surfaces, FRES gives the highest solar gain, which is approx. twice as high as the lowest calculated by SUNREP/TRNSYS. With light surfaces, FRES still gives the highest value, which is approx. 4 times as high as the lowest calculated by DEROB-LTH.

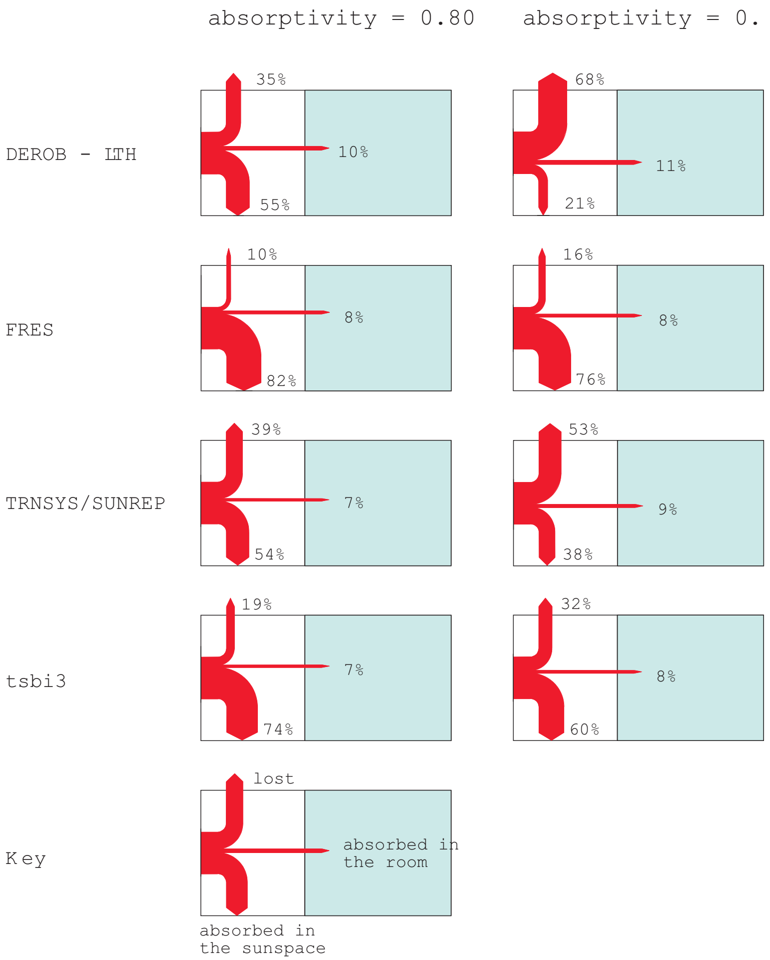


Figure 4.54 *Solar energy balance for the summer day. Solar radiation transmitted into the sunspace is defined as 100% (IEA Task12A3, 1996).*

Table 4.17 Absorbed solar radiation in the sunspace during the 7th of June (IEA Task12A3, 1996).

computer program	absorbed solar radiation (kWh) a = 0.80	a = 0.20
DEROB-LTH	165.5	63.9
FRES	291.6	267.5
SUNREP/TRNSYS	145.3	102.2
tsbi3	213.3	176.4

The solar gains taken from the four programs are put into Equation 4.25 in order to calculate the mean temperature during the winter day. P_{abs} in Equation 4.25 is the solar energy presented in Table 4.16, divided by 24 hours and multiplied by 1000. Figure 4.55 shows the calculated temperatures in the sunspace. As can be expected, solar radiation has little effect on the temperature in the winter. The greatest difference is approx. 2°C. The highest temperatures are given by tsbi and FRES due to the fact that these programs estimated the highest solar gains.

With light surfaces, heating requirements for heating the sunspace to 10°C are about 30% higher when the solar gains are based on DEROB-LTH than when they are based on FRES. See Figure 4.56 which shows the energy requirement during the winter day. Equations 4.28 and 4.29 are used. FRES and tsbi3 give the lowest energy requirements due to higher solar gains.

The four methods to calculate solar gains cause large differences in estimated mean temperatures during the summer day. See Figure 4.57. These temperatures are calculated from Equation 4.26. P_{abs} in Equation 4.26 is based on the solar energy presented in Table 4.17. Using the solar gain from FRES gives a temperature of 43.1°C with the high absorptivity. The corresponding temperature using the solar gain from TRNSYS/SUNREP is 31.0°C. With light surfaces the solar gain from FRES gives 41.1°C which is still the highest temperature. The lowest temperature is then given by using the solar gains from DEROB-LTH, 24.3°C. The presence of light surfaces means a large number of reflections of the radiation which must be taken into account in the calculations.

As the calculations of the solar gains during the summer day differ so greatly among the programs, the calculation of the cooling requirements also exhibits wide variations. In Figure 4.58, the energy requirements for cooling the glazed space to 25°C during the summer day are presented. Equations 4.31 and 4.32 are used. According to the solar gain calculated by DEROB-LTH, there is no cooling demand in the sunspace with light surfaces. Using the solar gain from tsbi3 gives a cooling demand of 109 kWh and the solar gain from FRES gives 200 kWh. Note that these figures are based on the mean temperature.

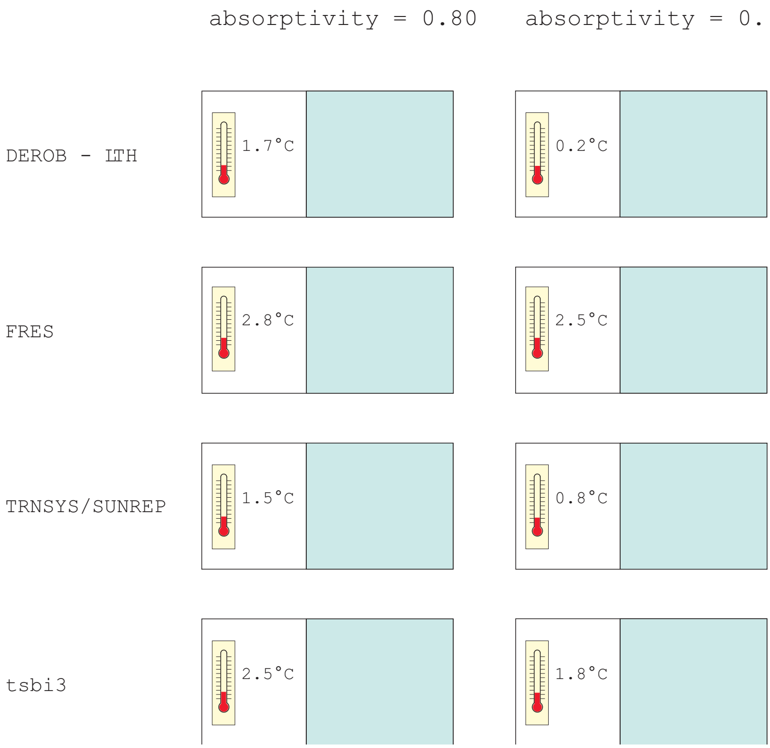


Figure 4.55 *Mean temperature for the winter day. The solar gains are based on the four programs.*

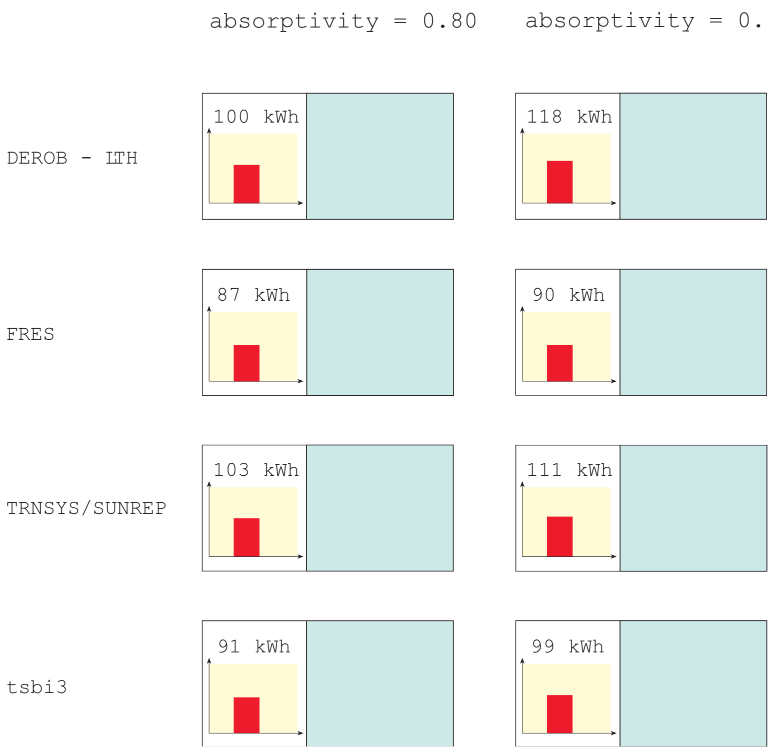


Figure 4.56 *Heating demand to maintain 10°C in the sunspace during the winter day. The solar gains are based on the four programs.*

Figure 4.57 *Mean temperature for the summer day. The solar gains are based on the four programs.*

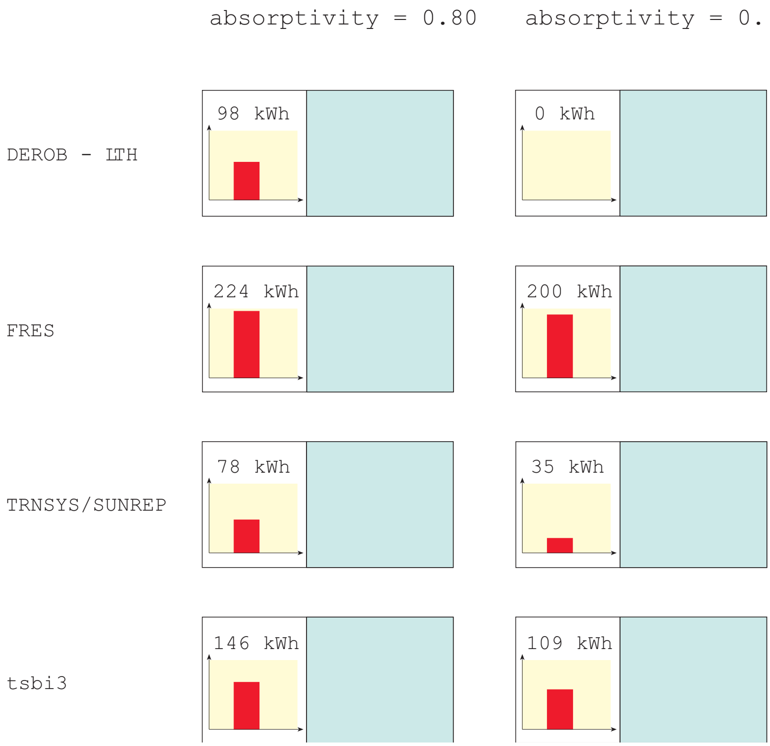


Figure 4.58 *Cooling demand to reduce the temperature to 25°C in the sunspace during the summer day. The solar gains are based on the four programs.*

4.11.7 Discussion and conclusions

Comparisons of the four simulation programs reveal very large differences in the calculation of solar gains. Glazed spaces with light surfaces give rise to larger differences in calculation results, because simpler methods do not calculate reflections. An appropriate method must take into account that a large part of the transmitted radiation can be lost through retransmission, via reflections or directly, through the glazed surfaces.

Since the simpler calculation methods overestimate the solar gains, the temperatures will also be overestimated. By assuming that the main proportion of the transmitted radiation will be absorbed in the opaque surfaces, and not distributed to and transmitted out through the glazed surfaces, the calculated solar gains will be too high. The method in FRES is an example of this. This type of method can only be appropriate for studies on buildings with small areas of glass.

When temperatures in a glazed space are to be calculated, a correct estimation of solar gains is of varying importance depending on the time of year. A correct estimation is especially important during summer conditions. The choice of calculation method may also influence the estimation of temperatures during spring and autumn, or quite simply, whenever the solar radiation is powerful.

Due to the overestimation of solar gains by the simpler calculation methods, the energy requirements for heating the sunspace are underestimated. Calculations for a period in midwinter at high latitudes are not influenced as much as they may be during spring or autumn. It is significant for the spring and autumn that heating is required at the same time as solar radiation is powerful.

Cooling requirements will be strongly overestimated if the calculation method used assumes that almost all transmitted radiation is absorbed and utilised. The highest calculated solar gain was four times as large as the lowest. As the solar gain is the most important part of the energy balance for a glazed space during the summer, an inaccurate calculation method will cause large errors in the calculation of the cooling demand.

The programs are more consistent regarding the solar gains in the adjacent room than those in the glazed space. However, for a correct estimation of the buffer effect of the glazed space on an adjacent building, there must be a precise calculation for the glazed space.

Thermal comfort may be strongly misjudged if the calculation of the solar radiation distribution not is correct. This is due to the fact that studies of thermal comfort have to be based on calculations of solar radiation, surface temperatures, air velocities, etc.

If programs are to be used in the calculation of energy requirements and temperatures in glazed spaces, it is essential to base the calculations on a geometrical description of the buildings which takes account of the transmission of solar radiation through windows, as well as reflection and absorption. In tsbi3, the user of the program must decide the distribution of solar radiation, which is impossible even for an expert. In FRES, the existing calculation method is not especially designed for studies of glazed spaces. This simplified method of calculating the solar distribution is therefore not suitable for glazed spaces. Among the programs studied, only TRNSYS/SUNREP and DEROB-LTH have appropriate methods to calculate solar gains.

The use of simplified methods in the design stage is appropriate only if these programs are specially made for studies of glazed spaces and based on calculations with a more advanced program which accurately calculates the solar distribution and gains. One example of such a method is *A Design Tool for Glazed Spaces* (Wall, 1995; Fredlund, 1995).

Acknowledgements

Calculations were made by experts on each program within IEA Task12. The author would like to thank the contributors from the other participants: Kjell Kolsaker (FRES) SINTEF, Norway, Kjeld Johnsen (tsbi3) Danish Building Research Institute, Denmark and Dominique Chuard (SUNREP/TRNSYS) Sorane S.A., Switzerland.

4.12 Summary

In Northern Europe, the aim is to keep the temperature level in glazed spaces as high as possible during the winter months. The temperature level, obtained by passive climatic control, is mainly determined by the relationship between the specific losses and the gains in the glazed space. This relationship can be written

$$G = \frac{\textit{specific losses from the glazed space to the outside}\ (\mathrm{W/^\circ C})}{\textit{specific gains from the buildings to the glazed space}\ (\mathrm{W/^\circ C})}$$

The smaller the value of G, the higher the temperature level is in the glazed space. When $G = 1$, the temperature in the glazed space is equal to the mean value of the outside temperature and the temperature in the surrounding buildings. This applies under steady-state conditions without insolation but is also a good approximation of the minimum temperature in the glazed space in a normal climate, i.e. the temperature that occurs overnight during a winter period.

The temperature in the glazed space is naturally affected by e.g. insolation and thermal inertia. The minimum temperature can in this way be a few degrees higher owing to the heat storage capacity, but this occurs mainly when the value of G is quite small and the glazing has a low U-value. The significance of thermal inertia namely increases as the value of G decreases, and in addition glazing with a low U-value has a better capacity to retain the solar energy which has entered. Thermal inertia has very little effect on the temperature in a glazed space in the winter. When insolation increases in the spring, thermal inertia has a greater significance in smoothing temperature fluctuations in the courtyard. Note that the best way to make use of the thermal inertia is to let the glazed space have passive climatic control. If a constant temperature is required in the glazed space, then the thermal inertia will be of minor importance.

If the glazed space is heated, thermal inertia has a greater influence on heating requirements in a glazed space with glazing of low U value than in a glazed space with glazing of high U value. However, if the glazed space is cooled in the summer, thermal inertia has a greater influence on cooling requirements in a glazed space with glazing of high U value than in a space with glazing of low U value.

The properties of the glass, the sizes of the glazed surfaces and their orientation obviously affect the amount of solar radiation that can enter the glazed space. However, the orientation has little effect on the minimum temperature in the courtyard.

A courtyard with only the roof glazed, completely surrounded by buildings, does not have such a large gain from the sun, except during the summer months when the sun is high in the sky. This type of atrium does however represent a substantial "additional insulation" of the adjacent walls, which means that this can be an effective way of reducing the losses of courtyard facades in older buildings without having to apply additional insulation to the walls themselves.

A high temperature level in the glazed space, obtained by passive climatic control, will at the same time give rise to reduced heating requirements in adjacent buildings. Thus, the glazed space should in this case have a low value of *G*.

The smaller the value of *G*, the more sensitive is the glazed space to ventilation and air leakage. Glazed spaces with a low value of *G* in particular should therefore have a relatively airtight climatic envelope so that ventilation can be controlled on the basis of existing need. Unintended ventilation during the winter can otherwise have drastic consequences for the temperature in the glazed space.

During the summer months it is essential that proper ventilation should be possible. In addition, the use of solar control curtains is an effective way of keeping out the sun and maintaining the temperature at a low level. However if the outside temperature during the day is high, ventilation by opening vents will obviously have a limited effect.

Obviously, if the glazed space is heated, an airtight climatic envelope is essential irrespective of the value of *G*. The energy requirement for heating the glazed space is greatly influenced by the design of the glazed space and adjacent buildings. If the glazed space is to be heated, it is important to have highly insulated glazed surfaces towards the outside and a minimum of ventilation losses.

During the summer, the temperature in a glazed space can be very high if the space is insufficiently ventilated and shaded. If passive climatic control is not sufficient, an active cooling system can be used. Energy requirements for cooling can however be considerable. If the demand on the temperature level is lowered, the energy requirements can be reduced significantly.

Different ventilation systems can be used in order to achieve a higher temperature in the glazed space and/or lower energy requirements. The glazed space can be used as a preheater for the supply air to the adjacent buildings. The exhaust air from the buildings can also be used as supply air to the glazed space in order to obtain a higher temperature level. A good ventilation system design is to use the exhaust air from the buildings as supply air to the courtyard and at the same time to use a heat exchanger to transfer the heat from the exhaust air from the courtyard to the supply air to the buildings in order to reduce the ventilation losses of the buildings. In this way a high temperature level in the glazed courtyard is obtained in combination with low fabric and ventilation losses of adjacent buildings.

Solar radiation has a major influence on the climate in a glazed space. The solar radiation can be utilised in more or less efficient ways. Care should be taken to ensure that the solar gains are calculated accurately when the climate in the glazed space and energy requirements are to be estimated during the design stage. Otherwise the result may be a poor climate, high energy requirements and disappointed building users.

Comparisons of four simulation programs were carried out for a sunspace with an adjacent room. The distribution of solar radiation between the glazed space and the adjacent room as well as the proportion of short wave radiation lost to the outside were studied.

The programs show very large differences in the calculation of the distribution of solar radiation. The simpler methods overestimate the utilisation of solar radiation. This means for example that the temperature in the glazed space will be overestimated and the energy requirements for heating will be underestimated. Energy requirements for cooling the glazed space will be overestimated.

The investigation shows that simulations of atrium buildings or other types of glazed spaces must be based on a geometrical description of the buildings which takes into account transmission through windows, reflection and absorption. In addition, energy simulation programs which assume that all transmitted solar radiation is utilised should only be used for buildings with ordinary window sizes.

5 Case studies - a brief presentation

This chapter gives a brief description of the case studies made to show the performance of different types of glazed space. The glazed roof over the abbey church ruins at Hamar is not yet built and has thus only been theoretically studied, while both calculations and field measurements have been made on the other glazed spaces. In some cases the field measurements have been extensive but in other cases the measurements have been limited to only a few parameters over a short period of time. In this chapter, descriptions of the buildings are presented together with a few examples from the field measurements or from calculations. Chapter 5 forms a background to Chapter 6 which contains analyses based on both field measurements and calculations.

5.1 Methods

5.1.1 Field measurements

The measuring systems used to study climate and energy were mostly in the form of automatic measurements with a computer system. These measurements were made once per hour by means of a datalogger and stored in a computer. Once a day the measured data were transferred to the central computer at the Department of Building Science. These types of hourly measurements were made over longer periods, from months to several years.

To a greater or lesser extent, the automatic measurements recorded the following:

- *the outside climate* such as temperature, global and diffuse insolation and wind speed
- *the climate in the glazed space* comprising details such as air temperatures at different points and levels, surface temperatures, transmitted solar radiation, vent opening and curtain opening

- *the heating system* such as energy use, water temperatures and flows
- *the ventilation system* such as air flows and temperatures of outside air, supply air, extract air and exhaust air.

In addition, manual measurements were made. In these measurements, a number of meters may be read at varying intervals as a complement to the automatic readings. Readings were typically made every or every other week and comprised separate and total use of electricity, heating requirements in adjacent buildings, use of cold water and domestic hot water, etc.

Short term measurements were also made on some occasions. These comprised, for instance, measurements of air change rate in the glazed space with the aid of tracer gas techniques and also measurements of airtightness in the glazed space with the aid of fan pressurisation tests.

Measurements of air change rate:

In order that an idea may be gained of how leaky the glazed space is under normal conditions, measurements can be made using the tracer gas method. The measuring apparatus comprises control and regulatory equipment and a gas analyser. Collection of air samples and reading of the gas analyser are fully automatic.

During such a measurement an arbitrary quantity of laughing gas (N_2O) is introduced into the glazed space, and the concentration of the tracer gas is then measured at 10 points for some hours. The measurement points are distributed uniformly in the glazed space, both horizontally and vertically. Because of air leakage, concentration decreases with time, and in this way an approximate air change rate can be calculated. This method is called the decay method.

The air change rate is calculated from the formula

$$n = \frac{1}{t} \cdot \ln \frac{C(0)}{C(t)} \tag{5.1}$$

where

n = number of air changes per hour
$C(0)$ = tracer gas concentration at time 0
$C(t)$ = tracer gas concentration at time t
t = the time in hours which has elapsed between the two values of tracer gas concentration

The difficulty with this type of measurement is that air leakage varies depending on the difference in pressure and temperature between the outside and the glazed courtyard, and on wind pressure. This means that leakage varies from day to day and from season to season. It is therefore also difficult to compare measurements made in different glazed spaces. On the other hand, the measurement gives a useful estimate of how leaky the glazed space is under normal conditions, which may constitute an important part of the energy balance. If this information is not available, it is difficult to estimate the temperature level in the glazed space concerned, and, above all, it is very difficult to calculate the energy requirement in cases where the space is to be heated.

Fan pressurisation tests:

In order that the airtightness of different glazed spaces may be compared, measurements using pressure tests can be carried out. The results of airtightness measurements are presented in the form of air leakage in m^3 per hour per m^2 of the surface at a pressure difference of 50 Pa between inside and outside. Airtightness can also be expressed in terms of the number of air changes in the glazed space per hour (ach).

This type of measurement can also be a means of checking airtightness and comparing it with a requirement. There is no special requirement at present regarding the airtightness of glazed spaces, in spite of the fact that many are heated to indoor temperature. In the present Swedish Building Regulations, BBR 94, the requirements at a pressure difference of 50 Pa are 2.9 m^3/m^2h for dwellings and 5.8 m^3/m^2h for other premises. A glazed space is obviously not a dwelling, implying that 5.8 m^3/m^2h would be an acceptable airtightness. However, such a leaky glazed construction can give rise to high heating costs which had not been allowed for.

In principle, an airtightness test can be carried out in the same way as for ordinary buildings. Using a large fan, vacuum or overpressure is set up in the glazed space. Simultaneously, the quantity of air that must be supplied to, or removed from, the glazed space in order to attain a certain pressure difference, is measured. All the fans in the ventilation system of the building are turned off and the ventilation terminals are sealed during the measurements.

The pressure test is carried out by mounting a large measuring pipe with a fan inside in the entrance to the glazed space; see Figure 5.1. By adjusting the blade angles in the pipe, the glazed space can be subjected to either an overpressure or a vacuum; see Figure 5.2. The pressure difference between the glazed space and outside is checked with a pressure gauge. Tracer gas is used to check the flow of air through the measuring pipe. A certain quantity of tracer gas is supplied at the beginning of the pipe, and after mixing had taken place the concentration of tracer gas is measured at the end of the pipe (Lundin, 1986). The airtightness measurements were made in accordance with Swedish Standards (airtightness tests in accordance with SS 02 15 51).

The fan pressurisation tests were carried out jointly by the Department of Building Science at Lund University and the Swedish National Testing and Research Institute [SP]. At the time the measurements were made, the temperature inside the glazed space was about the same as that outside. No correction need therefore be made for buoyancy.

In conjunction with airtightness measurements in the glazed space, the same measurements were also made in rooms adjoining the glazed space. In principle, the measurements were made by measuring leakage of air from the room at a number of differential pressures, with the blower in the glazed space both in and out of operation. The pairs of measurements for the wall abutting on the glazed space, one of which refers to the case where there is no differential pressure across the wall, gives an idea of air leakage through the facades abutting on the glazed space.

For a more detailed description of the field measurements, see the specific reference for each case study.

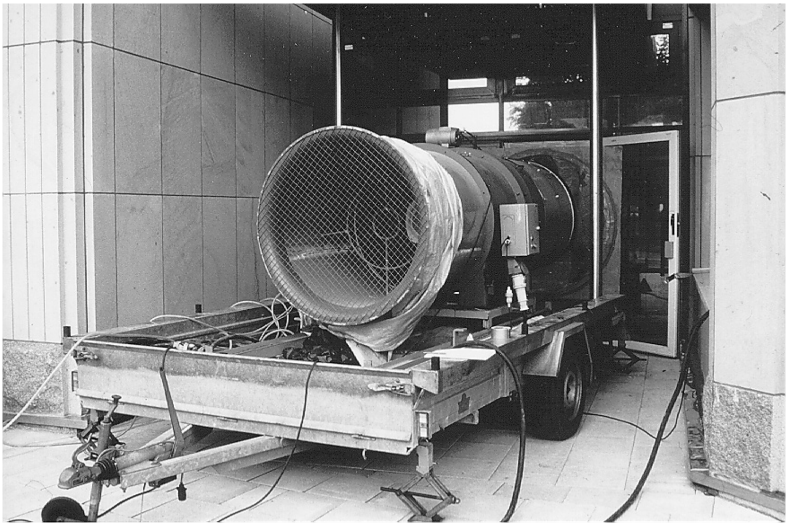


Figure 5.1 *Example showing how the blower was installed in the entrance to an atrium; Scandinavian Center in Malmö (Wall & Blomsterberg, 1994).*

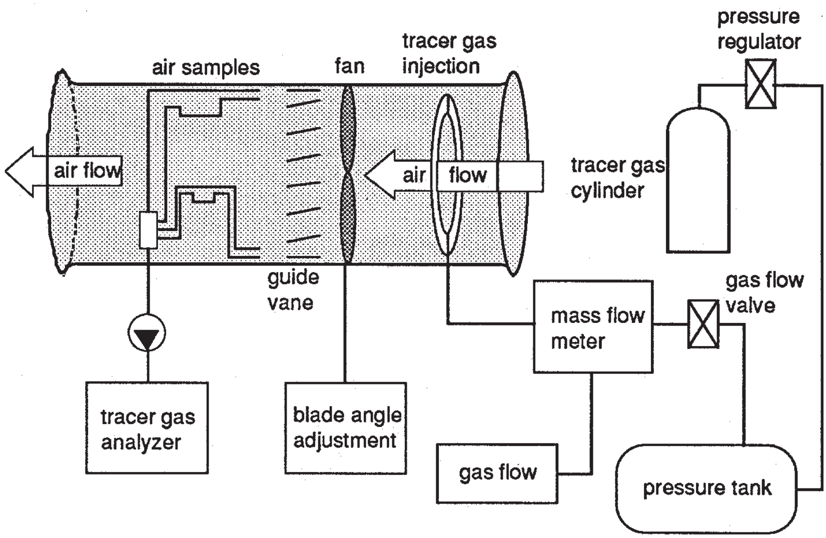


Figure 5.2 *Principle of fan pressurisation test for large premises (Wall, 1992a).*

5.1.2 Calculations

As a complement to measurements, calculations were made in order to analyse the case studies and to compare measurements with calculations.

The simplest calculations were steady-state calculations which do not take thermal inertia into account. This simplified calculation method is described in Chapter 3.

Calculations were also made using a dynamic energy simulation program; DEROB-LTH. This program takes into account the thermal inertia and other factors and makes detailed calculations of the distribution of solar radiation and the solar energy gains. Hourly calculations can be compared with hourly measurements. This program is briefly described in Chapter 2.

In order to study in greater detail the ventilation in the glazed space and surrounding buildings and the coupling between these, the program MOVECOMP was used. MOVECOMP is a multicell program for calculation of air flow rates (Herrlin, 1987; Bring & Herrlin, 1988). These calculations were based on the design air flow rates in the ventilation systems in the surrounding buildings and the glazed space. The air flow rates between the glazed space and the surrounding buildings, and between the glazed space and the external air, were then calculated using MOVECOMP. These calculations were made by Åke Blomsterberg at the Swedish National Testing and Research Institute (Wall & Blomsterberg, 1994).

5.2 The abbey church ruins at Hamar

Figure 5.3 *The abbey church ruins at Hamar (1855). Oil painting by Joachim Frich (1810-1858).*

5.2.1 Description

The abbey church at Hamar was built in the 12th Century. It is made of limestone. The church was destroyed by fire in 1567 during the Seven Year War, and it was not until the 1920s that measures were taken to preserve the ruins. Different methods have been tried, but the ruins are in a very poor condition, mainly due to exposure to the elements and frost damage.

After discussions lasting over many years during which the views of different experts were sought, it was decided that the erection of a superstructure, climatic protection, is probably the only way in which the ruins can be preserved (Central Office of Historic Monuments, 1988).

In February 1987, the Central Office of Historic Monuments and the Hedmark Museum jointly announced an architectural competition for a superstructure over the ruins. The object of the competition was to see whether a superstructure over the ruins could be designed so as to fit in with the ruins, the location and the landscape. The winning proposal "Poetry of reason" was put forward by Kjell Lund and Nils Slaatto, Architects MNAL. Professor Kristoffer Apeland was technical consultant. This building has not yet been constructed, but this will probably be done in 1997.

The Department of Building Science studied what consequences the winning proposal will have on climate and energy requirements (Wall, 1990a).

The glazed superstructure covers an area of ca 65 × 37 m, i.e. 2 400 m^2, and the volume is ca 23 000 m^3. The height to the ridge is ca 20 m, see Figure 5.4. The underlying idea is that the glazed structure must be slender so that it will be possible to see through it, i.e. the ruins must continue to dominate. In view of this, single glazing is preferable. The architect proposed Lexan which is a plastics material (polycarbonate). Since it is essential that the material should be as clear as glass, we did not recommend it since we have not yet seen a project where the plastics material has retained its transparency over an extended period.

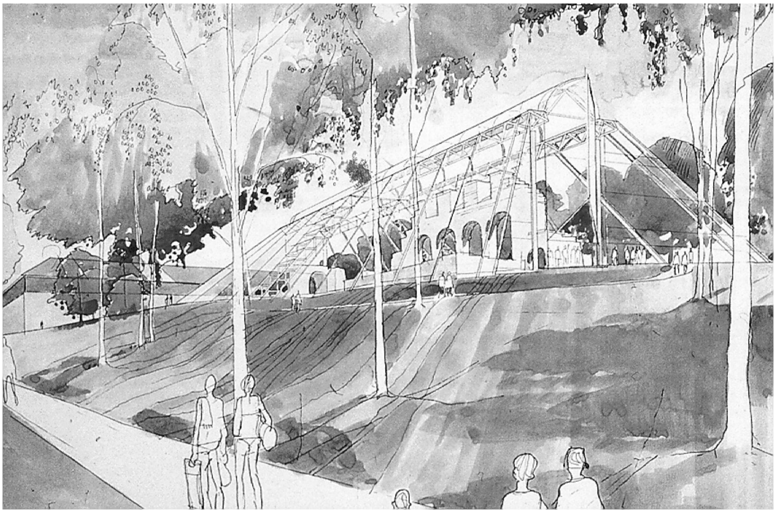


Figure 5.4 *Perspective drawing of the glazed superstructure (Kjell Lund and Nils Slaatto, Architects MNAL) (Wall, 1990a).*

Latitude:	60.8°N
Function, glazed space:	climatic protection
Floor area, glazed space:	2 400 m^2
Occupancy year:	not yet built

The drawback of a multilayer structure is that the loadbearing construction must be heavier. The advantage is that the energy requirement for heating is reduced. The intention is to prevent freezing inside the glazed structure so that the load on the ruins due to the external climate is reduced. It is therefore essential that fabric losses should be as small as possible.

5.2.2 Results

In selecting a glazed structure, a balance must be struck between the perception of the glazing and the operating costs and climatic requirements. Since it is an essential stipulation that the glazed structure should have the greatest possible transparency, single glazing is aimed for. Computer runs show however that the energy required to maintain a temperature of 1°C inside the glazed structure is ca 2.8 times as much for single glazing as for triple glazing. Even though there is considerable energy increment from the sun, there are long periods during the winter when the sun is below the horizon or when it is cloudy and insolation is very low. The value of the factor G, which is the relationship between the specific losses and gains for the glazed space is equal to infinity ($G = \infty$). In such a case there is no source of additional energy other than that stored in the ruins and the ground and the energy requirement for this type of glazed structure is therefore very high. See also Section 4.2.

For a single glazed structure the energy required to maintain a temperature of 1°C during a heating season is ca 250 MWh, assuming that the sky temperature is equal to the outside air temperature. However, calculations based on a method which estimates a sky temperature depending on the cloud cover indicate that the long wave sky radiation has a very large influence on this type of glazed structure. The energy need increased by more than 70% when this method of calculating sky radiation was used (Wall, 1992b). Single glazing with a low emissivity coating reduces the influence of sky radiation. A heat pump can reduce the energy costs.

If no heating is provided, the minimum temperature inside the glazed structure during the calculation year varies between ca -9°C and -12°C depending on the type of glazed structure selected. This temperature occurs in December when insolation is very low and the minimum outside temperature is -16.2°C.

During the summer, owing to the high outside temperature and the fact that insolation is at times powerful, high temperatures must be expected inside the glazed structure. By means of effective ventilation which can be achieved by opening large vents, the temperature can be reduced to an acceptable level. There will however still be times on hot sunny days when visitors may find the temperature uncomfortably high. Sunshades are useful on these occasions since they screen out some of the solar heat. They also prevent the visitors being directly exposed to the rays of the sun - direct sunshine is perceived as a source of discomfort when it is hot. The drawback is that sunshades screen the ruins and nullify the airy impression which the glazed structure is intended to convey.

The ruins do not tolerate large and sudden temperature oscillations or excessive temperature differences between different sides of the wall. The calculations

show that in winter when heating up to 1°C is provided, the surface temperature of the wall is quite constant and only varies between 1°C and 3°C. During this time insolation is low and there are therefore no large temperature oscillations. In the spring when there is a large variation in air temperature over the day and there is considerable insolation, the surface temperature of the wall may be raised by ca 10-15°C during the day and may be as high as 40°C on the south side. The maximum temperature difference between the south and north sides is then ca 10°C. According to the Central Office of Historic Monuments in Norway, these temperature movements are not excessively high and the ruins are not damaged by these. If the temperature differences are to be reduced and the oscillations damped, sunshades inside the glazed roof are an effective means of preventing the direct solar radiation from falling on the wall.
For further information, see Wall (1990a) and Wall (1992b).

5.3 Glazed verandas – Taberg

Figure 5.5 The south facade with its characteristic glazed verandas (Fredlund, 1995).

Latitude:	57.7°N
Function, glazed space:	veranda
Floor area, glazed space:	10/16 m²
Function, adjacent buildings:	residential
Occupancy year:	1981

5.3.1 Description

This housing estate consists of four two-storey blocks of flats with their garage buildings, store rooms, communal premises and laundry room. It was built 1981. The buildings were designed by Professor Bengt Hidemark together with Professor Bo Adamson and the firm Hidemark and Danielsson Arkitektkontor. An evaluation was carried out at the Department of Building Science. A detailed description of this study is found in Fredlund (1989) and Lundgren (1989).

The housing estate is contiguous with the community of Taberg. This is situated ca 9 miles (15 km) to the south of Jönköping in the south of Sweden. The development comprises four buildings containing eight flats each, arranged as follows:

- Four flats of 4 rooms and kitchen, 106 m²
- Two flats of 2 1/2 rooms and kitchen, 68 m²
- Two flats of 2 rooms and kitchen, 62 m²

The development also comprises a communal building which contains a laundry room, a sauna and an all-purpose room with a kitchenette.

The buildings are two storey blocks of flats with the large flats on two storeys. The southerly facades with their glazed verandas next to the balconies and patios are a characteristic feature of the development. The layout of the estate is illustrated in Figure 5.6. The development is surrounded by dense coniferous woodland. A piece of the original woodland with some tall pine trees has been left between the buildings.

Each flat has a glazed veranda. The area of the veranda for flats with 2 and 2 1/2 rooms is 10 m² on one storey, and that of flats with 4 rooms 16 m² on two storeys. The layouts of the flats are shown in Figures 5.7 and 5.8.

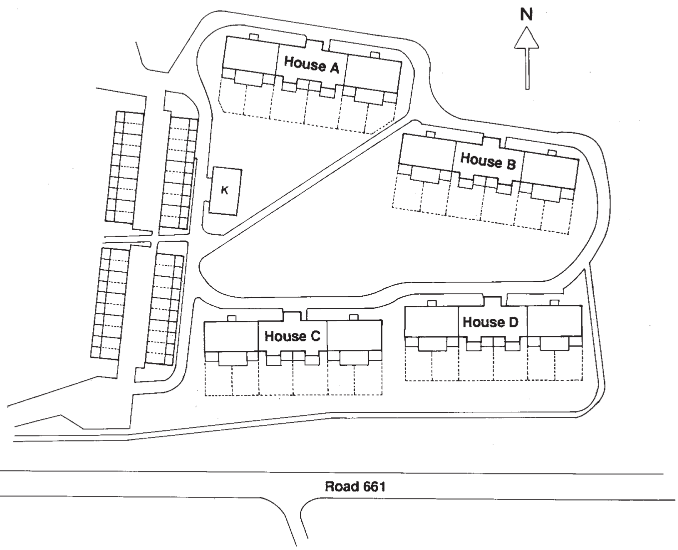


Figure 5.6 *The housing estate (Fredlund, 1989).*

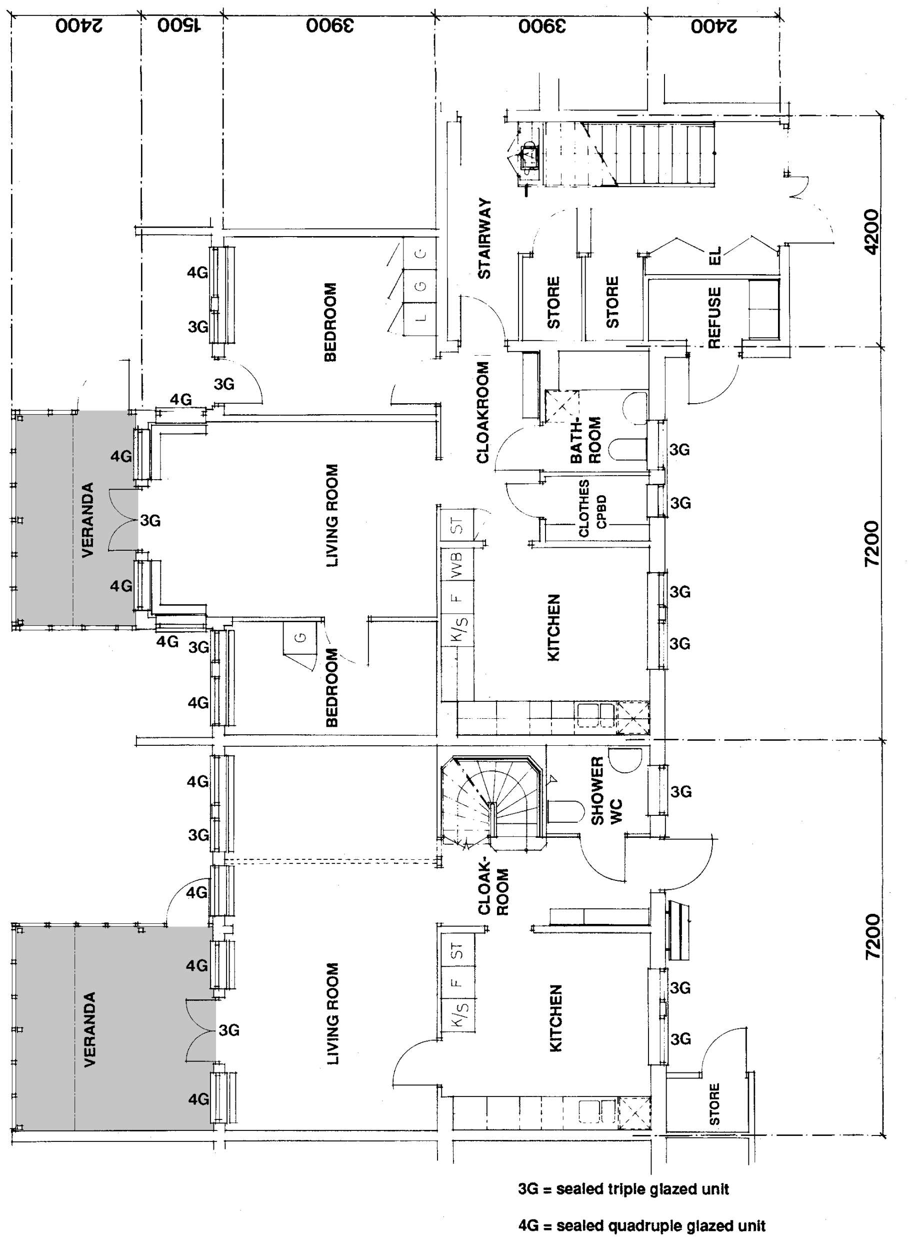


Figure 5.7 *Part of 4 rooms+kitchen and 2½ rooms+kitchen, ground floor (Fredlund, 1989).*

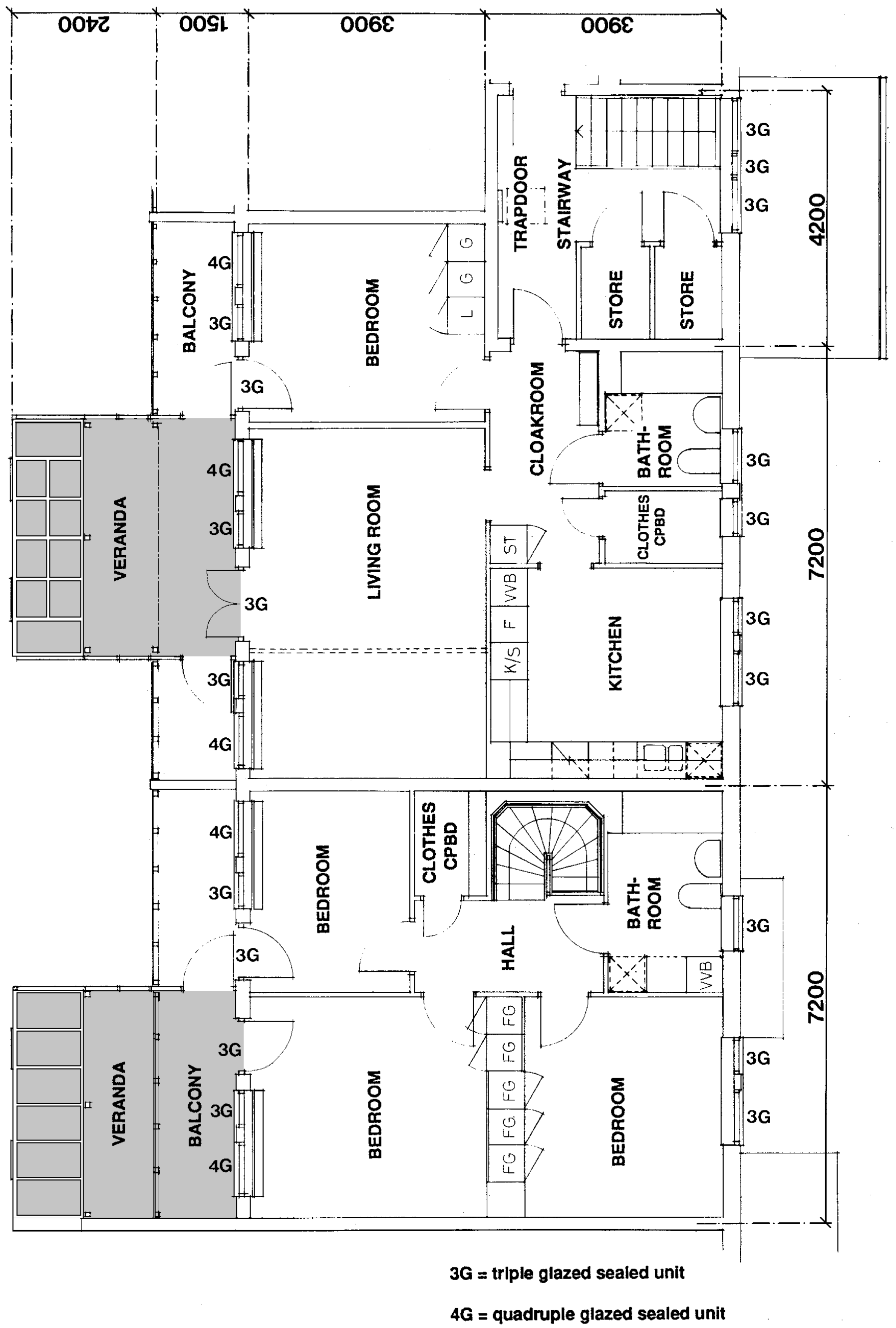


Figure 5.8 *Part of 4 rooms+kitchen and 2 rooms+kitchen, first floor (Fredlund, 1989).*

The ground floor construction is a single layer concrete slab on a ground slab underlain by stabilised expanded clay. The first floor construction is 180 mm concrete and the attic floor comprises glued laminated timber joists running along the building. The ceiling consists of vapour barrier, spaced boarding and plasterboard. The roof comprises trapezoidal metal sheeting on transverse purlins and hard wood fibre board.

The longitudinal external walls to the north and south are non-loadbearing frame constructions with upright masonite studs: between the studs the wall contains mineral wool. The internal lining is plasterboard underlain by vapour barrier, and the outside is clad with rendering and horizontal wall panels on vertical battens. The gable walls are loadbearing. On the ground floor, the loadbearing part comprises concrete, and on the first floor a framework with mineral wool and vapour barrier and plasterboard on the inside.

All the transverse partitions on the ground floor are of concrete, and between flats of concrete plus mineral wool between studs, with an external lining of plasterboard. On the first floor, all the load-bearing walls are framed structures clad with plasterboard.

The heating system comprises direct acting electric radiators in each room. The radiators incorporate radiator thermostats.

The living areas are provided with a mechanical inlet and extract system. The ventilation system is supplemented by a heat recovery installation where energy from the extract air is transferred to the inlet air. Recovery of heat takes place in a plate heat exchanger.

The verandas have a loadbearing frame of zinc coated rectangular hollow sections. The walls and roofs consist of 4 mm single panes mounted in aluminium profiles, with external cover strips of plastics. The panes are mounted overlapped as in conventional greenhouses. The floors of the upper verandas are 135 mm concrete, and those on the ground floor footway slabs laid on sand.

Climatic regulation of the verandas comprises openable vents and sunblinds. The vents are placed in the roofs, above the door to the balcony or patio, and in the southerly facade of the veranda both in the glazed portion and in the breast wall directly above the floor. The roof vents are operated by a chain which, through a sprocket, moves the bars on the vents. The blinds can screen the inclined glazed roof and the glazed portions of the southerly facade. The blinds which are of unbleached cotton are operated by lines.

Table 5.1 Data for one building with eight flats (Fredlund, 1995).

characteristic dimensions		U values (W/m²°C)		design temperatures
length, m:	47	veranda glazing	5.90	veranda free floating
width, m:	8	walls towards		flats 20°C
height, m:	7	veranda	0.21	
living area, m^2	765	windows towards		
living volume, m^3	1 890	veranda	1.60	
		exterior walls	0.16/0.21	
		exterior windows	1.60/1.70	

5.3.2 Results

Measurements show that the temperature in the verandas is highly influenced by the outside climate. The value of the factor G, which is the relationship between the specific losses and gains for the glazed space (see Section 4.2), is approx. 16 for the glazed verandas. This means that the temperature during nights and the darker part of the year will be very near the outside temperature. The relationship between the veranda temperature and the outside temperature is shown in Figure 5.9 (Fredlund, 1989). The bottom line shows the relationship if the veranda temperature is equal to the outside temperature. The line above represents a steady-state calculation based on the factor G (see Equation 4.2). This relation represents the lowest temperature to be expected in the veranda under the given outside temperature. Solar gains are then omitted. The top line represents the measured monthly mean temperature in a two-storey veranda. The temperature is the mean value of the measured top and bottom veranda temperature.

Far from all solar radiation is transmitted into the veranda and into the flat behind. The woodland provides horizontal screening about 10° above the horizon, see Figure 5.10. Isolated trees and the veranda construction also cast shadows. Field measurements show that only a small part of the incident solar radiation is transmitted into the living room behind the glazed veranda, see Figure 5.11 (Fredlund, 1989). Isolated trees, the veranda construction and the quadruple glazed windows between the room and the veranda reduce the transmitted radiation into the room to about 20% of the veranda incident radiation.

According to Lundgren (1989) the normalised annual electric energy use showed very large differences between dwellings of the same type. The definition of the normalisation of the energy use is that the flats are inhabited throughout the year and that climatic variations are neutralised. The largest flats on two storeys had then an energy use between 6 700 and 18 000 kWh/year. The flats with 2½ rooms and kitchen had a variation between 7 700 and 12 300 kWh/year while the smallest flats showed a variation between 6 400 and 9 300 kWh/year. Differences in internal temperature during the heating season together with the yearly water consumption could explain half the variation.

The energy use for space heating was approx. 60 kWh/m² annually, mainly due to a high standard of insulation (Fredlund, 1989). The energy contribution from the veranda is limited to reduction of fabric losses from the flat owing to the higher temperature in the veranda than outside. This contribution was calculated as 4 kWh/m² annually. As the veranda reduces insolation into the flat, the net contribution was in fact not more than 2 kWh/m² which corresponds to an approximate energy saving of 3% of the heating requirement (Fredlund, 1989).

The interviews with the inhabitants showed that the housing estate was well appreciated and the verandas were frequently used (Lundgren, 1989).

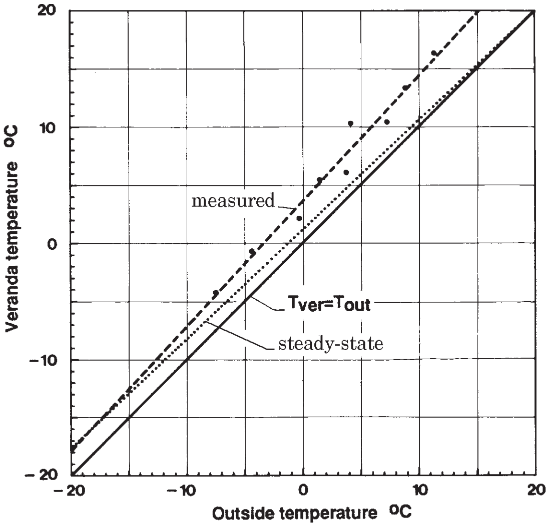


Figure 5.9 *Relationship between veranda temperature and outside temperature (Fredlund, 1989).*

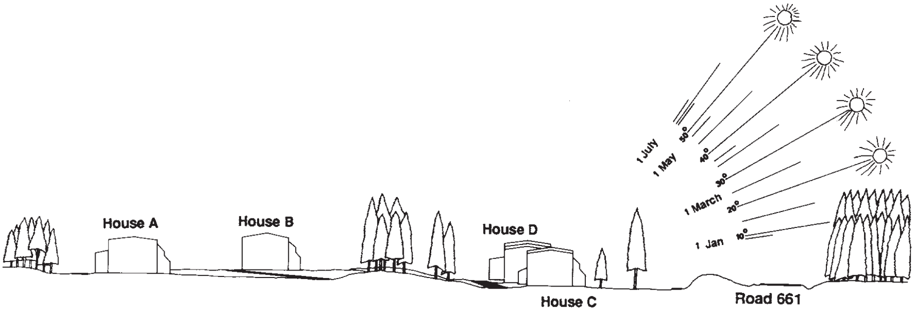


Figure 5.10 *Section through the housing estate at Taberg (Fredlund, 1989).*

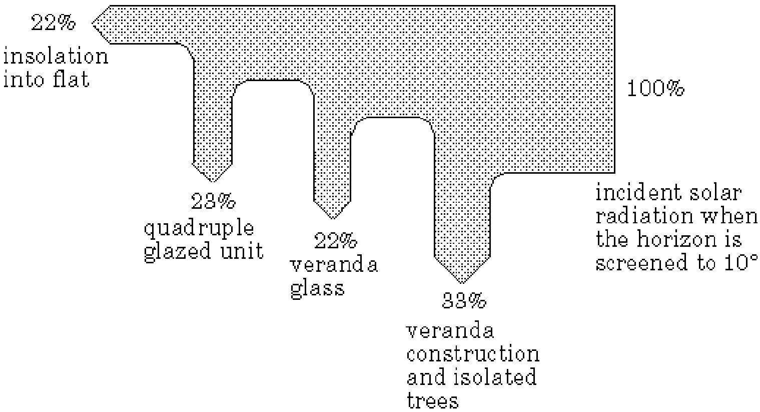


Figure 5.11 *Breakdown of incident solar radiation with respect to screening effect and reflection by different building components (Fredlund, 1989).*

5.4 Glazed balconies – Sätuna

Figure 5.12 Flats for the elderly at Sätuna (Wall, 1994a).

Latitude:	59.5°N
Function, glazed space:	balcony, extra room
Floor area, glazed space:	12 m^2
Function, adjacent buildings:	flats for the elderly
Occupancy year:	1990

5.4.1 Description

At Sätuna outside Stockholm an estate comprising flats for the elderly has been built. The estate which was ready for occupation in the autumn of 1990 had been designed by Hidemark and Danielsson Arkitektkontor. It consists of service flats and communal premises. A glazed balcony of ca 12 m^2 is attached to each flat; see Figure 5.12. Along the bottom surface of the outside wall of the glazed balconies there are solar collectors.

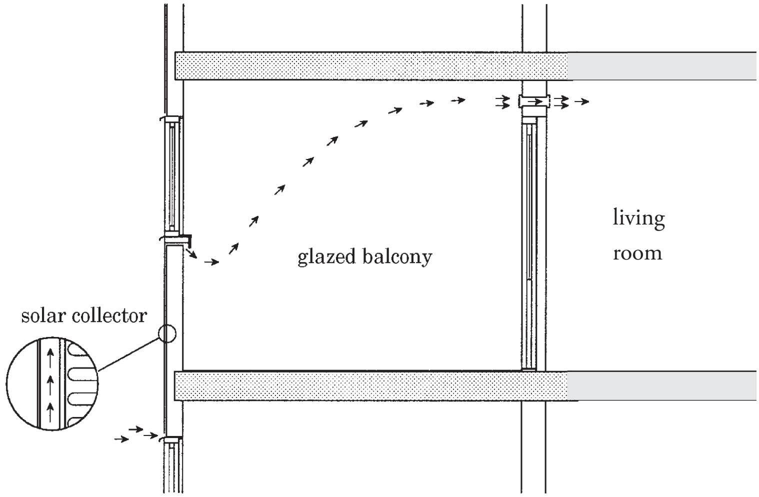


Figure 5.13 Preheating of supply air via solar collectors and glazed balconies.

Ventilation in the flats consists of an extract system. The supply air is preheated by passing outside air through the solar collectors, the glazed balcony and into the flat via ventilation terminals in the wall between the glazed balcony and the living room; see Figure 5.13. Supply air is drawn in through the negative pressure created in the flat by the extract system. Some of the supply air is however admitted into the flat via FAREX outside air terminals behind radiators along the external walls. The glazed balconies have double glazed windows while the flats have triple glazed windows even in the wall facing the glazed balcony.

Already during the preliminary design stage calculations were made with the DEROB-LTH program to gain an idea of the temperature in the glazed balcony and preheating of the supply air to the flat. A flat of three rooms plus kitchen with a glazed balcony and solar collectors towards the south was studied. The glazed balcony is counted as a room.

The solar collector consists of two sheets of polycarbonate with a black surface behind these. Behind the solar collector on the wall of the glazed balcony there is 95 mm mineral wool. Between the transparent plastics sheets and the black surface there is an air gap through which the outside air is drawn and preheated before it passes into the glazed balcony. The area of the solar collector in this case was 5.6 m^2.

Calculations were made using climatic data from Stockholm, reference year 1971. The air flow rate through the solar collector and glazed balcony and into the flat was assumed to be 86 m^3/h. On the basis of this air flow rate, preheating of the supply air was calculated to be equivalent to 1 098 kWh during January-

April and October-December. The calculations were based on perfect conditions, and it was considered important that attention should be paid to the following points during the final design:

- It was assumed in the calculations that the supply air to the flat really passed through the solar collector and the glazed balcony and not through leakage paths.
- It was assumed that the flat needed heating during the entire calculation period, i.e. October-April.
- It was likely that the occupants would remove the very high estimated maximum temperatures in the glazed balcony by ventilation.
- The calculations showed that the temperature in the glazed balcony will at times become very low in the winter, which means that the way air is supplied to the flat is important.
- The calculations assumed a free horizon, i.e. that no shadow would be cast on the solar collector and glazed balcony by any surrounding building or natural feature. If the solar collector or glazed balcony is shaded at times, this reduces solar utilisation.

The calculations at the preliminary design stage thus referred to *maximum utilisation* of the solar collector and glazed balcony.

The buildings were constructed and occupied in the autumn of 1990. The Swedish Council for Building Research financed an evaluation of both energy issues and climate and a study of how the occupants like their flat and the glazed balcony (Sundbom, Nilson & Blomsterberg, 1996).

The Swedish National Testing and Research Institute [SP] performed measurements of the outside climate, temperatures in the solar collectors, glazed balconies and flats. The flats were also subjected to airtightness tests which form the basis for the calculations which were subsequently made. Åke Blomsterberg, SP, made calculations with the air flow program MOVECOMP (Bring & Herrlin, 1988) in order that an assessment may be made of the distribution and magnitude of the air flows between solar collector, glazed balcony and flat. These calculation results together with the measured outside climate were then used as the basis of new computer calculations with the energy balance program DEROB-LTH at the Department of Building Science. This study in its entirety is described in Wall (1994a). The temperatures in the solar collector and glazed balcony calculated by DEROB-LTH were then compared with the measurements to see whether the calculations were reasonable. Calculations were in addition made for a whole year using the climate for Stockholm in 1971, both with “real” air flow rates and with a modified design. The function of the solar collector and glazed balcony as preheaters for the supply air were studied.

Measurements were made in a type of flat different from the one studied at the preliminary design stage. The new calculations were therefore made for the flat where measurements had been made in order that measurements and calculations may be compared. The measurements were made in a flat of 4 rooms plus kitchen (inclusive of glazed balcony), of 104 m² area; see Figure 5.14. The glazed balcony is oriented 13° east of south. The glazed balcony has a 5.3 m² solar collector towards the south and one of 2.8 m² towards the west.

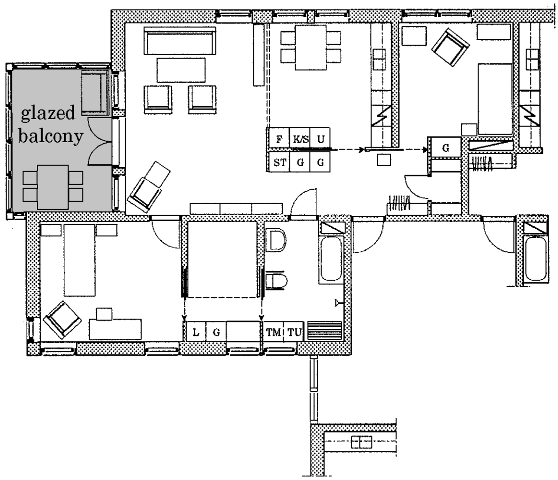


Figure 5.14 Plan of the studied flat (Wall, 1994a).

5.4.2 Results

Use of the solar collector and the glazed balcony for preheating the supply air may pose problems during the winter, since the air will not be preheated at all over long periods. Unsuitable siting of the supply air terminal can easily give rise to cold downdraughts and unpleasant draughts in the flat, especially since the supply air is mainly admitted at only one point in the flat.

In the summer and in actual fact already in the spring the air is heated to a very high temperature by the solar collector. Already in the middle of a spring day, the air which enters the glazed balcony from the solar collector may have a temperature of 50°C. Unfortunately, the solar collector cannot be disconnected and ventilated to the outside, which means that occupants are forced to have very warm air entering the glazed balcony and the flat during the summer. Nor can the supply air terminal between the glazed balcony and the flat be closed easily. And who wants preheated supply air in the summer?

The energy saving owing to the presence of the solar collector and the glazed balcony as preheaters of the supply air is equivalent to ca 7% of the heating requirement of the flat. Of the total energy saving, the proportion due to the solar collector accounts for only ca 20%. The rest of the saving is due to the glazed balcony. Use of the solar collectors is thus not justified, nor can the energy saving defray the cost of building a glazed balcony. The justification for this type of glazed balcony is that it makes the flat larger and more pleasant during the spring, summer and autumn. Energy saving is of subordinate importance.

5.5 Glazed courtyard – Tärnan

Figure 5.15 The glazed courtyard at Tärnan.

Latitude:	55.9°N
Function, glazed space:	communication, meeting place
Floor area, glazed space:	200 m^2
Function, adjacent buildings:	residential
Occupancy year:	1983

5.5.1 Description

The block Tärnan is situated in Landskrona and is surrounded by residential development. It was built in 1983. Landskrona is on the coast about 45 km north of Malmö in the south of Sweden. Tärnan consists of two detached single family houses and seven terrace houses. The terrace houses are in two rows with a glazed courtyard of about 200 m² between them. See Figure 5.15 - 5.17. Together, they form a tenant-owner association. The terrace houses are on 2½ storeys with a floor space of 123 m² and contain 5 rooms plus kitchen, see Figure 5.18. In the vicinity of the dwellings there is a communal refuse storage room/store and a building which houses the heat pumps.

The Department of Building Science carried out a study which comprised both field measurements and calculations. This study is described in Wall (1992a).

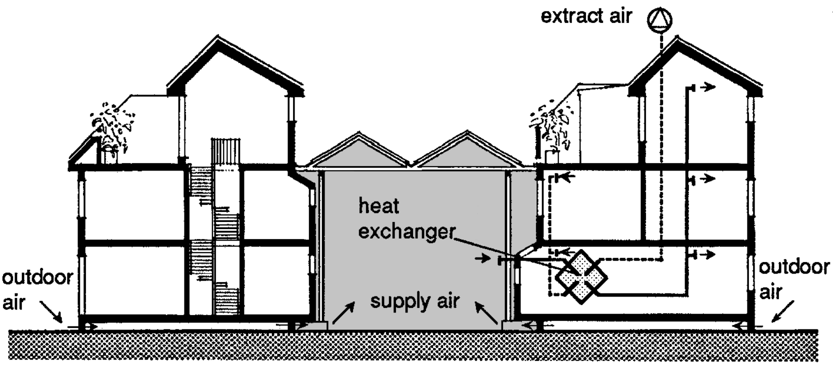


Figure 5.16 Section, Tärnan (Wall, 1992a).

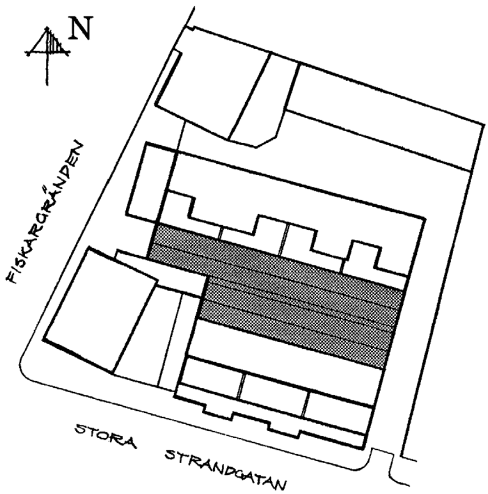


Figure 5.17 Layout plan, Tärnan (Wall, 1992a).

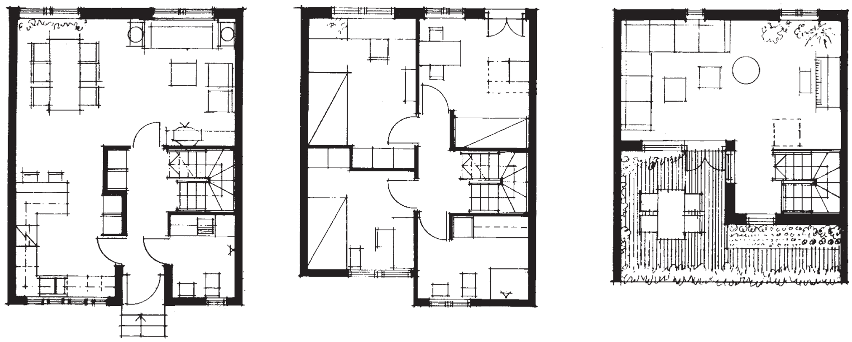


Figure 5.18 *Plan of terrace house. The second floor is above the glazed courtyard (Broberg & Thulin, 1987).*

Tärnan has been developed by the Foundation for Industrial and Ecological Construction/Landskrona Group, and the architects responsible for the research were Peter Broberg and Arne Winquist. Ann Thulin was responsible for the research carried out by the Landskrona Group. The Swedish Council for Building Research gave an experimental loan for the construction project. The principal aim of the foundation was to study the technical linkage between dwellings with a glazed courtyard and to study the design of an energy system based on the specific ground conditions in the area (Broberg & Thulin, 1987).

The loadbearing walls of the buildings consist of prefabricated concrete units with cast-in timber studs. Between the studs the wall units contain mineral wool which is covered by a plastics foil and gypsum plasterboard.

The facades towards the external air consist mainly of painted concrete units with internal mineral wool insulation and gypsum plasterboard. Towards the courtyard the walls are clad with minerite fibre cement slabs, with mineral wool and gypsum plasterboard on the inside. The U value of the walls towards the courtyard is 0.27 W/m^2°C (145 mm mineral wool) and the windows are reduced to double glazing. Towards the external air the windows are triple glazed, and the walls towards the external air, which have extra insulation, have a U value of 0.22 W/m^2°C (45+145 mm mineral wool). See Table 5.2.

The floors consist of prefabricated concrete units with cast-in studs, with the concrete on the bottom. The ground floor slab has 195 mm mineral wool, and the intermediate floor 50 mm.

On the top storey the rooms have no ceilings. The roof has concrete tiles on the outside, and between the rafters there is 295 mm mineral wool with spaced boarding, and gypsum plasterboard on the inside.

Table 5.2 Building data, Tärnan.

characteristic dimensions		U values (W/m²°C)		design temperatures
length, m:	26	atrium glazing	5.9	atrium free floating (>0°C)
width, m:	8	walls		apartments 20°C
height, m:	6	towards atrium	0.27	
volume, m³		windows		
- atrium	1 200	towards atrium	2.9	
- buildings	2 100	exterior walls	0.22	
		exterior windows	1.9	

The heating system is based on three heat pumps which extract heat from the groundwater. Two of these are used only for the radiator system while the third supplies energy to both the water heater and the radiator system.

The groundwater is brought up from an 80 m deep well. At this level the temperature of the water is 10°C throughout the year. Heat is first extracted from the water with the heat pump which is coupled to the water heater, and the water is then passed to the other two heat pumps which are coupled to the space heating system. This reduces the temperature of the groundwater to approx. 4-5°C. The cooled groundwater is returned to another well of the same depth about 40 m away. Studies of the groundwater system have been made by Gedda and Ejdeling (1982) and by Gedda, Bennet, Claesson and Holm (1989).

Each dwelling has its own supply and extract ventilation system with a heat exchanger. See Figure 5.16. The supply air for the dwellings is taken from the glazed courtyard. The extract air passes through the heat exchanger and is discharged directly. Replacement air for the courtyard is designed to be taken in through small grilles on the outside of the foundations and to pass below the buildings which have a crawling space of about 30 cm below the ground floor. In this way the air would be heated to some extent before it enters the courtyard.

The framework of the glazed roof is of steel, and the glazing consists of 4 mm toughened single panes. The floor in the courtyard is paved with concrete slabs.

Vents are provided in both the roof and the gables. About 25% of the roof surface can be opened. In the roof there are horizontal curtains of acrylic fabric which are used both as insulation and for solar control.

The vents and curtains are controlled automatically by means of a special control equipment made by Dansk Gartneri Teknik (DGT) Sweden AB. This system has long been used in greenhouses. The control equipment is connected to temperature sensors and a smoke detector in the courtyard, and to humidity (rain), light and wind sensors outside.

When the temperature in the courtyard reaches a certain preset value, the vents are opened. If it begins to rain, the vents are half shut, and if there is strong wind, they are shut so that they have 10% opening area. The vents on the leeward side are opened first. These vents are opened to a larger angle than those on the windward side. The side which is to the leeward is determined by measurement, but it can also be set on the controls manually.

When the temperature in the courtyard reaches a certain (high) level, the curtains are drawn across in one layer, see Figure 5.19. A gap is left in the middle so that warm air can easily rise and leave through the open vents. The curtains are also controlled by a light meter.

At night when it is dark and cold, the curtains are drawn across in two layers to provide insulation, see Figure 5.19. The curtains can also be used as insulation in daytime when it is very cold outside. If the curtains were drawn during the night, they are opened in stages in the morning so that the cold downdraught should not be too strong for the plants. On the whole, the control of the vents and curtains can to a large extent be tailormade for each project.

In principle, the courtyard is unheated. However, in order that the plants should survive, two 9 kW building dryers have been used to prevent the temperature dropping below freezing.

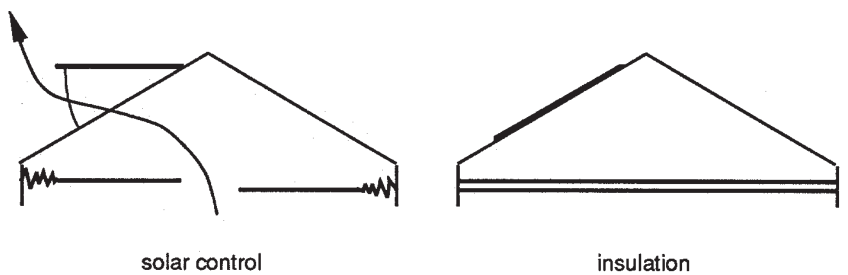


Figure 5.19 Use of the curtains as solar control and as insulation (Wall, 1992a).

5.5.2 Results

The field measurements at Tärnan, carried out at the Department of Building Science, continued for several years. A complete description of the study, also comprising calculations, is found in Wall (1992a).

In Figure 5.20, the temperature in the courtyard is plotted as a function of outside temperature. The plots represent hourly values measured at Tärnan during 1987. Both summer and winter were colder than during the normal year.

The annual mean temperature in 1987 was 5.7°C as against 7.1°C in the normal year. The temperature is measured in the courtyard at a height of 1.4 m. The line represents the theoretically lowest temperature in the atrium at different outside temperatures. This applies under steady-state conditions, i.e. at constant temperatures and without any insolation. The factor *G* is 7.8 which means that the specific losses of the glazed space are 7.8 times higher than the specific gains from adjacent buildings, under steady-state conditions (see Section 4.2). The actual temperature in the courtyard can vary considerably, but the lowest temperature at a certain outside temperature is very near the steady-state line. When the outside temperature is below freezing, the measurements deviate from the line. The reason for this is that building dryers have been placed in the courtyard in order to maintain the temperature above freezing so that the plants can survive.

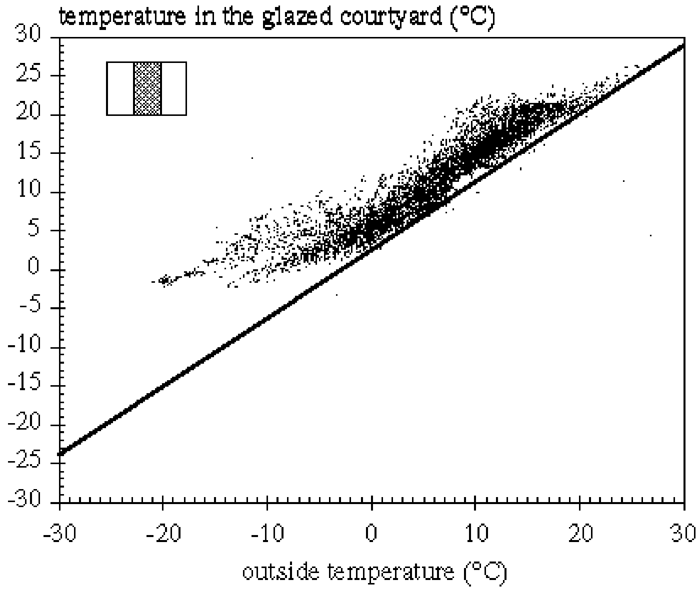


Figure 5.20 *Temperature in the courtyard at Tärnan measured at a height of 1.4 m during 1987 as a function of outside temperature. The plots represent measured hourly values. The line represents the calculated lowest temperature in the courtyard under passive climatic control conditions, without solar radiation (Wall, 1992a).*

The air change rate in the atrium with the vents closed was measured as approx. 0.6 ach during a day in May. A fan pressurisation test showed that at an overpressure at 50 Pa inside the atrium, the leakage flow was equal to 8.8 ach.

The effect of the glazed courtyard on energy requirement in the surrounding buildings can be calculated as a reduction of the fabric and ventilation losses from the buildings surrounding the glazed courtyard. Since, generally speaking, the temperature in the courtyard during the heating season is higher than the outside temperature, the fabric losses from the surfaces abutting onto the courtyard decrease. In addition, the supply air temperature is higher in the 7 terrace houses which take their supply air from the courtyard.

From October to April, the temperature in the glazed courtyard is, on average, about 3-5°C higher than the outside temperature when the glazed space is not heated. The temperature difference varies depending on climatic variations in different years.

The reduction of fabric and ventilation losses due to the atrium is approx. 8 000 kWh compared with the same buildings without the atrium. A more correct assessment is obtained if the actual construction towards the courtyard is supposed to be the same as the facade construction of the buildings towards the outside, i.e. triple glazed windows and thicker insulation when there is no glazed space. On the basis of these assumptions the energy saving due to the atrium is approx. 5 000 kWh which corresponds to approx. 7% of the energy required for heating the buildings.

5.6 Glazed street – Gårdsåkra

Figure 5.21 The block Gårdsåkra with the glazed street.

Latitude:	55.8°N
Function, glazed space:	communication, meeting place
Floor area, glazed space:	5 000 m²
Function, adjacent buildings:	residential, schools
Occupancy year:	1983

5.6.1 Description

The block Gårdsåkra at Eslöv was built in 1983. It comprises a 375 m long glazed street with buildings along the long sides; see Figures 5.21-5.23. These buildings contain 126 flats and schools. The flats on the second storey are reached via access balconies which face the glazed street. The width of the street varies between 11 and 22 m. In actual fact, the block Tärnan was intended to be a preliminary study for the much larger block Gårdsåkra, but owing to delays the two projects were completed at about the same time.

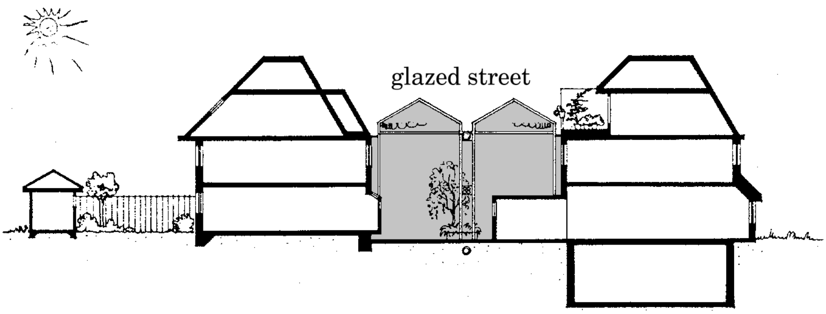


Figure 5.22 *Section of the glazed street with surrounding residential buildings, Gårdsåkra. (Lange, 1986).*

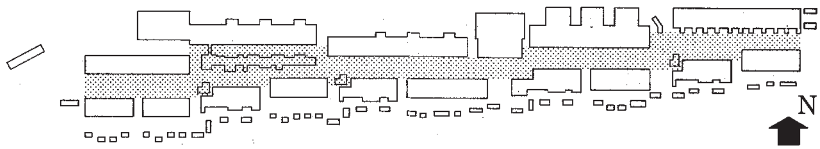


Figure 5.23 *Layout plan, Gårdsåkra. (Lange, 1986).*

Gårdsåkra has great constructional similarities to Tärnan and has also been designed by the Landskrona Group. In this case also, the insulation of the walls facing the glazed street was reduced, and they had double glazed windows instead of the triple glazed ones in the facades facing the external air.

The glazed street is of east-west orientation and is surrounded by buildings on 2½ storeys, two of which are below the level of the glazed roof. The roof is of 6 mm toughened single glazing in aluminium profiles carried on a steel frame.

In order to reduce the temperature in the glazed street during the summer, automatically controlled vents and solar control curtains are used. The curtains were installed during the first summer that the buildings were occupied, since it was found that the temperature in the glazed street was too high, especially on the access balconies. In order to reduce the fabric losses from the street in the winter, the curtains are drawn overnight.

In the winter the glazed street is heated to a minimum temperature of 5°C. Sixteen electric air heaters totalling 160 kW, spread out along the street, are used for this. In addition, preheated supply air is blown into the street; this is equivalent to ca 300 kW. This was however not enough to meet the temperature requirement, and waterborne air heaters of 210 kW were also installed as a supplement. The return pipe from the radiator system was used for these.

The heating system of the buildings is based on large heat pumps which take heat partly from the municipal sewers and partly from the air extracted from the flats and schools at Gårdsåkra. There are also two oil fired boilers which are used to cover peak loading. The pipes for the radiator system and also the hot water pipes are laid exposed along the glazed street.

The ventilation system for the glazed street and the surrounding buildings is combined. Air is blown into the street centrally. In the winter the supply air is preheated. The surrounding buildings have a supply and extract system with a heat exchanger. Heat from the air extracted from the buildings is transferred to the supply air which is taken from the glazed street. Each flat and school has separate heat exchanger units. Further heat is extracted from the exhaust air from the buildings in a central heat pump.

The original building design and the design of the heating and building services system were not sufficient to maintain a minimum temperature of 5°C in the glazed street. The energy needed to heat the street was also very high. The operational experiences etc from Gårdsåkra are described in Lange (1986). The measurement results formed the basis for an energy evaluation which resulted in a redesign of the installation; this was completed in April 1986. The aim of the measures taken was to try and reduce the fabric and ventilation losses of the glazed street. Reduction of fabric losses was to be achieved by additional insulation of unglazed components in contact with the external air, such as gutters, and improvement of the airtightness of the insulation curtains. Reduction of ventilation losses was to be achieved by increasing the airtightness of the glazed roof, reducing the flow of supply air into the glazed street, and reducing the mechanical extract air flow from the glazed street so as to make it equal to the supply air flow into the surrounding buildings.

5.6.2 Results

At Gårdsåkra, measurements of limited scope were made hour by hour in the glazed street and outside of temperatures and solar radiation. Measurements of the temperature in the glazed street at a height of 3 m, as a function of the outside temperature, are plotted in Figure 5.24. The figure is based on hourly values during 1985, i.e. before redesign of the installation. During the exceptionally cold winter, it was not possible to maintain 5°C in the street. Even temperatures below freezing occurred, and a number of plants were damaged. Owing to the design of Gårdsåkra, the relationship between specific losses and gains in the glazed street was unfavourable (factor $G = 8$); see also Section 4.2. Heating of the glazed street therefore requires large amounts of energy since the street has very large single glazed surfaces.

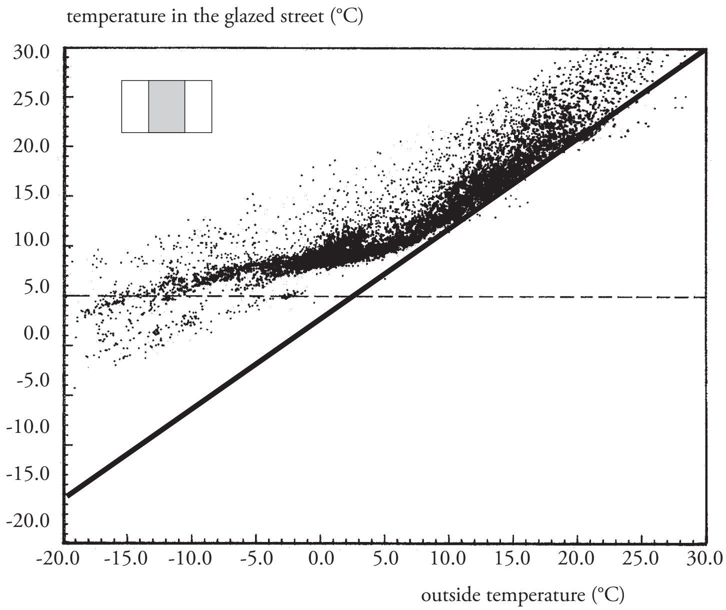


Figure 5.24 *Temperature in the glazed street at Gårdsåkra measured at a height of 3.0 m during 1985 as a function of outside temperature. The plots represent measured hourly values. The line represents the calculated lowest temperature in the glazed street under passive climatic control conditions, without solar radiation (Wall, 1993).*

Measurements were continued after redesign when fabric and ventilation losses had been reduced. Measurements of the temperature in the glazed street as a function of the outside temperature in 1987, i.e. after the redesign, are plotted in Figure 5.25. The scatter in the measurements is larger than in 1985, but the temperature in winter is a little higher. For a few hours the temperature drops below 5°C, but never below freezing.

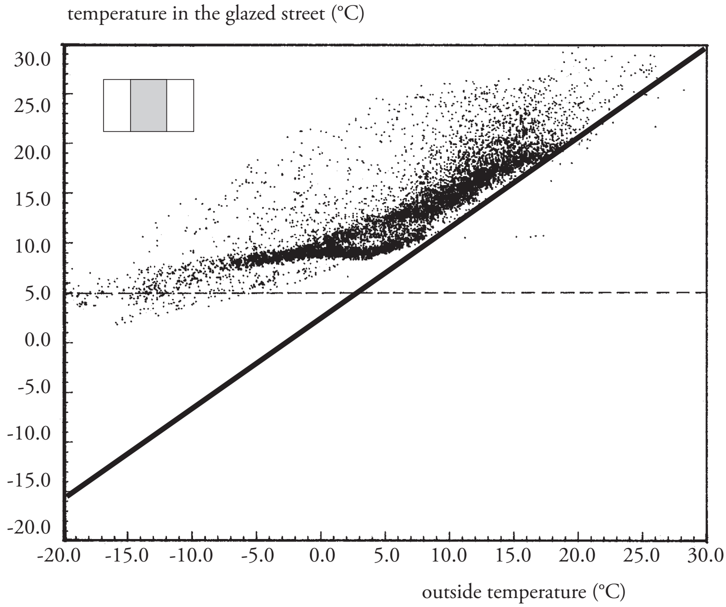


Figure 5.25 *Temperature in the glazed street at Gårdsåkra measured at a height of 3.0 m during 1987 as a function of outside temperature. The plots represent measured hourly values. The line represents the calculated lowest temperature in the glazed street under passive climatic control conditions with the original design, without solar radiation (Wall, 1993).*

5.7 Glazed courtyard – Piggvaren

Figure 5.26 The block Piggvaren.

Latitude:	55.6°N
Function, glazed space:	communication
Floor area, glazed space:	240 m²
Function, adjacent buildings:	residential
Occupancy year:	1986

5.7.1 Description

The block Piggvaren in Malmö consists of a U shaped building on 3½ storeys with a glazed courtyard; see Figures 5.26 and 5.27. The glazed courtyard of 240 m² area is surrounded by 28 flats. The courtyard acts as a stairwell, and the flats are reached via access balconies and a lift in the courtyard. Below the courtyard there is a garage for the occupants.

Piggvaren was built in 1986 in conjunction with a housing fair in Malmö. It was subsequently evaluated at the Department of Building Science (Blomsterberg, 1993). These studies comprised extensive hourly measurements of the outside climate, the climate in the glazed courtyard, and the energy system of the building. Measurements of the airtightness of the courtyard and some flats were also made.

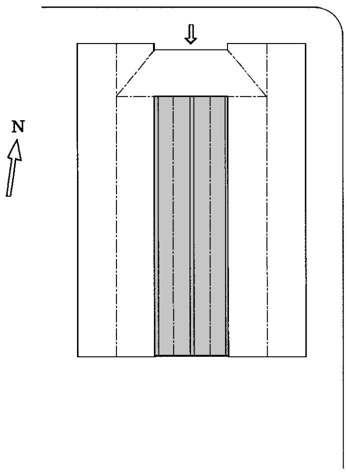


Figure 5.27 Layout plan, Piggvaren (Blomsterberg, 1993).

At the preliminary design stage a target was defined regarding energy management and the temperature level in the glazed courtyard. According to this target, the building as a whole, inclusive of the glazed courtyard, was to have the same heat losses as a similar building without a glazed courtyard constructed in accordance with the Swedish Building Code SBN 80 in force at the time. The idea was that the facades towards the courtyard, together with the courtyard, would act as a well insulated external wall, and at the same time the glazed courtyard would act as a solar collector. The facades towards the courtyard therefore have higher U values than the facades towards the external air. The building was designed so that the specific losses and gains in the courtyard would be equal under steady state conditions and without the influence of solar radiation. This meant that the value of the factor *G* was 1. (See Section 4.2).

The building has a concrete loadbearing frame and lightweight curtain walls. Exterior walls in contact with the external air, as well as the attic floor and the ground floor slab, comply with the requirements in SBN 80. The facades towards the glazed courtyard also meet the insulation requirements, provided that the courtyard is counted as additional insulation (Blomsterberg, 1993). U values for some elements of construction are set out in Table 5.3.

The glazed courtyard has double glazed sealed units in the southern facade and toughened single glazing in the roof. At the preliminary design stage it was assumed that curtains which could be drawn in a double layer as overnight insulation would be installed horizontally below the glazed roof. When these curtains were drawn, the insulation capacity of the single glazed roof in combination with the curtain would be equivalent to that of a double glazed construction. This type of curtain was not installed however; the curtains which were installed were the type that can be drawn in only one layer.

In addition, the control system for the curtains was to draw them during the dark part of the 24 hour period, but this did not work. In the summer the curtains are drawn automatically when solar radiation exceeds 700 W/m². Furthermore, vents in the glazed roof are opened automatically when the temperature in the courtyard rises above 25°C.

Table 5.3 Building data, Piggvaren.

characteristic dimensions		U values (W/m²°C)		design temperatures
length, m:	22	atrium glazing		atrium free floating
		- roof	5.9	
width, m:	8	- wall	3.0	apartments 20°C
		walls		
height, m:	10	towards atrium	0.47-0.66	
volume, m³		windows		
- atrium	2 400	towards atrium	2.3	
- buildings	4 900	exterior walls	0.15	
		exterior windows	1.6	

The flats are heated by a district heating plant via a waterborne radiator system. The flow temperature to the radiators is controlled by temperature sensors both outdoors and in the glazed courtyard. The radiator system is separate and is designed so that the rooms facing the glazed courtyard are controlled by the temperature sensor in the courtyard. Unfortunately, the temperature in the glazed courtyard also controls the radiators in the rooms which face the courtyard but are above the level of the glazed roof.

The glazed courtyard and the surrounding building have a combined ventilation system comprising mechanical supply and extract air with a heat exchanger; see Figure 5.28. Air extracted from the flats is blown into the basement garage and is then passed through a heat exchanger. Heat from the extract air is transferred to the outside air which is thus heated before entering the glazed courtyard. Through ducts in the intermediate floor slabs, air from the courtyard is drawn into the flats. Air enters via terminals placed behind the radiators in the bedrooms and living room on the outside.

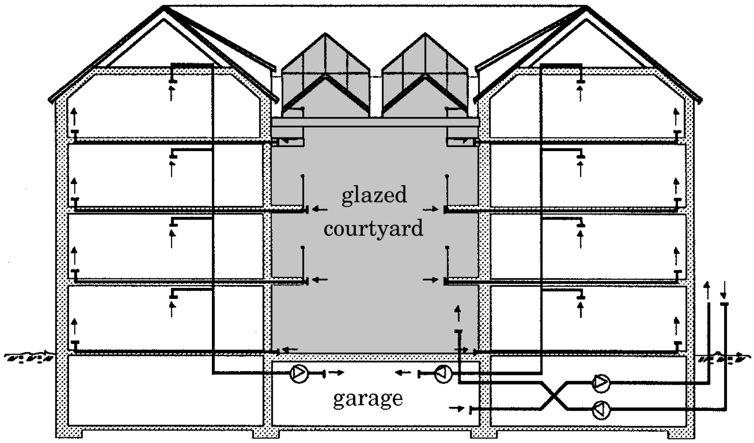


Figure 5.28 Section showing the ventilation system, Piggvaren (Blomsterberg, 1993).

5.7.2 Results

In the glazed courtyard the temperature was automatically measured every hour at different levels. The mean value of the temperature in the glazed courtyard at four levels, as a function of the outside temperature, is plotted in Figure 5.29. The plots represent the hourly values in 1988. The line represents the mean value of the outside temperature and the temperature of the surrounding buildings (factor *G* = 1), i.e. the least temperature which the courtyard should have according to the target set up at the preliminary design stage. For about 100 days in the year, this target was not reached. Blomsterberg (1993) considered one of the reasons to be that double insulation curtains had not been installed underneath the glazed roof. The single, and pervious, curtains which were installed were to be automatically drawn during the dark part of the day. But this control did not work, and this also gave rise to higher losses through the glazed roof.

Airtightness tests also showed that the roof was very leaky. At an overpressure of 50 Pa in the courtyard, air leakage was 14 ach which was equivalent to 64 m^3/m^2h counted over the area of the glazed roof and glazed gable. The glazed roof had large longitudinal gaps along the line of contact with the surrounding buildings.

The energy needed to heat the flats was higher than intended. For the six winter months in 1988 the measured radiator heat was 57 kWh/m^2 as against the design requirement of 48 kWh/m^2, which means that the actual heating requirement was ca 19% higher than the design figure (Blomsterberg, 1993).

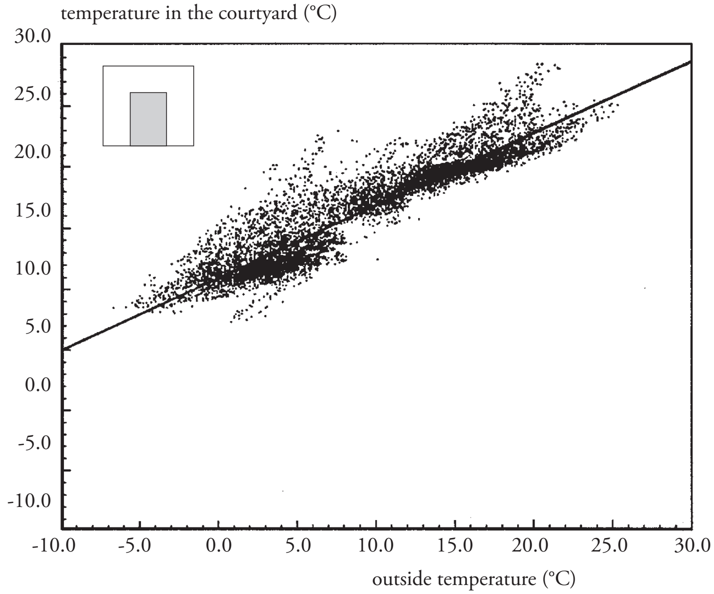


Figure 5.29 *Mean temperature in the glazed courtyard at Piggvaren during 1988 as a function of outside temperature. The plots represent measured hourly values. The line represents the calculated lowest temperature in the courtyard under passive climatic control conditions, without solar radiation, as decided during the design stage (Blomsterberg, 1993).*

5.8 Atrium – Kabi Pharmacia

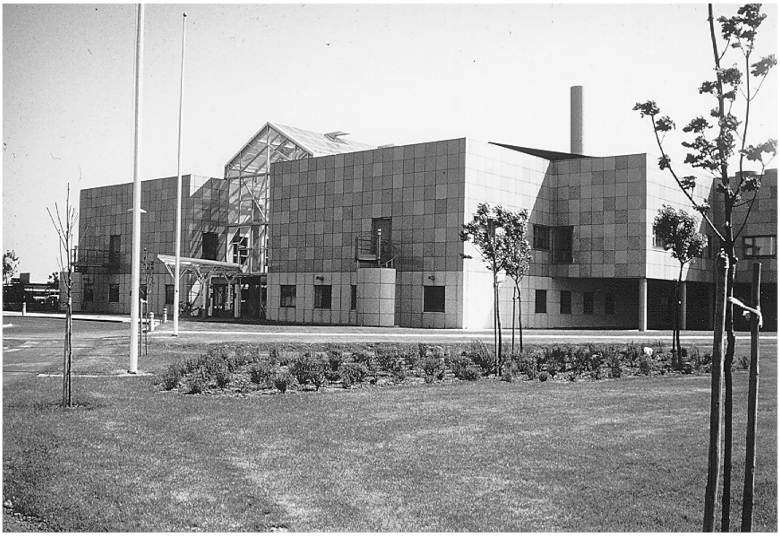


Figure 5.30 The laboratory of Kabi Pharmacia at the science park Ideon Lund (Wall & Blomsterberg, 1994).

Latitude:	55.7°N
Function, atrium:	communication,reception, lunchroom, cafeteria
Floor area, atrium:	700 m²
Function, adjacent buildings:	offices, research laboratories
Occupancy year:	1991

5.8.1 Description

The cancer research laboratory of Kabi Pharmacia is situated at the science park Ideon Lund. It was completed in the spring of 1991. It comprises a central atrium in the shape of a cross. At three of the corners there are buildings, and the fourth corner is prepared for a further building which now (1996) is under construction. See Figure 5.31. The surrounding buildings each have three storeys; the top storey only houses building services.

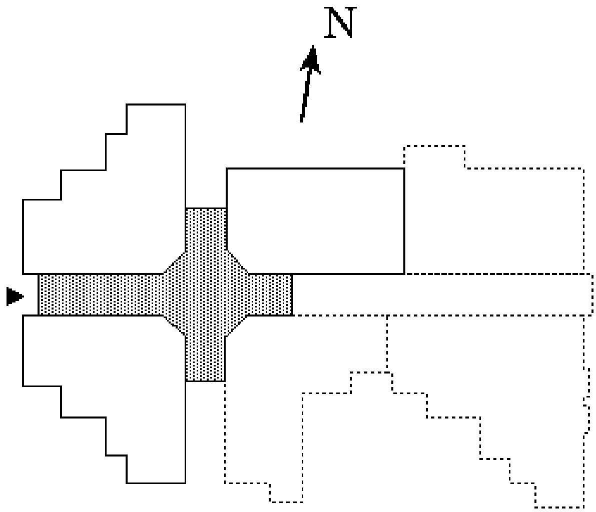


Figure 5.31 Plan of the Kabi Pharmacia laboratory (Wall & Blomsterberg, 1994).

At the main entrance to the atrium there is a reception desk staffed by one person who greets visitors etc. There is also a cafeteria and a lunch room in the atrium, and communication between the buildings also takes place through the atrium, which is therefore an important centre for the activity in the laboratory.

The width of the atrium is about 9 m, and its height to the eaves is 11 m. The volume of the atrium is approx. 8 900 m^3, and the glazed surface towards the outside is approx. 1 580 m^2, 1 150 m^2 of which is the roof. The total facade area of the three buildings towards the atrium is approx. 870 m^2, and at the corner of the atrium where the fourth building will be constructed there are walls of approx. 220 m^2.

The roof of the atrium is double glazed, with 6 mm toughened Kappa Antisun Green on the outside and 6 mm laminated Float Clear Glass on the inside. Its U value is 2.8 $W/m^2°C$. The facades are triple glazed and have a U value of 1.9 $W/m^2°C$. The outermost pane is 6 mm toughened Kappa Antisun Green, and the two inner panes are laminated 6 mm Float Clear Glass. This solar control glass has high absorptance, and primary energy transmission on perpendicular incidence is therefore only 36% for the glazed roof and 28% for the glazed facades. The profile system has been supplied by Viktoria System A/S, Denmark.

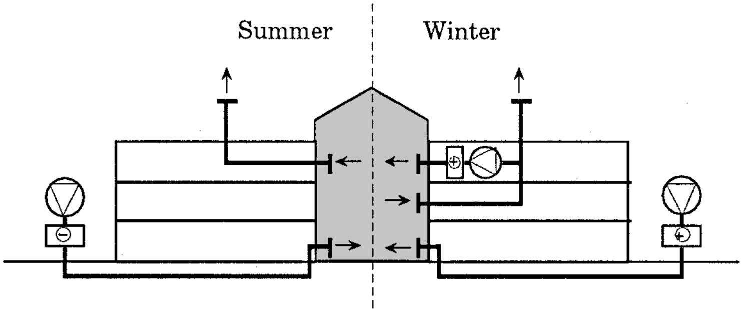


Figure 5.32 Schematic section through Kabi Pharmacia (Wall & Blomsterberg, 1994).

The temperature requirement in the atrium is 20-25°C which is attained by heating in the winter and cooling in the summer. In the winter air is extracted at the level of the middle storey, and some of the extracted air is recirculated as heated return air through terminals at the glazed roof to prevent condensation. Some of the extracted air is also returned near the glazed end walls to counteract cold downdraughts. Preheated supply air enters at the bottom storey, see Figure 5.32. In the summer, all air is extracted near the glazed roof while supply air (if necessary cooled) enters the atrium at the bottom storey; i.e. ventilation is by displacement air flow, see Figure 5.32. The supply air flow in the winter is 2 000 l/s and in the summer 4 000 l/s. The endeavour is to achieve balanced ventilation. The surrounding buildings have a separate ventilation system which is not coupled to the atrium. Vents in the roof and end walls are used only in an emergency to admit outside air if the cooling plant is out of action. In certain areas, for instance near the cafeteria, curtains and venetian blinds were installed in the summer of 1992 to reduce insolation.

The study on this atrium building was limited to measurements of airtightness using fan pressurisation tests. The magnitude of unintended ventilation under normal conditions was also calculated using the air flow program MOVECOMP (Wall & Blomsterberg, 1994).

5.8.2 Results

In order that the airtightness of the atrium may be judged, an assessment must first be made of the airtightness of the surrounding buildings. A conference room on the second storey which has 19 m² wall surface abutting on the atrium was subjected to an airtightness test, with the large blower in the atrium both in and out of operation. From the measurements, the airtightness of the wall facing the atrium was calculated as 3 m^3/m^2h at 50 Pa. The inaccuracy in this determination is considerable. In the same way, the air leakage through the wall on the first storey which abuts on the atrium was determined as 6 m^3/m^2h at 50 Pa. The airtightness level of the wall on the first storey is inferior due to a different construction technique, for instance larger glazed surfaces.

The airtightness of the wall surfaces in the office section which abut on the external air was assumed to conform to the requirement for dwellings in Swedish building regulations, viz 3.0 m^3/m^2h. The floors are of concrete and were assumed to be completely airtight, i.e. all services penetrations were assumed to be airtight. The combined airtightness of the office wall abutting on the atrium and on the external air was calculated as 3.5 m^3/m^2h at 50 Pa. The calculation was carried out by putting the air flow rate between the atrium and the offices equal to that between the offices and the external air. A pressure difference was assumed between the atrium and the external air, and the resulting pressure in the atrium and the air flow rate was then calculated.

According to the airtightness measurements, air leakage in the atrium is approx. 1.1 ach at an overpressure of 50 Pa. Air leakage through the roof and the end walls is approx. 4 m^3/m^2h or 0.7 ach at 50 Pa; this was determined by correcting for leakage via the offices, as shown in Table 5.4.

Table 5.4 Airtightness at 50 Pa (Wall & Blomsterberg, 1994).

	airtightness (m^3/m^2h)
wall between atrium and office (Storey No 2)	3.0
wall between atrium and office (Storey No 1)	6.0
between atrium and external air via the office	3.5

5.9 Atrium – Scandinavian Center

Figure 5.33 Interior of the office complex Scandinavian Center in Malmö (Wall & Blomsterberg, 1994).

Latitude:	55.6°N
Function, atrium:	communication
Floor area, atrium:	400 m^2
Function, adjacent buildings:	offices, shops
Occupancy year:	1991

5.9.1 Description

Scandinavian Center is situated near the railway station in Malmö. It was ready for occupation at the end of 1991 and consists of two buildings each of six storeys connected by an atrium. See Figure 5.34. The buildings contain offices, and on the bottom storey there are shops entered from the atrium. Below the buildings and the atrium there is a basement garage. Scandinavian Center is owned by the property firm Skanska Fastigheter.

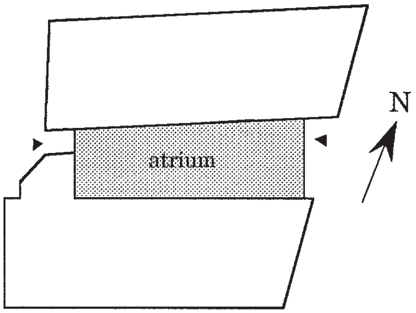


Figure 5.34 Plan of Scandinavian Center (Wall & Blomsterberg, 1994).

The atrium is used mainly as a circulation area, both to reach the shops on the bottom storey and to enter the buildings to visit the various companies. On the upper storeys near one end wall of the atrium there are waiting areas near the company entrances.

The length of the atrium is approx. 35 m and its width is 11 m. The atrium is approx. 22 m high in the centre, and its volume is approx. 9 000 m^3. The glazed surfaces towards the outside amount to 1 230 m^2, 580 m^2 of which is the glazed roof. The area of the facade surfaces of the two surrounding buildings towards the atrium is approx. 1 000 m^2.

The bow shaped roof is double glazed with sealed units, 6 mm toughened Kappa Antisun Blue on the outside and 6 mm laminated clear glass on the inside. The U value is 2.8 $W/m^2°C$. The end walls are triple glazed with Glaverbel sealed units with a U value of 1.9 $W/m^2°C$; the outermost pane is 6 mm toughened Stopsol Super Silver (reflecting) and the two inner panes are 6 mm laminated clear glass. The profile system is Schüco SK60.

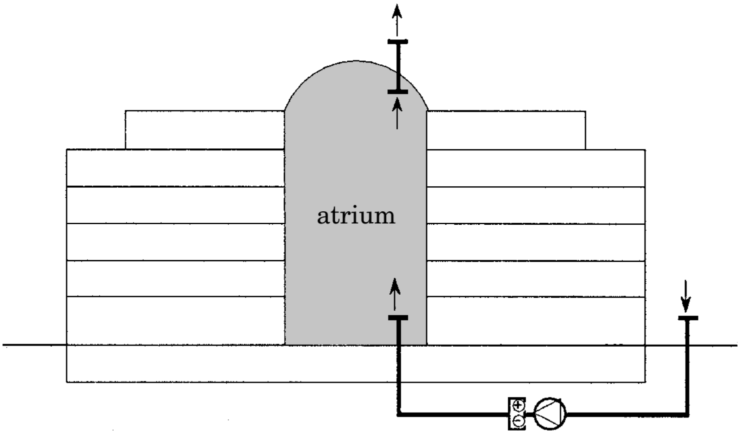


Figure 5.35 Schematic section of Scandinavian Center (Wall & Blomsterberg, 1994).

The temperature requirement in the atrium is 18°C, but this is allowed to drop to 15°C when the outside temperature is -14°C. Heating is by radiators and by the supply of preheated air at the level of the bottom storey; see Figure 5.35. The inlet temperature in the winter is 18°C and the flow rate is 850 l/s. Air is extracted through the lift machine room at the rate of 450 l/s. The buildings on either side of the atrium have a separate ventilation system which is not coupled to the atrium.

There is also circulated air which is drawn in below the stairs on the bottom storey in the atrium, heated and supplied through slots at floor level near the eastern glazed facade. This air flow rate is 360 l/s; air is heated to 38°C when the outside temperature is -14°C and to 15°C when the outside temperature is 15°C. When the outside temperature is above 16°C, the plant is not in operation.

In the summer the supply air to the atrium is cooled to 15°C. There are no solar control curtains, but vents can be opened in the summer to let in fresh air.

The study of this atrium building was limited to measurements of airtightness using fan pressurisation tests. The magnitude of unintended ventilation under normal conditions was also calculated using the air flow program MOVECOMP (Wall & Blomsterberg, 1994).

5.9.2 Results

In order that the airtightness of the atrium may be judged, an assessment was first made of the airtightness of the surrounding buildings. An office room on the third storey, with 16 m^2 wall surface abutting on the atrium, was subjected to an airtightness test with the large blower in the atrium both in and out of operation.

On the basis of the measurements, the airtightness of the wall abutting on the atrium was estimated at approx. 6 m^3/m^2h at 50 Pa; the uncertainty of this value is however considerable.

The airtightness of the wall surfaces in the office section which abut on the external air was assumed to conform to the requirement for dwellings in Swedish building regulations. The floor is of concrete and it was assumed to be completely airtight including all services penetrations. The combined airtightness of the office wall abutting on the atrium and that abutting on the external air was calculated as 5 m^3/m^2h at a differential pressure of 50 Pa. In the calculation, the air flow rate between the atrium and the surrounding buildings was put equal to that between the surrounding buildings and the external air. A pressure difference was assumed between the atrium and the external air, and the resulting pressure in the atrium and the air flow rate was then calculated.

Table 5.5 Airtightness at 50 Pa (Wall & Blomsterberg, 1994).

	airtightness (m^3/m^2h)
wall between atrium and office	6.0
between atrium and external air via the office	5.0

The results of airtightness measurements show that air leakage in the atrium in Scandinavian Center is approx. 0.8 ach at an over-pressure of 50 Pa. Air leakage through the roof and the end walls is approx. 2 m^3/m^2h or 0.3 ach at 50 Pa; this was determined by correcting for leakage via the offices, as shown in Table 5.5.

5.10 Atrium – Sirius

Figure 5.36 The office building Siriushuset in Malmö (Wall & Blomsterberg, 1994).

Latitude:	55.6°N
Function, atrium:	communication
Floor area, atrium:	380 m²
Function, adjacent buildings:	offices
Occupancy year:	1992

5.10.1 Description

Siriushuset is situated behind the railway station in Malmö near the building Slagthuset. It was completed during the spring of 1992. It is a six storey office building complex completely surrounding a central atrium; see Figure 5.37. The top storey in the building houses only services. Below the buildings and the atrium there is a basement garage. Siriushuset is owned by the firms Skanska Fastigheter and Euroc.

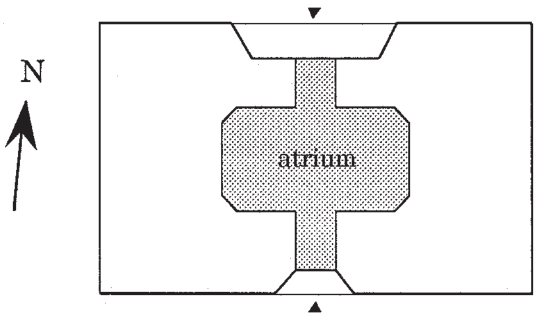


Figure 5.37 *Plan of Siriushuset in Malmö (Wall & Blomsterberg, 1994).*

The atrium is approx. 26 m long, 14 m wide and 23 m high to the ridge; see Figure 5.38. Two entrances on the bottom storey lead to the atrium where there are stairways and lifts and entrances to the various companies.

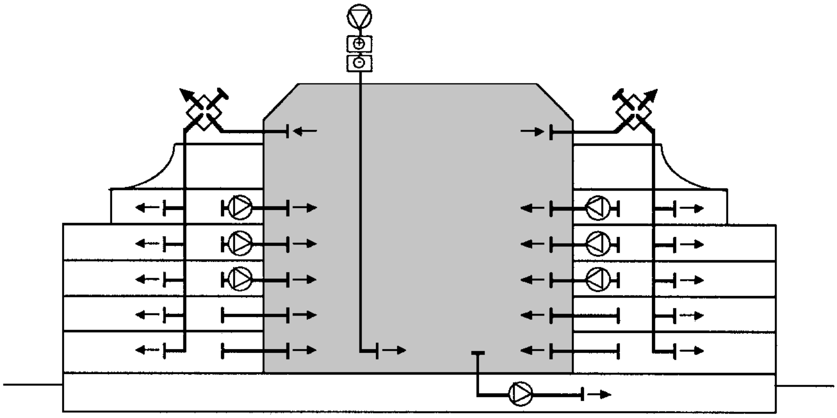


Figure 5.38 *Schematic section of Siriushuset (Wall & Blomsterberg, 1994).*

The area of the glazed roof is approx. 500 m² and the volume of the atrium is approx. 8 700 m³. The area of the office facades towards the atrium is approx. 1 440 m², which means that, even with passive climatic control, the atrium would have a relatively high temperature level.

The roof is double glazed with sealed units, with a U value of 2.8 W/m²°C; the outer pane is 6 mm toughened Kappa Antisun Grey and the inner pane 8 mm laminated clear glass. Kappa Antisun Grey is an absorbent glass, and primary energy transmission is only 33% together with one clear glass pane (transmission through two clear panes is 68%). The profile system is the same as at Scandinavian Center, i.e. Schüco SK60.

The atrium is mostly used as a communication area. There is no definite temperature requirement for the atrium; it is specified in general terms as occupation temperature which is interpreted as not less than 16-18°C. Air to the atrium, in the form of outside air which may be preheated or cooled, is supplied at about the centre of the atrium on the bottom storey. Air is also supplied to the atrium from the surrounding offices through transferred air terminals on storeys 1 and 2 and with the assistance of fans on storeys 3-5. Air from the atrium is extracted partly on the bottom storey from where it passes to the basement, and partly at the top near the glazed roof through two terminals from which the air passes through heat exchangers before being exhausted. There are no solar control curtains, but vents can be opened to let in fresh air.

The study on this atrium building was limited to measurements of airtightness using fan pressurisation tests (Wall & Blomsterberg, 1994).

5.10.2 Results

In order that the airtightness of the atrium may be judged, an assessment was first made of the airtightness of the surrounding buildings. The airtightness test was made in an office room with 8 m^2 wall surface abutting on the atrium, with the blower in the atrium both in and out of operation. From the measurements, the airtightness of the wall abutting on the atrium was calculated as 7 m^3/m^2h, but the inaccuracy is considerable.

The airtightness of the wall surfaces in the office section which abut on the external air was assumed to conform to the requirement for dwellings in Swedish building regulations. The floor is of concrete and in this case also it was assumed to be completely airtight, i.e. including all services penetrations. The combined airtightness of the office wall abutting on the atrium and that abutting on the external air was calculated as 4.3 m^3/m^2h.

Table 5.6 Airtightness at 50 Pa (Wall & Blomsterberg, 1994).

	airtightness (m^3/m^2h)
wall between atrium and office	7.0
between atrium and external air via the office	4.3

According to the airtightness measurements, air leakage in the atrium is approx. 1.0 ach at an overpressure of 50 Pa. Air leakage through the roof is approx. 4.5

m^3/m^2h or 0.3 ach at 50 Pa; this was determined by correcting for leakage via the offices, as shown in Table 5.6.

5.11 Atrium – Oncological clinic

Figure 5.39 *Oncological Clinic, Lund University Hospital. The picture was taken during the fan pressurisation test (Wall & Blomsterberg, 1994).*

Latitude:	55.7°N
Function, atrium:	communication, waiting room for patients
Floor area, atrium:	330 m^2
Function, adjacent buildings:	wards, hospital
Occupancy year:	1992

5.11.1 Description

On the hospital site in Lund new premises have been built for the Oncological Clinic. They were completed in the summer of 1992. For the first time, rooms for radiation treatment were to be placed above ground so that patients and staff should not need to spend their time in basement premises. A light and pleasant environment is achieved by means of an atrium in the centre, with treatment rooms on two sides and other areas on the third side; see Figure 5.40. On the fourth side there is a glazed wall which faces an ecological park. In the atrium there are four small control rooms with glazed roofs, one for each treatment room. The walls between the atrium and the treatment rooms on the long sides are approx. 1.5 m thick and have no windows. From the other part of the clinic two corridors lead out into the atrium. Below the atrium and the buildings there is a basement.

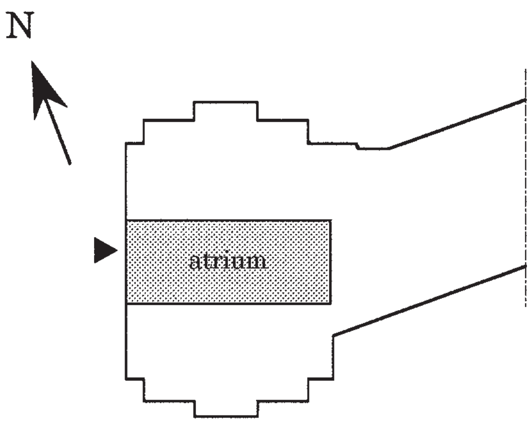


Figure 5.40 Plan of the Oncological Clinic (Wall & Blomsterberg, 1994).

The length of the atrium is 28 m, its width 11.5 m and its height 6 m to the eaves and 12 m to the ridge; see Figure 5.41. The volume of the atrium is approx. 5 200 m^3, and the glazed area towards the outside is approx. 607 m^2, 466 m^2 of which is the glazed roof. The area of the facades towards the atrium is approx. 480 m^2. Note that the corridors which open into the atrium are completely open, so that there is unobstructed movement of air.

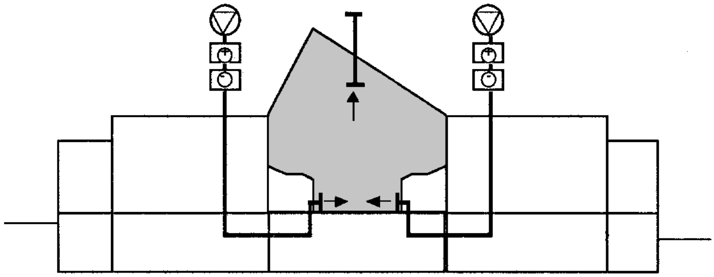


Figure 5.41 Schematic section of the Oncological Clinic (Wall & Blomsterberg, 1994).

The roof is double glazed with sealed units, with 6 mm toughened Emmaboda Cool-Lite SS 132 on the outside and 6 mm laminated Ekoglas, with argon in the space, on the inside. The U value is 1.8 W/m²°C. The end walls consist of triple glazed sealed units, with 6 mm toughened Emmaboda Cool-Lite SS 132 on the outside, 6 mm Floatglas in the centre and 6 mm Ekoglas on the inside, with argon in both spaces. For the triple glazed unit the U value is 1.4 W/m²°C. Emmaboda Cool-Lite is a solar control glass which has 26% primary solar energy transmission for the glazed roof and 17% for the end walls. Reflection is 15%, and in daylight the glass has the appearance of a mirror from the outside. The profile system is from Robertson Nordisk AB, Göteborg. The design specifications contained airtightness requirements, for instance that average air leakage through glazed and insulated fixed panels, inclusive of joints and any service penetrations, should not exceed 1.1 m³/m²h at 50 Pa differential pressure.

In addition to being a communication area, the atrium is also used as a waiting room for the patients. The temperature requirement throughout the year is 22°C, which means that both heating and cooling is needed. Four ventilation terminals at ground level in the atrium supply air which may be either heated or cooled. High up at the end wall near the adjoining building there is an extract terminal. Openable vents and solar control curtains are used to reduce the cooling load in the summer.

A study was made already during the preliminary design stage of what consequences the proposal would have on climate and energy requirements for heating and cooling.

The field measurements on this atrium building were limited to measurements of airtightness using fan pressurisation tests (Wall & Blomsterberg, 1994).

5.11.2 Results

Calculations of the energy requirement for heating the atrium to 22°C were carried out during the design stage. These calculations showed that the amount of energy required for heating was highly dependent on the airtightness of the atrium, see Figure 5.42.

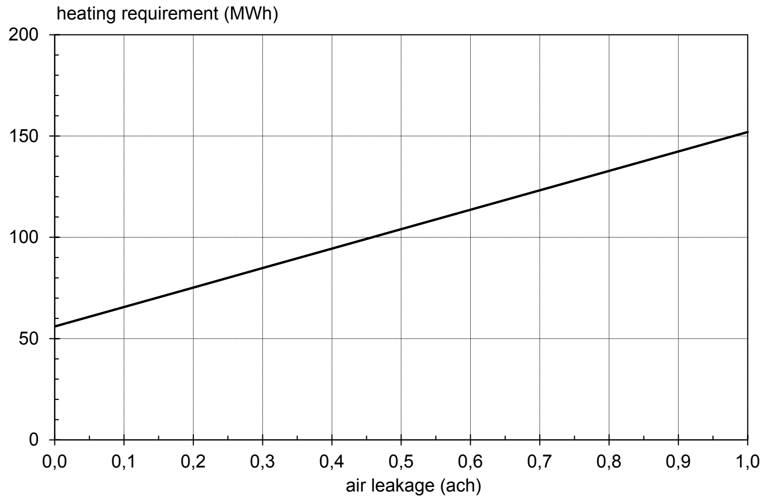


Figure 5.42 *Energy requirements for heating the atrium to 22°C at different air leakage rates during January-May and September-December 1971 in Malmö. 1971 is a reference year.*

In order that the airtightness of the atrium may be judged, an assessment must first be made of the airtightness of the surrounding buildings. No airtightness measurements were made on the surrounding buildings since the walls on the long sides are 1.5 m thick without windows, and leakage through these is considered to be marginal. The two glazed portions with doors, one on each side, were carefully sealed during the pressurisation test. The corridors which open into the atrium and which are completely open were screened off with plastics sheeting during the measurements.

Airtightness measurements at an overpressure of 50 Pa yielded 0.7 ach in the atrium. This is equivalent to an air leakage of approx. 6 m^3/m^2h through the glazed roof and the glazed end walls, provided that all air leakage takes place through these surfaces, which appears reasonable.

Before the airtightness test was carried out, it was discovered that the junction between the atrium and the surrounding buildings was not sealed. This was done before the measurements were made, otherwise the measured air leakage would have been greater.

5.12 Summary

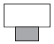
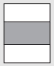
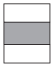
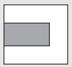
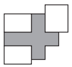
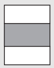
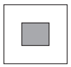
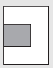
At the Department of Building Science several studies have been made on different glazed spaces. The sizes of these spaces vary between 10 and 5 000 m^2, corresponding to 25 - 30 000 m^3. Some of the studies comprised both field measurements of climate and energy use and calculations with different computer programs. Other studies have been limited to only calculations or measurements, for a limited time, of a few parameters.

The buildings are of varying ages. The estate at Smålands Taberg with glazed verandas was built in 1981 and is thus the oldest, while Siriushuset and the Oncological Clinic are the youngest, built in 1992. The glazed superstructure over the abbey ruins at Hamar has not yet been constructed.

Table 5.7 presents a summary of the projects described briefly in this chapter. Of the 10 glazed spaces, 6 are heated and of these, 4 are also actively cooled. The rest have passive climatic control. The studied projects which contain flats have a lower requirement for the temperature in the glazed space than those which contain offices etc. Solar control curtains have been installed in 6 of the glazed spaces.

Five of the ten projects have a combined ventilation system for the glazed space and the surrounding buildings. The most common type of ventilation system is the one in which the glazed space is used to preheat the supply air to the surrounding buildings. In one case, the flats for the elderly at Sätuna, supply air is preheated with both solar collectors and glazed balconies.

Table 5.7 Summary of the studied buildings.

	shape	occu-pancy year	function		glazed space								combined ventilation system	
			glazed space	adjacent buildings	floor area (m²)	height (m)	volume (m³)	auxiliary heating	auxiliary cooling	required temperature (°C) winter	required temperature (°C) summer	sun-shades	buildings to glazed space	glazed space to buildings
Hamar		–	climatic protection	–	2 400	20	23 000	yes	no	>0	–	no	–	–
Taberg		1981	veranda	residential	10/16	2.5/5	25/62	no	no	–	–	yes	no	no
Sätuna		1990	balcony/ extra room	flats for the elderly	12	2.4	29	no	no	–	–	no	no	yes
Tärnan		1983	communica-tion/meet-ing place	residential	200	6	1 200	no (yes)	no	>0	–	yes	no	yes
Gårdsåkra		1983	communica-tion	residential/ schools	5 000	6	30 000	yes	no	≥5	–	yes	no	yes
Piggvaren		1986	communica-tion	residential	240	10	2 400	no	no	–	–	yes	yes	yes
Kabi Pharmacia		1991	communica-tion/recep-tion/cafeteria	offices/ research lab.	700	13	8 900	yes	yes	20	~25	yes	no	no
Scandinavian Center		1991	communica-tion	offices/shops	400	22	9 000	yes	yes	15-18	~25	no	no	no
Sirius		1992	communica-tion	offices	380	23	8 700	yes	yes	16-18	~25	no	yes	yes
Oncological clinic		1992	communica-tion/waiting room	wards, hospital	330	12	5 200	yes	yes	22	22	yes	no	no

6 Analysis of the case studies

This chapter contains an analysis of field measurements and calculations for the buildings described in Chapter 5. The manual calculation method described in Chapter 3 is also tested by comparing the calculation results with measurements in two glazed spaces.

6.1 Type of glazed space

The fundamental temperature level in a glazed space which is under passive climatic control is determined by the magnitude of the factor *G*. This factor was defined in Chapter 4. The endeavour should be to achieve a low value of this factor since this implies a relatively high temperature level in the glazed space.

How is a low value of the factor *G* achieved in a glazed space? To a high degree, this factor is determined by the geometrical configuration of the glazed space in combination with the adjacent buildings. A glazed veranda with a warm building on only one side has the largest surfaces towards the external air, which gives rise to high losses, and at the same time it has small surfaces in contact with the adjacent building which can provide an energy increment. This results in a high value of the factor *G* and a low temperature level even if ventilation losses are cut to the minimum. For the same reason, a glazed courtyard with buildings on two sides has a lower temperature level than a glazed courtyard surrounded by heated buildings on three or all four sides. See also Section 4.2.

The great significance which the geometry has for the temperature level in the glazed space thus implies that the fundamental temperature level of the glazed space is already determined at an early stage of the design process. If the glazed space has a relatively low value of *G*, there are greater opportunities later on to modify the temperature level than if *G*, owing to the geometry, has a high value right at the beginning.

Some glazed spaces which are wholly or to a high degree under passive climatic control are described in Chapter 5. *The ruins at Hamar* are to be covered by a single glazed construction and heated to at least 1°C in the winter. This glazed construction has no adjacent buildings and thus has only specific losses and no gains under steady state conditions without solar radiation, which yields the factor $G = \infty$. *The glazed verandas at Smålands Taberg* are also single glazed, and here the factor $G \approx 16$. *The glazed courtyard at Tärnan* and *the glazed street at Gårdsåkra* are single glazed and have buildings on two sides, which means that the value of the factor G is approx. 8 with passive climatic control. *The glazed courtyard at Piggvaren* has a single glazed roof and a double glazed gable and has buildings on three sides. This courtyard also receives an energy increment from the ventilation since the heat from the air exhausted from the adjacent buildings is transferred to the supply air to the courtyard via a heat exchanger. The design value of the factor G in this glazed courtyard was 1, but owing to the fact that the glazed construction is very leaky and double insulation curtains had not been installed underneath the roof, the actual value is $G \approx 1.3$.

The temperature level in these glazed spaces as a function of the outside temperature, calculated by reference to the factor G, is plotted in Figure 6.1. The lines show the estimated minimum temperature in each glazed space at a certain outside temperature. As shown in Chapter 5, these lines give a good approximation of the real minimum temperature in the glazed spaces at different outside temperatures. In all the examples in the figure, with the exception of the glazed courtyard at Piggvaren, there is little prospect of a high temperature level. This means that in these glazed spaces with a climate such as that in northern Europe, there is a high risk that, with passive climatic control, the temperature will drop below freezing in the winter. In the glazed courtyard at Piggvaren, on the other hand, the temperature at no time dropped below 7°C during the year of measurement; the winter in that year was however exceptionally warm, with the minimum outside temperature -7°C (see also Figure 5.29).

In view of the fact that plants are in most cases set out in these glazed spaces, it would have been comforting to be assured that the temperature in the glazed space would not drop below freezing. At Gårdsåkra, not only the ventilation ducts but also the supply pipes for the radiators and domestic hot water are laid exposed, and this also makes it necessary for the glazed street to be heated.

When a glazed space is being planned, it is therefore important to know that some types of glazed space are less suitable, when a minimum temperature level is specified, for planting shrubs or siting a cafeteria in the glazed space. If the client is not aware of this, the result may be lack of comfort and/or a high energy requirement for heating the glazed space so as to make up for the difference between expectations and reality.

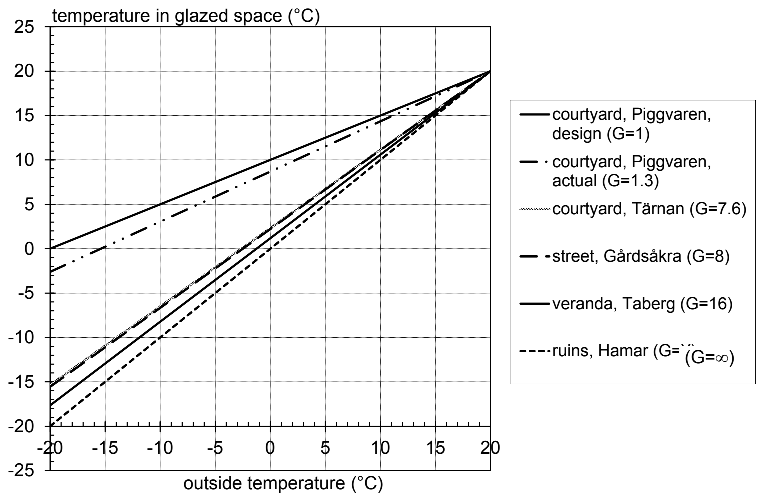


Figure 6.1 *Temperature level in different glazed spaces as a function of outside temperature. The lines are based on steady-state calculations without the influence of solar radiation and thermal inertia, and represent the theoretically lowest temperature in the glazed space under passive climatic control.*

6.2 Type of glazing

The thermal characteristics of the glass and the number of panes obviously influence the climate in the glazed space, as well as the energy requirement, if any, for heating or cooling. The term thermal characteristics refers here to the U value of the glazed construction and the properties of the glass with regard to transmission, reflection and absorption of solar energy. When different theoretical models for glazed spaces were compared in Section 4.3, it was seen that the number of panes of glass can be very significant for the temperature, especially when the factor *G* is small. In some of the case studies, described briefly in Chapter 5, analyses have in addition been made regarding the influence of different types of glazed construction. Some of the important results are set out below.

With the *glazed structure over the abbey ruins at Hamar*, which has not yet been built, the ruins will be completely covered by a single large volume of glass; see Section 5.2. In order to investigate the consequences of this, calculations of temperatures and energy requirements for heating were made for different types of glazed construction. The calculations which were made with the computer program DEROB-LTH studied five different types, namely

- ordinary single glazing, U = 5.8 W/m²°C
- EKO single glazing (Emmaboda), U = 4.0 W/m²°C
- ordinary double glazing, U = 2.9 W/m²°C
- EKO double glazing (Emmaboda), U = 2.0 W/m²°C
- ordinary triple glazing, U = 2.0 W/m²°C

Emmaboda EKO is a low transmission glass with a semiconductor layer consisting of a metallic salt. With this layer, the emissivity for long wave radiation has been reduced from 0.85 to 0.3 on one side of the glass. Emmaboda EKO was used in the calculations as an example of this type of glass. There are other manufacturers and types of glass.

For a single glazed construction with EKO glass, the manufacturer recommended that two toughened EKO panes should be laminated together. For double glazed EKO it was recommended that toughened EKO should be used on the outside and ordinary laminated glass on the inside. Toughened glass is used on the outside to resist environmental loads and stresses. The drawback of toughened glass is that if it breaks it often falls down in large sharp pieces. Laminated glass is therefore used on the inside since the glass fragments are retained by the plastics laminate and the risk of injuries from the glass is reduced.

Calculations were made on two occasions. The first time it was not possible to specify emissivities for glass surfaces in DEROB-LTH. The program used the emissivity 0.9 for all glass surfaces. The effect of the low emissivity layer was therefore described in the program as a reduction in the U value, as stated by the manufacturer. This first study is described in Wall (1990a). The then version of DEROB-LTH calculated long wave radiation towards the sky by assuming that the sky temperature was the same as the outside air temperature. This necessitated another study at a later date after DEROB-LTH had been given the capability to specify sky temperature as input data in the climate file for calculation of the long wave radiant heat transfer between the sky and the building. In this more recent version, the emissivity for long wave radiation of the inside and outside of the glazed structure is also given as input data for the program. This later study is described in Wall (1992b).

In the first study, among other things the temperature in the glazed construction was calculated without any heating. In these calculations it was assumed that the ventilation or infiltration was equal to 0.5 ach from October to April and to 2.0 ach in the remaining months. The difference in minimum temperature between the different glazing alternatives was relatively small, between 2°C and 4°C over the year. The lowest temperature was obtained in the single glazing case with ordinary clear glass, and the highest minimum temperatures with triple glazing and with double glazing with a low emissivity layer. With ordinary single glazing the minimum temperature was between 3°C and 5°C higher than the outside minimum temperature in the winter. If double glazing with EKO or triple glazing is used, the minimum temperature in the winter is raised by a further 2-3°C. Depending on the glazing alternative, the lowest temperatures in the glazed construction over the year were between -9°C and -12°C.

The mean temperature in the glazed construction during the calculation year, without any heating, is very near the outside temperature in the winter since there is little energy gain from the sun. In the winter, the mean temperature is only between 0 and 3°C higher than the outside mean temperature. The difference between the glazing alternatives is less than 1°C. During the summer months the mean temperature is approx. 7-12°C higher than outside. The mean temperature is lowest in December, between -3°C and -4°C. In the summer the mean temperature is between 20°C and 30°C.

Nor is there any appreciable difference in maximum temperature between the glazing alternatives. The difference is mostly 3-4°C, but in December there was no difference at all. The maximum temperature then is only ca 5°C. In December and January the maximum temperature in the glazed construction is lower than that outside. The reason may be that the energy increment from the sun is very small and at the same time the construction has a very high thermal inertia owing to the ruins. Temperature fluctuations in the glazed construction are damped out, and a sudden increase in outside temperature gives rise to a slower and smaller temperature increase inside the construction. The ruins exert an influence not only in raising but also in lowering the temperature. In the summer the very powerful solar radiation gives rise to high temperatures inside the construction, with a maximum of 40-45°C. During the calculation year, the maximum outside temperature was 30.5°C. The ventilation which in the calculations was assumed to be 2 ach in the summer months can naturally be increased. However, since the outside temperature is also high, increased ventilation would not be particularly effective.

Figure 6.2 sets out the energy required to heat the glazed construction to 1°C during a standard year. The results are given in per cent, with the energy requirement for heating the single glazed construction with clear glass defined as 100%. A double glazed construction halves the energy requirement, and if a double glazed EKO or a triple glazed construction is used, the energy requirement is reduced to about one third of that for an ordinary single glazed construction. In this first calculation run, with the sky temperature assumed equal to the outside temperature, the energy requirement for the single glazed construction with clear glass amounted to 250 MWh (100%) over the standard year. The energy requirement for triple glazing was just over 90 MWh. This energy is required to maintain a temperature of 1°C in the glazed construction.

To sum up, with passive climatic control, the choice of glass type and the number of panes has no major significance in this glazed construction. The construction has such large glazed surfaces that the losses are in any case very high, and this type of glazed space is influenced to an extremely high degree by the outside climate. Since, however, it must be heated to at least 1°C, the choice of glass has a great influence on the energy requirement; when a glazed space is heated, it is always important to reduce the fabric and ventilation losses as much as possible.

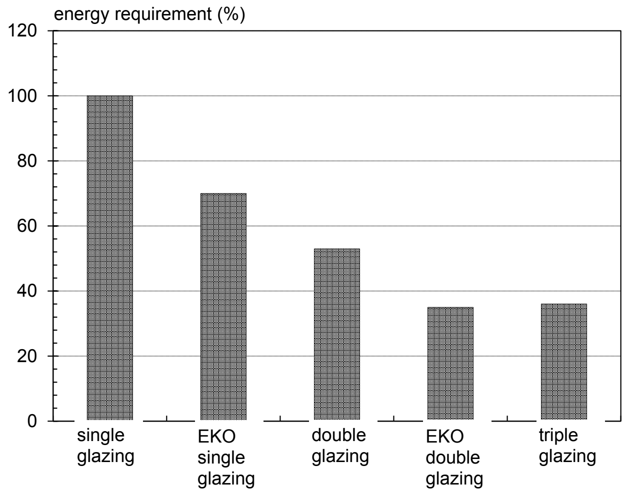


Figure 6.2 *Energy requirement as a percentage of the energy requirement of single glazing. The abbey church ruins at Hamar (Wall, 1990a).*

In Fredlund (1989), the temperature in the *glazed verandas at Smålands Taberg* was calculated with the program DEROB-LTH. A veranda on two levels was studied, and the actual construction with single glazing was compared with a double glazed construction. The minimum and mean temperatures in the veranda with double glazing were on average ca 2°C higher during the calculation period in August 1982. The maximum temperature was a little over 3°C higher with double than with single glazing. The calculations assumed that there were no solar control curtains and that the air change rate was 3.0 ach. The difference in temperature between the glazing alternatives is not greater but smaller in the winter. This shows that not even in this type of glazed construction has the choice of glazing any decisive significance for the temperature. Compared with the glazed construction at Hamar, the glazed verandas at Taberg nevertheless receive a certain energy increment from the adjoining wall of the flat. The losses are however still predominant, and the effect of one more pane of glass is limited.

The *glazed courtyard at Tärnan*, Landskrona, has buildings on two sides and the relationship between losses and gains is therefore a little better. This courtyard still has a temperature level which is fairly near the level of outside temperature; see Section 5.5. It would have been desirable to attain a higher minimum temperature by passive climatic control. With the actual configuration there is a risk that the plants will freeze during cold winter periods. One thing which has often been suggested by visitors we have shown round is that the construction should be double or triple glazed. The general idea is that the courtyard would then have been much warmer. The fact is that the temperature would not have been affected very much.

In Wall (1992a), calculations were made for the year 1987 in order to study the effect of various parameters. In these calculations the solar control curtains were drawn at night throughout the year. In the summer they were also drawn during the day, which corresponded to reality as much as possible. The air change rate in the courtyard was 2 ach during the summer and 0.6 ach during the rest of the year. These ventilation and shading strategies were mainly based on measurements.

The calculations show that if triple glazing is used instead of single glazing, the minimum temperature is approx. 2 - 4°C higher. The greatest difference between the glazing alternatives occurs in January and February. The minimum temperature is then almost 5°C lower with single than with triple glazing; -12°C instead of -7°C in January when the minimum outside temperature was approx. -24°C. Whichever alternative is chosen, it is still too cold if the object is to keep the courtyard frost free. In December to March, the minimum temperature is below zero even with triple glazing. Heat must be supplied to achieve a frost free space. In summer the difference in minimum temperature between single and triple glazing is only about 2°C.

The difference in mean temperatures is smaller still. Triple instead of single glazing will increase the mean temperature by only 1 - 2°C. During the year, depending on the time of year and the type of glazing, the mean temperature is approx. 3 - 10°C higher than the mean temperature outside.

The calculations also showed very small differences between the maximum temperatures. The difference between single and triple glazing is approx. 2°C during the year, except for December when there is no difference at all. Another exception occurred in May when the maximum temperature for triple glazing was approx. 40°C, 8°C higher than for single glazing. This large difference is due to the very low ventilation rate, 0.6 ach, which was set for August - May. It was probable, however, that in actual fact the glazed courtyard was ventilated to a much higher degree and the differences were thus reduced.

The reason why the difference between the glazing alternatives is not greater is the high *G* value of the courtyard, which is to say that the losses are much higher than the gains. Even if the U value is considerably reduced by using double or triple glazing, the glazed surfaces are so large that the losses of the courtyard are still very high compared with the gains. In the middle of the day the difference may be greater when there is powerful solar radiation, but the temperature rapidly drops when the sun goes down, since the losses are so large. At night the difference is therefore extremely small. During the summer months the difference in temperature would have been greater if the solar control curtains and vents had not been used effectively.

If the temperature in the courtyard at Tärnan is to be maintained at a level higher than is possible by passive climatic control, heat must be supplied. In such a case it is much more important to have a greater number of panes of glass in order to keep the energy requirement low. In Figure 6.3 the energy requirement during 1987 has been calculated for the glazed courtyard heated to a certain minimum temperature. The calculations have been made for single, double and triple glazing. As can be seen, supplementary energy is needed even to keep the courtyard free of frost. With the existing single glazed construction, the energy requirement increases drastically when the temperature requirement is raised. Even for double or triple glazing there is a steep rise in energy requirement, but at a higher temperature. A quite normal energy use figure for a Swedish detached house is approx. 20 MWh per year. The same quantity of energy is needed to maintain the minimum temperature in the courtyard at about 4°C with single glazing. The same energy is sufficient to maintain about 8°C with double glazing, and about 10°C with triple glazing. It is therefore obvious that this glazed construction is not suitable for heating. To be fair, however, it must be said that the calculations were made for an unusually cold year. In a standard year the energy requirement would not be so high. The energy losses during October - April in a standard year are approx. 94% of the losses during 1987. However, the energy requirements will still be high.

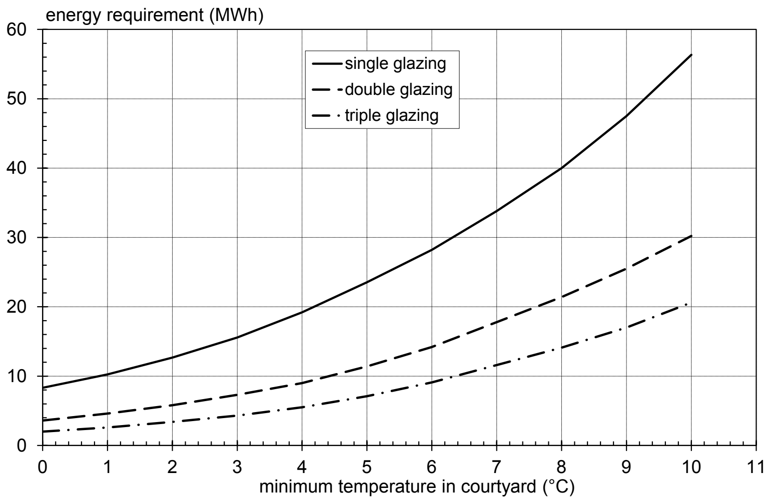


Figure 6.3 *Energy required in 1987 to maintain a certain minimum temperature in the courtyard, for different glazing alternatives. The glazed courtyard at Tärnan (Wall, 1992a).*

Studies of these three buildings show that for passive climatic control the choice of glass type has little significance for the temperature in the glazed space when the factor *G* has a high value. A high value implies that losses are much greater than gains, which means that even if the U value of the glass is reduced the losses will still dominate. If, however, the glazed space is to be heated, the choice of glass is very significant for the energy requirement irrespective of the value of *G*.

The results of calculations described in Chapter 4 also showed that, with passive climatic control, the lower the value of factor *G* is for the glazed space, the greater will be the significance of the choice of glass for the temperature in the glazed space.

The results from Chapter 4 also showed that for a glazed courtyard with buildings on two sides the mean temperature could in fact be up to 6°C higher with triple than with single glazing during a winter week. However, calculations showed that the glazed courtyard at Tärnan would only have 1-2°C higher temperature with triple than with single glazing. The reason for the difference in the results is that in the calculations for the glazed courtyard at Tärnan account was taken of ventilation in the courtyard. The glazed surfaces in the courtyard were in addition shaded by the surrounding buildings. This reduces the effect due to the choice of glazing. The model of the same type of glazed courtyard in Chapter 4 was on the other hand unventilated and completely unshaded. At the same time, the change from single to triple glazing in the I shaped courtyard also involved a simultaneous reduction in the insulation capacity of the walls of the buildings abutting on the courtyard.

The difference in temperature between different types of glazing is greater in the summer than in the winter. However, the use of solar control curtains and ventilation to reduce the temperature in summer reduces the difference between different types of glazing. Excess temperatures need not therefore be a greater problem in a glazed space with e.g. triple glazing than in one with single glazing. In an unventilated and unshaded glazed space the difference between different types of glazing is a maximum, but in reality this type of difference is not particularly relevant for the summer case. The results from Chapter 4 show this maximum effect.

6.3 Orientation

In addition to the geometry of the building and the thermal characteristics of the glass, the amount of solar radiation which is utilised in the glazed space also depends on the orientation of the glazed surfaces. The surrounding buildings also cast shadows to different extents depending on their orientation in relation to the glazed space.

It was stated in Chapter 4 that the choice of orientation has only a marginal effect on the temperature in the glazed space. The effect on a glazed courtyard with buildings on two sides is extremely small when the orientation of the courtyard is changed from east-west to north-south. A glazed courtyard with buildings on three sides is affected more, and will be warmer if the glazed gable is oriented towards the south than if it faces west or east. If the courtyard only has a glazed roof, the difference in temperature is negligible for different orientations, provided that the surrounding buildings are the same height. The calculations also showed that the energy required for heating the surrounding buildings was affected only marginally for different orientations, irrespective of the type of courtyard (Wall, 1991b).

Within the study of *the glazed verandas at Smålands Taberg*, calculations were made for the larger type of veranda, with the real south orientation of the veranda compared with a south-west orientation (Fredlund, 1989). The calculation was limited to August 1982. The calculation showed that the maximum temperature occurs about two hours later when the veranda is oriented towards the south-west. The maximum temperature also increases by ca 2-3°C. In the evenings, however, when the occupants have a greater opportunity to use the verandas, the difference is marginal. The calculated maximum temperatures in August were ca 35-39°C when the maximum outside temperature was 29-30°C. This unacceptably high temperature in the glazed veranda occurs on the assumption that the vents are closed, infiltration is only 3 ach, and no sunshades are used. With the vents open and sunshades drawn, the difference between the two orientations would have been smaller. But not even this attempt at maximum utilisation of solar radiation, by a south-west orientation, increases the temperature in the glazed veranda in the evening. Losses are too high and the temperature in the glazed veranda rapidly drops from the high temperature in the middle of the day to ca 16-18°C during the hottest week in August, irrespective of the type of glazing. This is however still ca 6-7°C higher than the outside temperature, and since the verandas are sheltered from sky radiation and the wind, the evenings can nevertheless be pleasant inside the glazing.

The glazed courtyard at Tärnan is oriented with the glazed gables towards east and west. In the study of this glazed courtyard, calculations were made for an alternative north-south orientation (Wall, 1992a). The western gable which serves as the main entrance was instead oriented due south. The surrounding buildings still had the same relation to Tärnan. It was assumed in these calculations that the solar control curtains were drawn overnight throughout the year. In the summer they were also drawn during the day for some hours in order to simulate actual conditions. The ventilation in the courtyard was 2 ach in the summer and 0.6 ach the rest of the year, which would be equivalent to air leakage only.

Calculations for 1987 showed that the minimum, mean and maximum temperatures were all practically identical irrespective of orientation. The results are naturally influenced by the fact that the glazed courtyard is sited among other buildings. In the winter when the solar altitude is low, only a small amount of direct solar radiation enters. In the summer when solar radiation is powerful, the solar altitude is so high that most of the radiation comes in through the glazed roof, and orientation has not much effect on the courtyard. But even an unshaded and unventilated courtyard of this type is not affected a lot by orientation (Wall, 1991b).

6.4 Thermal inertia

It is the heat storage capacity which affects the range over which the temperature fluctuates during the day when the temperature is allowed to vary. It also influences the power requirement for heating and cooling and, to a certain extent, the energy requirement also. In the glazed spaces described in Chapter 5, the significance of heat storage capacity varied. The conditions for utilisation of the heat storage capacity were also variable.

In the *glazed construction over the abbey ruins at Hamar*, the thick walls have a high heat storage capacity. This means that the glazed construction has a comparatively high heat storage capacity even though it has a very high value of the factor G (= ∞) and no adjacent buildings. This extreme glazed construction has a time constant of 48 hours as calculated according to Equation 4.4 (Wall, 1990a). The time constant calculated according to Equation 4.4 does not take energy gain into account. Since there are no adjacent buildings, this time constant may be considered to be a measure of real conditions. It may be compared with similar time constants for the three different types of glazed courtyard; see Table 4.3. The glazed construction over the ruins is then comparable with a triple glazed courtyard which has buildings on two sides, with the walls abutting on the courtyard made of concrete. The temperature fluctuations in the glazed construction over the ruins are thus damped out to a considerably greater extent than if the ruins had not been there. For instance, with passive climatic control, the minimum temperature in a single glazed construction will be 3-5°C higher than the outside minimum temperature. Although this construction will be heated, this will be of such limited extent that the heat storage capacity will nevertheless be utilised.

The glazed verandas at Smålands Taberg have a high value of G (≈ 16) and very little capacity to store energy from the day to the evening. Temperature fluctuations are therefore extensive, with the risk that the minimum temperature in the winter will be very near the outside temperature. Fredlund (1989) studied the heat storage capacity of one of the glazed verandas together with the flat situated behind it. The floor of the veranda is of concrete and is the element of construction which may be thought to have heat storage capacity. The time constant calculated according to Equation 4.4 is ca 1.2 hour for the veranda. This calculation was based on the adjacent flat being unheated. The time constant for the flat was calculated as ca 76 hours. Fredlund calculated that increasing the number of panes of glass in the veranda would have only marginal effects on the time constant. This type of glazed space has such very high losses that heat storage capacity has no significance for the climate in the space. The surfaces which absorb and emit heat are of limited size, and thermal inertia may therefore be considered to be of no interest for glazed spaces such as verandas and balconies.

Nor was it found that *the glazed courtyard at Tärnan* had an appreciable heat storage capacity. The walls of the adjacent buildings have a low heat storage capacity, but calculations showed that even if they consisted of bricks and thus had a higher heat storage capacity, the temperature in the glazed courtyard would not have been changed appreciably (Wall, 1992a). The calculations showed that only the maximum temperature was reduced by a few degrees. The time constant was not calculated for this glazed courtyard. In view of the actual configuration, the courtyard may according to Table 4.3 be expected to have a time constant of ca 2 hours according to the definition that the surrounding buildings are not supplied with any heat. This glazed courtyard thus has a considerably lower time constant than the glazed construction at the abbey ruins at Hamar.

As pointed out before, heat storage capacity can be best utilised if the temperature in the glazed space is allowed to vary over the day. In the *atrium at the Oncological Clinic* in Lund, the walls of the adjacent treatment rooms consist of 1.5 m concrete. Immediately in contact with the courtyard the walls are clad with hollow bricks. These walls and the floor taken together obviously have a high heat storage capacity, but since the temperature in the atrium and the surrounding buildings must be maintained constant at 22°C over the day and the year, the heat storage capacity has no major significance for this atrium. The heating requirement is slightly reduced, while the cooling requirement is reduced less in percentage terms. On the other hand, heat storage capacity may have greater significance for the power requirement.

6.5 Airtightness and ventilation

6.5.1 Airtightness

Air leakage can be an important component of the energy balance for a glazed space. The influence of unintended ventilation on the temperature in a glazed space has been discussed in Section 4.6. The results of calculations for the Oncological Clinic also showed that unintended ventilation can have a large influence on energy requirements for heating the atrium (see Section 5.11). *But how leaky are glazed spaces in reality?*

In order to gain an idea of what air leakage is like in glazed spaces, field measurements were carried out. Measurements using the tracer gas method were made to study air leakage under normal conditions. For comparisons of different glazed spaces, fan pressurisation tests were also carried out. These two methods were briefly described in Section 5.1. Measurements using *the tracer gas method* were made in a glazed veranda at Smålands Taberg and in the glazed courtyard at Tärnan, Landskrona.

For *a glazed veranda at Taberg*, the air change rate was measured as approx. 3 ach (Fredlund, 1989). The veranda had large gaps between the glazed construction and the building.

Measurements in *the glazed courtyard at Tärnan* were made on 30 May 1988. The outside temperature was approx. 20°C, the temperature in the courtyard 25°C and the wind speed 2 m/s. It was a clear day with global insolation of 700 - 800 W/m². The air change rate with the vents closed was measured on this occasion as approx. 0.6 ach. Since the vents were closed and the solar control curtains open so that air movements should not be hindered, the temperature in the courtyard increased during the measurement and reached about 35°C. When the measurement with the vents closed was finished, the vents were fully opened and measurements continued. During the first 10 minutes after the vents had been opened the air change rate was about 15 per hour. During the next hour, still with the vents open, ventilation corresponded to approx. 4 air changes per hour. The temperature in the courtyard dropped rapidly.

Unintended ventilation is dependent on the temperature difference between the glazed space and outside, wind speed and wind direction. This means that the results presented above are valid only for the weather conditions during the time of measurement. However, this type of measurement gives an idea of the overall airtightness and is also useful in estimating unintended ventilation when calculations of temperatures and energy requirements are carried out.

In order to compare different glazed spaces, measurements using *the fan pressurisation method* were carried out. A total of six glazed spaces have been studied. In Table 6.1 the measured airtightness at an overpressure of 50 Pa is presented. The two older courtyards, in the blocks Piggvaren and Tärnan, are very leaky. The four new atria are much more airtight.

Table 6.1 *Airtightness measured in atria at an overpressure of 50 Pa (Wall & Blomsterberg, 1994).*

atria	ach	m^3/m^2h (glazed roof and facade)	remarks surrounding buildings	occupancy year
Kabi Pharmacia	1.1	4.0	offices [1]	1991
Scandinavian Center	0.8	2.0	offices/shops [1]	1991
Siriushuset	1.0	4.5	offices [1]	1992
Oncological Clinic	0.7	6.0	wards, hospital [1]	1992
Piggvaren	14	64	residential [2]	1986
Tärnan	8.8	36	residential [3]	1983

1 (Wall & Blomsterberg, 1994)
2 (Blomsterberg, 1993)
3 (Wall, 1992a)

The glazed courtyards at both Tärnan and Piggvaren are, in principle, unheated. Tärnan was built in 1983, and the roof and the two end walls of the glazed courtyard are of single glazing. Piggvaren was completed in 1986, and in this glazed courtyard the roof is single glazed and the end walls double glazed. The reason why Piggvaren is so leaky is that there are four longitudinal 1 cm wide gaps in the glazed roof, and most air leakage takes place through these (Blomsterberg, 1993).

The glazed panels for *the atrium at Kabi Pharmacia* were supplied by Viktoria System A/S, Denmark. SBI, the Danish Building Research Institute, made laboratory tests on some glazed panels from this system regarding air and rain tightness. The results showed that at 50 Pa pressure difference, airtightness was approx. 1.8 m^3/m^2h for a glazed roof panel (test performed in 1986) and approx. 0.8 m^3/m^2h for a facade panel (test performed in 1988). Obviously, these figures apply for the glazed panel itself without its junctions with the surrounding buildings. These figures may be compared with the leakage measured in the atrium at Kabi Pharmacia which was 4 m^3/m^2h for both the glazed roof and glazed facades at a pressure difference of 50 Pa.

The design specifications for *the atrium at the Oncological Clinic* laid down that the air leakage through fixed glazed panels should not be more than 1.1 m^3/m^2h at a pressure difference of 50 Pa. Owing to junctions, vents and other paths, the air leakage measured in the completed atrium as a whole was approx. 6 m^3/m^2h. Before the airtightness test was carried out, it was discovered that the junction between the atrium and the surrounding buildings was not sealed. It was however sealed before the measurements were made, otherwise the measured air leakage would have been greater.

6.5.2 Ventilation

Pressurisation tests provide information on how leaky the glazed spaces are at various pressure differences. The results for different buildings and any requirements which may have been specified can be compared. However, the real total ventilation of the glazed space under normal conditions is unknown. Temperature, insolation, wind velocity and wind direction will obviously affect the magnitudes and directions of air flows. The air flow rates which can be determined by measurements are those in the ventilation ducts. The unknown air flow rates are that between the glazed space and the surrounding buildings, that between the glazed space and the external air, and that between the surrounding buildings and the external air. The magnitudes of these air flows exert a great influence on air quality, comfort and energy use.

In order to gain an idea of these unknown air flows, simulations were made for two atria using the multicell air flow balance program MOVECOMP (Herrlin, 1987; Bring & Herrlin, 1988). The atria at Scandinavian Center and in the building of Kabi Pharmacia were selected. The calculations were made by Åke Blomsterberg, SP (Wall & Blomsterberg, 1994).

In the calculations with MOVECOMP, the buildings were simplified so as to have one single large room per storey and an atrium of the same height as the surrounding buildings. The surrounding buildings were assumed to have perfectly balanced ventilation, and their wall surfaces abutting on the external air were assumed to have an airtightness complying with the requirements for dwellings in the Swedish building regulations (3 m^3/m^2h at 50 Pa). The input data were

- measured values of the airtightness of the atrium
- measured values of the airtightness of the surrounding buildings (only some rooms in the surrounding buildings)
- design air flow rates in the ventilation system
- design air temperatures in the atrium
- design air temperatures in the surrounding buildings
- air temperature outside
- estimated values of wind velocity and wind direction
- estimated values of shape factors.

The shape factors were chosen according to Liddament (1986). For more details see Wall and Blomsterberg (1994).

Simulations were made for four different outside temperatures, -10°C, 0°C, +10°C and +20°C and for wind velocities of 0 and 5 m/s. At the free wind velocity of 5 m/s, the local wind velocity was calculated according to Liddament to be 4.3 m/s.

The results from the air flow rate calculations show that in *the atrium at Kabi Pharmacia* exfiltration from the atrium varies between 0.01 and 0.06 ach. See Table 6.2. Figure 6.4 shows a schematic outline of the air flow rates set out in Tables 6.2 and 6.3 for the atrium at Kabi Pharmacia. In the calculations, the temperature in the atrium was assumed to be +20°C.

The air flow rate between the atrium and the surrounding buildings at Kabi Pharmacia varies between 0.01 and 0.05 ach. See Table 6.3.

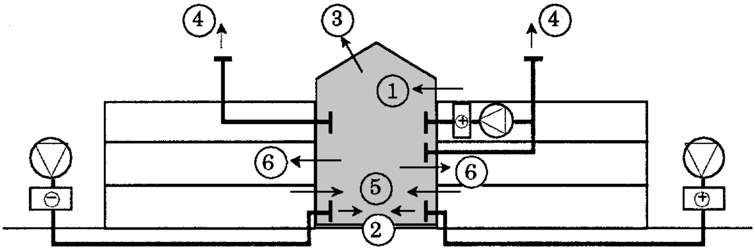


Figure 6.4 *Air flow rates, Kabi Pharmacia. See Tables 6.2 and 6.3. (Wall & Blomsterberg, 1994).*

Table 6.2 *The results of air flow rate calculations for the atrium at Kabi Pharmacia. 890 m³/h is equivalent to 0.1 ach in the atrium (Wall & Blomsterberg, 1994).*

outside temp. (°C)	wind velocity (m/s)	1 [1] infiltra-tion (m^3/h)	2 [1] supply air (m^3/h)	3 [1] exfiltra-tion (m^3/h)	4 [1] extract air (m^3/h)
-10	5	270	7 200	510	7 200
-10	0	120	7 200	460	7 200
0	5	220	7 200	370	7 200
0	0	70	7 200	310	7 200
10	5	200	7 200	230	7 200
10	0	20	7 200	150	7 200
20	5	190	14 400	160	14 400
20	0	10	14 400	80	14 400

1 air flows according to Figure 6.4

Table 6.3 *The results of calculations of air flow rates between the atrium and surrounding buildings at Kabi Pharmacia. 890 m³/h is equivalent to 0.1 ach in the atrium (Wall & Blomsterberg, 1994).*

outside temp. (°C)	wind velocity (m/s)	5 [1] air flow rate to atrium (m^3/h)	6 [1] air flow rate from atrium (m^3/h)
10	5	400	160
-10	0	450	110
0	5	290	140
0	0	330	90
10	5	140	110
10	0	200	80
20	5	90	110
20	0	120	60

1 air flows according to Figure 6.4

The results of air flow rate calculations for *the atrium at Scand-inavian Center* are set out in Table 6.4. The exfiltration from the atrium varies between 0.06 and 0.12 ach, i.e. it is higher than at Kabi Pharmacia. The air flow rates presented in Tables 6.4 and 6.5 are shown schematically in Figure 6.5. The temperature in the atrium is assumed to be 18°C.

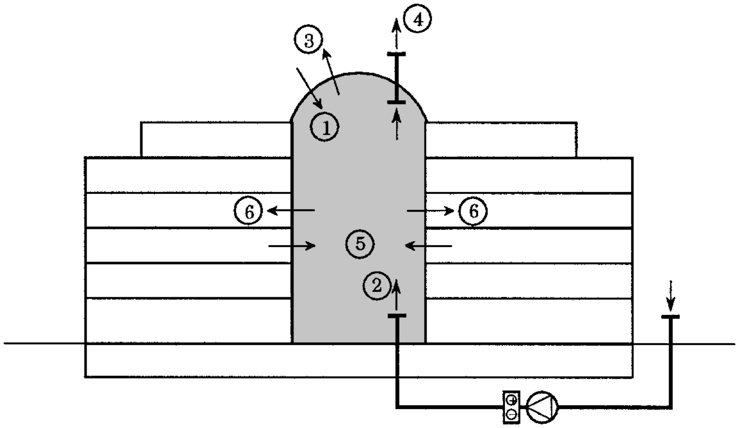


Figure 6.5 *Air flow rates, Scandinavian Center. See Tables 6.4 and 6.5. (Wall & Blomsterberg, 1994).*

Table 6.4 The results of air flow rate calculations for the atrium of Scandinavian Center. 900 m³/h is equivalent to 0.1 ach in the atrium (Wall & Blomsterberg, 1994).

outside temp. (°C)	wind velocity (m/s)	1 [1] infiltration (m^3/h)	2 [1] supply air (m^3/h)	3 [1] exfiltration (m^3/h)	4 [1] extract air (m^3/h)
-10	5	270	3 060	1 010	1 620
-10	0	170	3 060	1 070	1 620
0	5	220	3 060	840	1 620
0	0	100	3 060	900	1 620
10	5	210	3 060	640	1 620
10	0	30	3 060	730	1 620
20	5	190	3 060	520	1 620
20	0	0	3 060	550	1 620

1 air flows according to Figure 6.5

The air flow rates between the atrium and the surrounding buildings are set out in Table 6.5. At Scandinavian Center, the calculated air flow rate between the atrium and the surrounding buildings varies between 0 and 0.12 ach depending on outside temperature and wind velocity.

Table 6.5 The results of calculations of air flow rates between the atrium and surrounding buildings at Scandinavian Center. 900 m³/h is equivalent to 0.1 ach in the atrium (Wall & Blomsterberg, 1994).

outside temp. (°C)	wind velocity (m/s)	5 [1] air flow rate to atrium (m^3/h)	6 [1] air flow rate from atrium (m^3/h)
-10	5	360	1 050
-10	0	410	960
0	5	130	950
0	0	220	850
10	5	0	1 000
10	0	10	760
20	5	0	1 110
20	0	0	890

1 air flows according to Figure 6.5

There should be little unintended ventilation since air which leaks out must be replaced by new heated (or cooled) air. Exfiltration in *the atrium of Kabi Pharmacia* is 0.3 m^3/m^2h at -10°C outside temperature and 5 m/s wind velocity. The pressure drop across the glazed roof is then 13 Pa. In order to heat this air flow, power input of 5 kW is needed when the temperature of the atrium is 20°C; see Table 6.6.

Exfiltration at *Scandinavian Center* reaches 1.3 m^3/m^2h at -10°C outside temperature and 5 m/s wind velocity. The pressure drop across the roof is then 20 Pa. In order to heat this air flow, a power input of 9 kW is needed when the temperature in the atrium is 18°C; see Table 6.7. All values are higher than at Kabi Pharmacia.

It might be thought that total exfiltration ought to be greater when wind velocity increases. According to the calculations, it decreases a little when wind velocity increases while at the same time exfiltration through the roof increases. No simple explanation was found for this, further studies are needed with the wind direction, shape factors etc varied in the calculations.

Table 6.6 *Calculated exfiltration, pressure drop across glazed roof and power loss for the atrium at Kabi Pharmacia. 890 m^3/h is equivalent to 0.1 ach in the atrium. (Wall & Blomsterberg, 1994).*

outside temp. (°C)	wind velocity (m/s)	exfiltration through roof (m^3/m^2h)	pressure drop across roof (Pa)	exfiltration, total (m^3/h)	power (kW)
-10	5	0.3	13	510	5
-10	0	0.2	10	460	5
0	5	0.2	9	370	2
0	0	0.2	6	310	2
10	5	0.1	6	230	1
10	0	0.1	3	150	0.5
20	5	0.1	4	160	–
20	0	–	–	80	–

Table 6.7 Calculated exfiltration, pressure drop across glazed roof and power loss for the atrium at Scandinavian Center. 900 m³/h is equivalent to 0.1 ach in the atrium. (Wall & Blomsterberg, 1994).

outside temp. (°C)	wind velocity (m/s)	exfiltration through roof (m^3/m^2h)	pressure drop across roof (Pa)	exfiltration, total (m^3/h)	power (kW)
-10	5	1.3	20	1 010	9
-10	0	1.2	18	1 070	10
0	5	1.1	14	840	5
0	0	1.0	12	900	5
10	5	0.9	9	640	2
10	0	0.8	6	730	2
20	5	0.6	4	520	–
20	0	0.4	2	550	–

The endeavour at Kabi Pharmacia is to achieve balanced ventilation, which means that the design controlled air flow to the atrium is equal to the controlled extract air flow. At Scandinavian Center the controlled air flow to the atrium is considerably higher than the extract air flow. This means that the atrium of Scandinavian Center is at a pressure higher than that of the surroundings. Exfiltration is relatively high compared with infiltration, and the air flow rate to the surrounding buildings is also higher. When the supply air is used as the heating or cooling medium, high flow rates are needed. In these cases it may be appropriate to control the extract air flow rate also and to use heat exchangers if the air is to be exhausted directly. In such a way a lot of energy can be recovered, and control is exercised over the air flows.

Ventilation during summer is in some of the glazed spaces achieved by opening vents. Openable vents are a means of reducing the temperature in the glazed space during warmer periods. Vents at both low and high levels in the glazed space will act as inlets and outlets and the warm air rises up and out through the vents in the roof. Care must be taken not to cause draughts in places where people are present. If the glazed space is used mainly for communication and people are just passing through, the required level of comfort is of course much easier to satisfy than if the glazed space is used as a working place.

In the glazed spaces described in Chapter 5 which mainly use passive climatic control, opening of vents and the use of solar curtains are a means of reducing the temperature during the summer. The vents can be either manually or automatically controlled. In the larger glazed spaces, such as in the blocks *Tärnan, Gårdsåkra* and *Pigg-varen*, the vents are automatically controlled. The control equipment is connected to temperature sensors and smoke detectors in the glazed space and to humidity (rain) and wind sensors outside. Results from field measurements and calculations show that these glazed spaces can attain an acceptable temperature level in the summer if the vents and solar curtains are used. To use only vents as a means of reaching an acceptable temperature, without the use of shading devices, is very difficult. The solar gains can be very large and if at the same time the outside temperature is high, merely opening the vents is not very efficient. Calculations for *the proposed glass roof over the abbey ruins at Hamar* showed that with ventilation alone the maximum temperatures will still be 35 - 40°C. Most of the effect from the ventilation of this glazed space is obtained through the first 2 - 3 air changes per hour. A higher ventilation rate is therefore not meaningful. This type of glazed space is greatly exposed to solar radiation which means that high temperatures must be expected.

6.5.3 Conclusions

The investigated atria and also other atria demonstrate that there are many different ideas as to how an atrium is to be ventilated and how this ventilation is to be coupled to the surrounding buildings. There are also varying requirements for the temperature to be provided in the atrium. There is insufficient knowledge of the real airtightness of the completed building and of the real ventilation rate. The air flow rates which can normally be determined by measurements are those of the mechanical supply and extract air. The unknown air flows (the unintended ventilation) are air leakage between the glazed space and the surrounding buildings, between the glazed space and the external air, and between the surrounding buildings and the external air. It is shown by the rough estimates made for two atria by a multicell program for the calculation of air flow rates that these may be considerable in extent. The magnitudes of these air flow rates may have great significance for air quality and energy use. For a glazed space with passive climatic control, the lower the value of G is for the glazed space, the greater is the influence of airtightness on the temperature in the glazed space. If the glazed space is to be heated, it is essential to have an airtight envelope, just as it is for an ordinary building.

Glazed panels of the same system as that used in the atrium at Kabi Pharmacia were previously subjected to airtightness tests by the Danish Building Research Institute. The results indicate that less than one half of the air leakage measured in the atrium at a pressure difference of 50 Pa could have been predicted by pressurisation tests on individual glazed panels. The rest of the air leakage presumably takes place at the junctions between e.g. the atrium and the surrounding buildings and at other places on the roof and facades.

The newer atria studied are considerably more airtight than the older ones, as they should be since they are both heated and cooled. If the requirement concerning air leakage is assumed to be that according to Swedish building regulations for premises other than dwellings, viz. 6 m^3/m^2h, then all four newer atria would satisfy this requirement. However, since the newer atria are in principle heated to indoor temperature (and cooled in the summer), it may be appropriate to impose higher airtightness requirements in order to reduce the energy need.

Instead of using only cooled supply air to prevent the temperature from reaching unacceptable values in the summer, openable vents and solar control curtains should be used to the greatest possible extent.

6.6 Curtains used as solar control or insulation

In some glazed spaces curtains are used as solar control. The effect of solar control was discussed in Section 4.7. External sunshades are most effective since they prevent the entry of solar radiation into the glazed space. Internal sunshades can also be effective however if solar radiation is retained high up in the space and heat is removed through vents in the roof before it reaches the occupied zone. A brief description of some case studies on glazed spaces is given in Chapter 5. Some of these glazed spaces have solar control curtains.

Solar control curtains will presumably not be installed in *the glazed roof over the abbey ruins at Hamar* since one of the fundamental requirements is that it is the ruins and not the climatic protection, i.e. the glazed construction, that should be prominent. Solar control curtains would nullify the "invisibility" of the glazed roof which is aimed at. At excessive temperatures the ruins must instead be studied from the outside. Calculations show that at a ventilation rate of 2-3 ach solar control curtains in the roof would further reduce the maximum temperature by about 5°C. In spite of this, maximum temperatures of ca 35°C must be expected on a hot summer day.

In the *glazed verandas at Smålands Taberg*, solar control curtains were installed right at the beginning. These curtain were of cotton and were installed on the inside of the sloping glazed roof and inside the southerly glazed wall. In combination with open vents, this was found to be an effective way of keeping temperature down on hot summer days. The air temperature was reduced and because the curtains also enabled people to use the veranda without being exposed to direct solar radiation, comfort was in most cases acceptable. Owing to condensation and because rain sometimes penetrated into the verandas, the curtains became mouldy. Curtains used in glazed spaces should therefore be made of synthetic materials.

The glazed balconies at Sätuna were not fitted with sunshades in the beginning. These glazed balconies do not have such a high proportion of glass as the glazed verandas at Taberg, but they still receive a large amount of solar radiation in the summer. Some of the occupants have themselves installed curtains inside the windows or have awnings outside.

The glazed courtyard at Tärnan had solar control curtains fitted right at the beginning. These are placed horizontally below the glazed roof and serve both as a sunshade and overnight insulation. See Section 5.5. The curtains and vents are automatically controlled. Measurements show that transmission of solar radiation through the curtains is ca 40% (Wall, 1992a). The rest of the solar radiation is retained underneath the glazed roof or is reflected back again towards the outside. The warm air between the curtains and the glazed roof can be removed through vents in the roof. Since the curtains can be drawn in a double layer, they are also used as overnight insulation. The insulation effect of the curtains is about the same as that of single glazing. The way the temperature under and above the curtains is influenced when the curtains are used as overnight insulation is shown in Figure 6.6. Measurements show the temperature above and below the curtains and the outside temperature on 31 January 1987. The outside temperature does not vary a lot during the day and is between 1 and 3°C. For a short time during the day, global solar radiation has a maximum value of ca 200 W/m^2. The curtains were drawn in a double layer during the night and were fully open during the day. The temperature just below the glazed roof and above the curtains increases by about 5°C as soon as the curtains are drawn back since the curtains no longer prevent the upward rise of warmer air from further down. At the same time, the temperature below the curtains decreases until it is largely the same at both levels. In the evening when the curtains are drawn again, the temperature above the curtains drops rapidly.

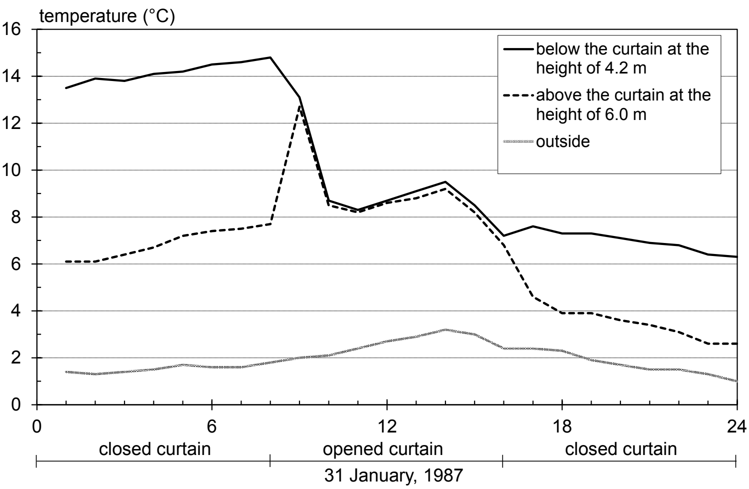


Figure 6.6 *The effect of the curtain on the temperature in the glazed courtyard at Tärnan on 31 January 1987 (Wall, 1992a).*

At the *glazed street at Gårdsåkra* no solar control curtains were installed initially, but in the first summer the temperature in the street rose to high levels, especially on the access balconies on the second storey below the glazed roof. In addition, when people were on the balcony they were also directly exposed to solar radiation, and this further reduced comfort. Solar control curtains were therefore installed during the first summer. These are the same type as those at Tärnan and are also automatically controlled together with the vents.

At the *glazed courtyard at Piggvaren*, curtains were fitted right at the beginning. These were however single ones and not the double type which had been planned and is installed at Tärnan and Gårdsåkra. Automatic control of the curtains also did not work (Blomsterberg, 1993). This was presumably one of the reasons why the temperature in the glazed courtyard was lower than had been intended.

The *central atrium at the Kabi Pharmacia buildings* was fitted with solar control glass of low solar energy transmission; see Section 5.8. No solar control curtains were however installed initially. The atrium contains a reception for visitors and a lunch room, as well as a cafeteria on the second storey below the glazed roof. It was however found that solar radiation was too powerful, and since the floor and walls are very light in colour daylight was extremely strong and caused glare. During the first summer solar control curtains were therefore installed below the glazed roof above the cafeteria on the second storey. Venetian blinds were also installed in certain parts of the glazed roof.

Neither the *atrium at Scandinavian Center* nor the *atrium at Sirius* have solar control curtains. The atrium at Scandinavian Center has large glazed surfaces since it has two large glazed gables. Sirius, on the other hand, has only a glazed roof which obviously limits solar radiation. These atria are mainly used as circulation spaces and have no occupied zones near the glazed roof. Both atria have glass of low solar radiation transmission. It is surely due to these factors that there has been no need for solar control curtains. The supply air is also cooled in the summer.

The atrium at the Oncological Clinic in Lund was fitted with solar control curtains right at the beginning in spite of the fact that the glass has low transmission for solar radiation. The atrium has a large glazed roof which mainly faces south and a glazed gable facing west. Curtains were installed below the glazed roof on the south side. Since the atrium is used as a waiting room for patients, comfort requirements were high, and the atrium is both heated in the winter and cooled in the summer to 22°C. Calculations at the preliminary design stage showed that solar control curtains could reduce the temperature during the day by at least 4°C and would at the same time protect those in the atrium from direct exposure to solar radiation.

It seems quite common for sunshades to be installed at a later stage, i.e. during the first summer. One reason for this may be that it is difficult to judge the influence of solar control curtains on temperatures, energy requirements and comfort. Not enough is known of the thermal characteristics of different sunshades and the way they function in combination with a glazed surface depending on whether they are fitted inside, between the panes or on the outside. It is therefore difficult to calculate total cost and the pay-off period. This is also the reason why it is difficult to justify sunshades at the preliminary design stage, which means that the first summer has to demonstrate the need for these. This may unfortunately have the result that total cost is higher and the cooling plant is designed incorrectly.

6.7 The glazed space as a part of the ventilation system

The glazed space can be used as part of the ventilation system of the whole building. In order to reduce the ventilation losses of the adjacent buildings, the glazed space can be used to preheat the supply air for these buildings. If however the temperature level in the glazed space is to be higher than can be achieved by passive climatic control, the air exhausted from the adjacent buildings can be supplied to the glazed space. The way different systems can influence the temperature in a glazed space and also influence the energy requirement was discussed in Section 4.8. A combined ventilation system for the glazed space and buildings can be used to reduce the energy requirement in adjacent buildings and at the same time to raise the temperature level in the glazed space. Some of the glazed spaces described in Chapter 5 have made use of different types of combined ventilation systems.

The flats for the elderly at Sätuna each have a glazed balcony and also a solar collector; see Section 5.4. The flats have a mechanical extract system and draw their supply air from the glazed balconies. In turn, the glazed balconies take in air through the solar collectors sited outside each glazed balcony. The difficulty is that there is no alternative way of admitting supply air. The supply air to both the glazed balcony and the flat is therefore preheated in the summer, which is undesirable. Measurements show that already in the spring the temperature in the middle of the day may be as high as 50°C in the solar collector (Wall, 1994a). Calculations show that in the summer the temperature in the solar collector may come up to 90-100°C. A glazed balcony of this type is warm enough on a sunny summer day without supply air at such high temperature. And the glazed balcony must in addition serve as the source of supply air for the flat.

In northern Europe the winter is characterised by very low solar radiation in combination with long nights and low outside temperatures. This means that the air in the solar collector is hardly warmed at all over a large part of the winter. Since the supply air for the glazed balcony is then not preheated and direct gains through transmission of solar radiation are very limited, the supply air for the flat is cold during the dark hours of the day. The supply air terminal for the flat is in the living room. Unsuitable placing of the terminal may easily give rise to cold downdraughts and unpleasant draughts.

Measurements and calculations with the air flow program MOVECOMP showed that ca 60% of the supply air of the flat entered via the glazed balcony (Sundbom, Nilson & Blomsterberg, 1996). It was estimated that ca 90% of the supply air into the glazed balcony entered via the solar collector. Calculations were made with DEROB-LTH for the period October-April in the reference year 1971 (Wall, 1994a). With the actual configuration, the energy increment due to preheating of the supply air was estimated at ca 870 kWh which is equivalent to ca 7% of the energy needed to heat the flat. Of this energy increment, the solar collector accounted for only ca 170 kWh. If the area of the supply terminal between the glazed balcony and the flat is increased by 60%, the total energy increment rises to ca 930 kWh. The flow of outdoor air via the glazed balcony has then been increased by ca 13%. If the supply terminal in the flat which directly takes in outside air is closed, so that more air is forced to enter through the glazed balcony, the air flow rate through the glazed balcony is increased by ca 25% compared with the "real" air flow rate. The energy gain then further increases to ca 990 kWh. One conclusion is that there is no justification for the solar collectors. Saving of energy due to the glazed balconies cannot on its own justify their construction.

Both the *glazed courtyard at Tärnan* and *the glazed street at Gårdsåkra* are used to preheat the supply air for the surrounding buildings. However, since both these glazed spaces have a high value of the factor G (≈ 8) and large fabric losses, this does not appreciably influence the temperature in the glazed space. At Gårdsåkra, however, where the glazed street is heated, this means that a larger volume of air in the form of supply air/infiltration into the glazed street must be heated than would have been necessary if the supply air for the adjacent buildings had not been taken from the glazed street. The contribution of the glazed courtyard to preheating the supply air for the terrace houses at Tärnan was estimated at ca 2 600 kWh in a standard year for the seven dwellings taken together (Wall, 1992a). This energy gain is equal to just over 3% of the energy needed for heating.

The *glazed courtyard at Piggvaren* is also used to preheat the supply air for the surrounding flats. There is however the difference that the heat from the air exhausted from the flats is transferred to the supply air into the glazed courtyard in a heat exchanger. Thanks to this system, the factor G can have a low value. The design value of G was 1 while the actual value was estimated at 1.3. Compared with e.g. Tärnan and Gårdsåkra, this type of glazed courtyard is affected to a greater extent by ventilation losses which may account for a considerable proportion of total losses. Blomsterberg (1993) showed through measurements and calculations that ca 30% of the supply air passed into the courtyard through the heat exchanger disappears through the leaky glazed roof. The airtightness specification for dwellings in the Swedish Building Code is 3 m^3/m^2h at 50 Pa. If the glazed courtyard had satisfied this requirement, heating for the flats would according to Blomsterberg have been reduced by ca 10%. In this type of glazed courtyard an airtight construction is important, with regard to both surrounding buildings and the temperature level in the glazed courtyard which in this case was lower than expected.

Siriushuset has an atrium where only the roof is glazed. The area in contact with the surrounding buildings is approx. three times as high as the area of the glazed roof. This means that the temperature level would have been relatively high even if the atrium had had passive climatic control. In this building also, the ventilation system is a combined one. Heat from the air exhausted from the atrium is transferred in a heat exchanger to the supply air for the surrounding buildings. Extract air from the atrium is also blown down into the basement. Supply air for the atrium is taken partly from outside and partly from the surrounding buildings without passing through a heat exchanger; see also Section 5.10. The outside air can be either heated or cooled as necessary before being passed into the atrium. This ventilation system makes good use of the opportunity to provide a high temperature level in the atrium in the winter months without giving rise to large ventilation losses.

6.8 Auxiliary heating and cooling

In Sweden it has become common for glazed spaces to be heated in the winter and also to be actively cooled in the summer. This applies in particular in the case of large glazed courtyards in office buildings and hotels where the glazed space is used not only as a circulation space but also as a cafeteria, restaurant and reception. In such cases the required thermal comfort is obviously higher than if people only pass through the space in a hurry. Of the ten glazed spaces described in Chapter 5, six are equipped with heating systems. Of these, four are heated to indoor temperature and also have facilities for cooling in the summer.

The glazed roof over the abbey ruins at Hamar is to serve as climatic protection for the ruins. It must however be heated to keep the temperature at least above freezing. The relative heating requirement for different glazing alternatives was set out in Figure 6.2. The heating requirement in a standard year is shown in Figure 6.7; it shows the results of both a dynamic calculation with DEROB-LTH in which account is taken of solar radiation and heat storage capacity, and a steady state calculation which takes no account of either. This calculation with DEROB-LTH was performed using the version which assumes that the sky temperature is the same as the outside temperature. The calculations show that the energy needed to maintain a temperature of 1°C in the glazed construction is ca 250 MWh for a single glazed construction without a low emissivity layer (Wall, 1990a). A low emissivity layer reduces the energy requirement to ca 185 MWh. Use of a double glazed construction with a low emissivity layer or a triple glazed construction reduces energy requirement to just over 90 MWh.

The plan is that the glazed roof over the ruins will be single glazed. This means that the energy required for heating will be high, ca 107 kWh per m² of roofed-over ground area per standard year, merely to prevent the temperature in the single glazed construction from dropping below freezing. With a low emissivity layer the energy requirement is ca 77 kWh/m² per year.

Calculations performed with a later version of DEROB-LTH which takes account of the fact that the sky temperature may be different from the outside temperature show that the energy requirement is higher still (Wall, 1992b). The lowest energy requirement with single glazing is obtained with a low emissivity layer on the outside, and amounts to ca 280 MWh or 117 kWh/m² in a standard year. This single glazing is the type Pilkington Kappa Energi Float and consists of two 6 mm panes of laminated glass. If the temperature requirement is increased, the energy required will be considerably greater. A roof with singe glazing requires almost twice as much energy to maintain 5°C than 1°C. If the requirement is 9°C instead of 1°C, the energy required is three times as much.

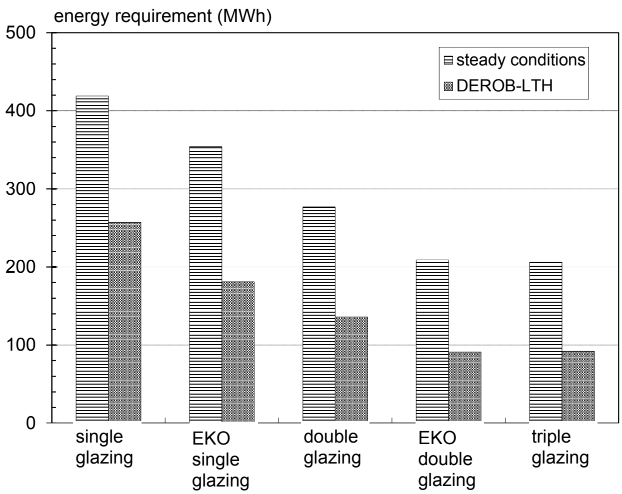


Figure 6.7 *Energy requirement during a standard year when heating to 1°C is provided. Calculations for steady conditions and with DEROB-LTH. The abbey church ruins at Hamar. The sky temperature is assumed to be equal to the outside air temperature (Wall, 1990a).*

The *glazed courtyard at Tärnan* is in principle unheated. Owing to the high value of the factor *G* in the courtyard, however, there is a risk of frost in the winter which may damage the plants set out in the courtyard. Calculations were made with the computer program DEROB-LTH; the temperature in the courtyard was estimated and compared with measurements (Wall, 1992a). The calculated and measured temperature in the glazed courtyard, and the outside temperature during the period 1/3 - 14/3/1987, are plotted in Figure 6.8. The figure shows the temperature in the lower part of the courtyard up to a height of 3.2 m. Global solar radiation was ca 500 W/m² in the middle of the day, with the exception of 4th and 8th March when the maximum value was ca 200-300 W/m². The curtains were drawn double overnight and were fully open during the day. The vents were closed during the period.

The calculated temperature in Figure 6.8 is based on passive climatic control in the courtyard, i.e. no heat is supplied. According to the calculations, the temperature in the glazed courtyard ought to drop to ca -4°C. The measured temperature in Figure 6.8 shows that this was not the case. On the first night during the period the temperature was below freezing, but during the rest of the first week the measured temperature was appreciably higher than that calculated. This is due to the fact that two 9 kW building driers were placed in the glazed courtyard to provide extra heat during extremely cold periods. Unfortunately, we did not know that these driers were used until after the event, and therefore no record was made of how long they were in operation. By comparing different calculation cases with measurements, it would seem however that both heaters were on during the night and one of them also during the day in the first week of the period. During the second week no extra heat was needed. In Figure 6.9 the temperature in the lower part of the courtyard is plotted on the basis of this theory and compared with the measured temperature. The agreement is much better even though certain differences still remain.

In order to keep the glazed courtyard frost free in 1987, ca 8-10 MWh would have had to be supplied; see Figure 6.10. This figure shows the energy requirement in the courtyard for different minimum temperature requirements. The top curve shows the total energy requirement. The bottom curve shows the reduction in heating requirement in the adjacent buildings due to the higher temperature level in the glazed courtyard, compared with passive climatic control. The reduction in energy requirement is defined as zero when the courtyard is not heated. The third curve shows the net energy requirement, i.e. the total amount of energy which must be supplied to the glazed courtyard *less* the saving in adjacent buildings. As will be seen, heating of this glazed courtyard cannot be compensated for by a reduction in the energy requirement in adjacent buildings. Occasional heating of the courtyard to keep it free of frost may however be considerably cheaper than to buy new plants. When the temperature requirement is increased, the energy needed to heat the glazed courtyard increases at a considerably higher rate than that at which the energy requirement in adjacent buildings is reduced. In order to maintain the temperature at a minimum 10°C in the courtyard, ca 50 MWh is needed. As has already been pointed out in Section 6.2, the glazed courtyard ought to be at least double glazed if it were to be heated continuously.

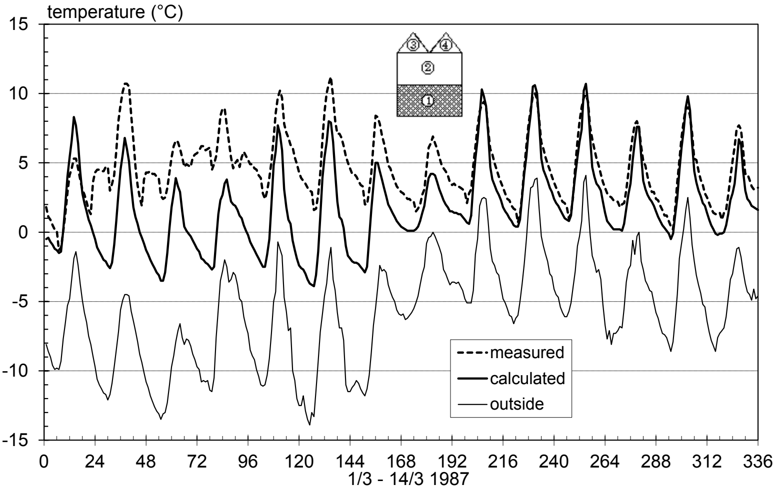


Figure 6.8 *Calculated and measured temperature in the lower part of the glazed courtyard at Tärnan during two weeks in March 1987. The outside temperature is also shown. The calculations do not allow for heating (Wall, 1992a).*

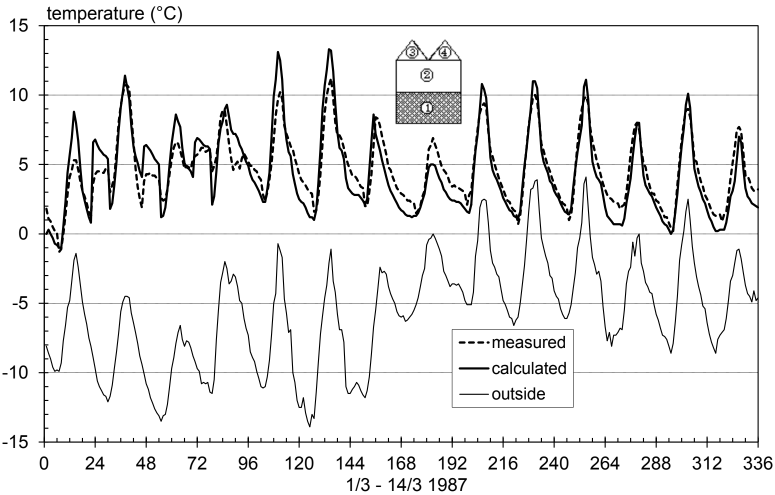


Figure 6.9 *Calculated and measured temperature in the lower part of the glazed courtyard at Tärnan during two weeks in March 1987. The outside temperature is also shown. The calculations allow for heating (Wall, 1992a).*

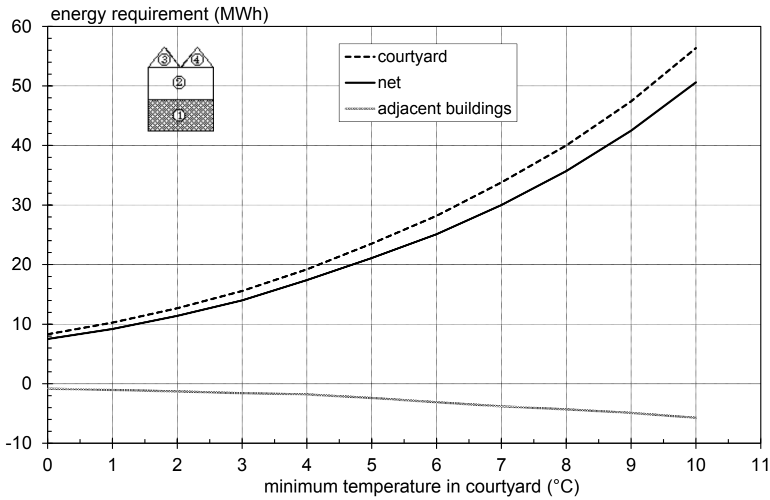


Figure 6.10 *Energy required in 1987 to maintain a certain minimum temperature in the glazed courtyard at Tärnan, the reduction in energy requirement in the surrounding buildings and the net energy requirement. The energy requirement in the adjacent buildings is defined as equal to zero when there is no heating in the courtyard (Wall, 1992a).*

The temperature in the *atrium at the Oncological Clinic* must be maintained at 22°C throughout the year, which means that the atrium is both heated during the winter and cooled during the summer. Calculations of the heating and cooling requirements were made at the preliminary design stage.

These calculations for the Oncological Clinic showed that the heating requirement is greatly influenced by the airtightness of the glazed construction; see Chapter 5, Figure 5.42. The reference year for Malmö 1971 was used in the calculations. With a completely airtight construction the energy needed for heating the atrium to 22°C would be ca 55 MWh, while infiltration corresponding to 1 ach in the atrium would increase the energy requirement almost three times, to ca 150 MWh. A reasonable airtightness may be 0.3 ach which would result in just under 85 MWh in heating requirement.

The cooling requirement was also calculated for the atrium in the Oncological Clinic. The condition was that the temperature was not to rise above 22°C. Infiltration in the atrium was put at 0.3 ach. It was also assumed that the curtains were drawn below the southerly glazed roof during the day. The cooling requirement for the whole of 1971 was calculated as ca 37 MWh. This energy is a measure of the amount of energy that must be removed by ventilation with outside air or the supply of cooled air. Obviously, the use of vents, the thermal characteristics of the curtains and the operational strategy also affect the cooling requirement.

6.9 Solar radiation

Naturally, solar radiation has very great significance for the climate in a glazed space and also great significance for the heating or cooling requirement. The significance of solar radiation varies depending on the type of glazed structure and the choice of glass type, as discussed in Section 4.10. The solar collection property *S* which was discussed in Chapter 3 for four different types of glazed space is a good measure of how effective the glazed structure is as a solar collector. The solar collection property *S* is defined as that proportion of the transmitted solar radiation which remains in the glazed space and is thus an energy gain.

All the enclosing surfaces of the *glazed roof at the abbey ruins at Hamar* are of glass, and large quantities of solar radiation are therefore transmitted into the glazed structure during the light part of the year. Owing to the fact that, due to the ruins, the glazed structure has a high heat storage capacity, it will be possible for some of the solar radiation to be absorbed into the walls to the benefit of the glazed structure. By comparing dynamic calculations of the heating requirement, carried out with DEROB-LTH, with steady state calculations without the effect of solar radiation, utilisation of solar radiation by the glazed roof can be studied. Utilisation of solar radiation by different types of glass is set out in Figure 6.11. The lower the U value of the glazed structure, the better is solar utilisation. The order of magnitude of the contribution due to solar radiation is one half of the heating requirement.

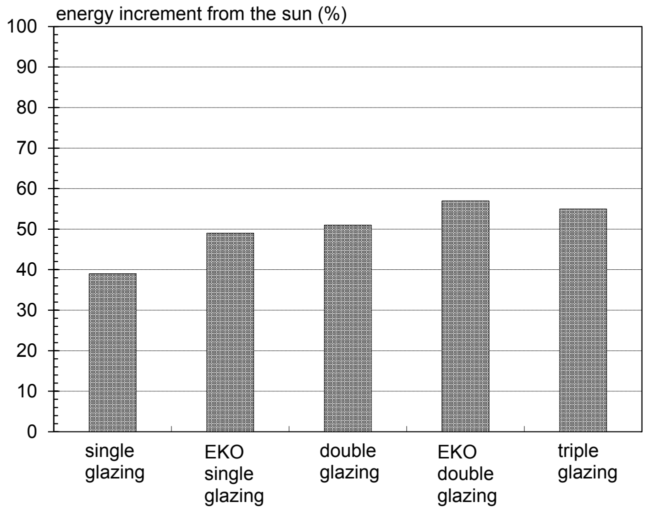


Figure 6.11 *Energy increment due to insulation. The abbey church ruins at Hamar (Wall, 1990a).*

The glazed courtyard at Tärnan is also highly dependent on solar radiation. During periods with cloudy weather in the winter, temperature fluctuations over the day are very small. As an example of this, measurements and calculations relating to two weeks in December 1987 are shown. Global solar radiation measured over the period 18/12 - 31/12/1987 at Tärnan is plotted in Figure 6.12. Solar radiation is low, and all radiation is diffuse. The temperature measured in the lower part of the courtyard during the same period and the temperature calculated with DEROB-LTH are plotted in Figure 6.13. The measured outside temperature and the temperature in the courtyard according to a steady state calculation which takes no account of solar radiation are also plotted. This steady state calculation is performed according to Equation 4.2, and for the glazed courtyard at Tärnan this means

$$T_g = T_o + \frac{1}{1 + 7.6} \cdot (T_i - T_o) \tag{6.1}$$

where

T_g = temperature in the glazed courtyard (°C)
T_o = outside temperature (°C)
T_i = mean temperature in adjacent buildings during the period (°C)

During the period in December the mean temperature in the adjacent buildings is 20.7°C. This mean temperature is weighted with respect to the different facade areas of the two long buildings facing the glazed courtyard. The vents were closed during the whole period and infiltration was set at 0.6 ach. The solar control curtains were drawn double at night and completely open during the day. Figure 6.13 shows that the temperature in the courtyard has small variations over the day and remains between 6 and 10°C during the period. The temperature calculated under steady state conditions is at times very near the measured temperature and the dynamically calculated temperature, which implies that the influence of solar radiation is insignificant and there is little heat storage capacity. The temperature in the glazed courtyard calculated with DEROB-LTH is in good agreement with the measured temperature.

In the spring the solar radiation is considerably more powerful and thus has greater significance for the temperature in the glazed courtyard. The global solar radiation measured during two weeks in April 1987 is plotted in Figure 6.14. The period comprises both sunny and cloudy days. The temperature measured in the lower part of the courtyard and the temperature calculated with DEROB-LTH are plotted in Figure 6.15. The measured outside temperature and the temperature in the courtyard calculated under steady state conditions with no account taken of solar radiation are also plotted. The steady state calculation of temperature in the courtyard is performed in accordance with Equation 6.1. During this period, the mean temperature in the adjacent buildings is 21.9°C; the vents were closed and infiltration was set at 0.6 ach. The solar control curtains were drawn double at night and were fully open during the day.

Figure 6.14 shows that the temperature in the courtyard varies steeply between day and night on the sunny days, while during 8-10 April when it is cloudy the temperature fluctuations are appreciably smaller. This is due to both the powerful solar radiation on the clear days and the fact that the outside temperature also has greater fluctuations over the day at the same time. On the warmest day, the outside temperature is ca 11°C in the middle of the day, and the temperature in the courtyard at the same time is ca 19°C. During this period the difference between the steady state calculation and the measured temperature (and the temperature calculated with DEROB-LTH) is much greater than during the period in December. This is due to the influence of solar radiation. During this period also, the temperature in the courtyard which is calculated with DEROB-LTH is in good agreement with the measured temperature.

To sum up, solar radiation may be said to have very great significance for the climate in a glazed space, and it is therefore very important that, in assessing the climate and energy requirements, the energy gain due to solar radiation should be calculated accurately.

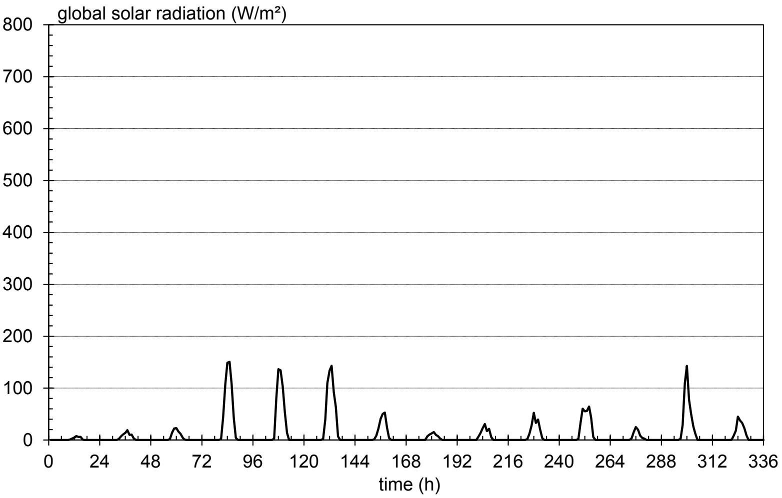


Figure 6.12 *Global solar radiation on a horizontal surface measured during two weeks in December 1987. The glazed courtyard at Tärnan (Wall, 1992a).*

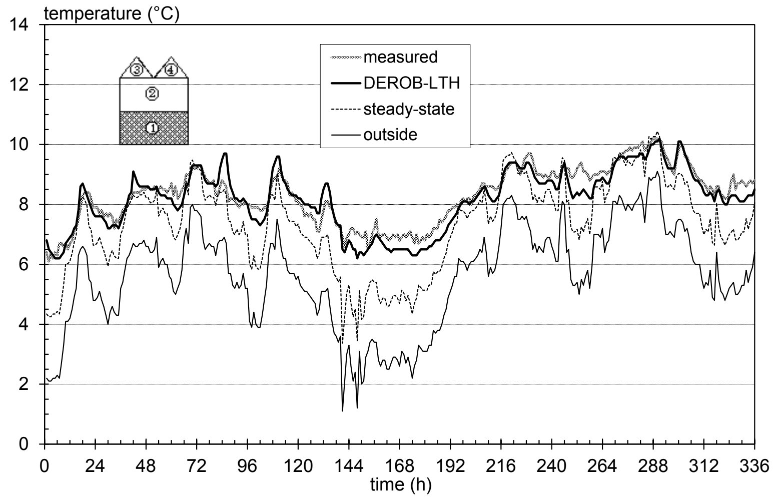


Figure 6.13 *Calculated and measured temperature in the lower part of the glazed courtyard at Tärnan during two weeks in December 1987 (Wall, 1992a).*

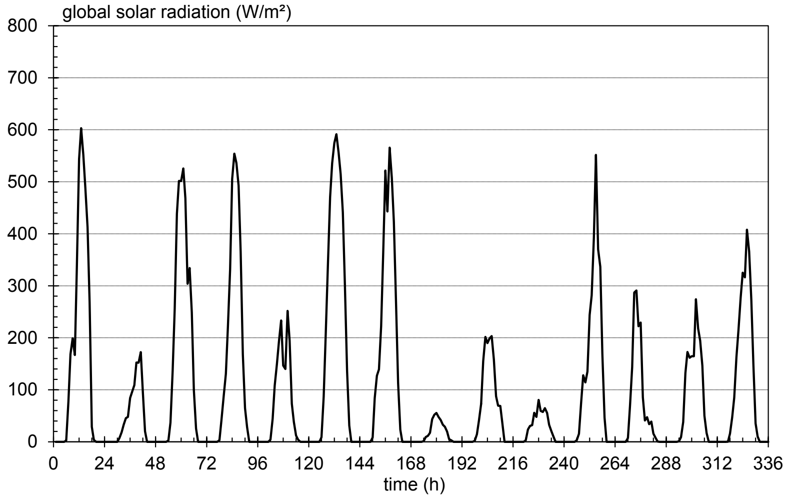


Figure 6.14 Global solar radiation on a horizontal surface measured during two weeks in April 1987. The glazed courtyard at Tärnan (Wall, 1992a).

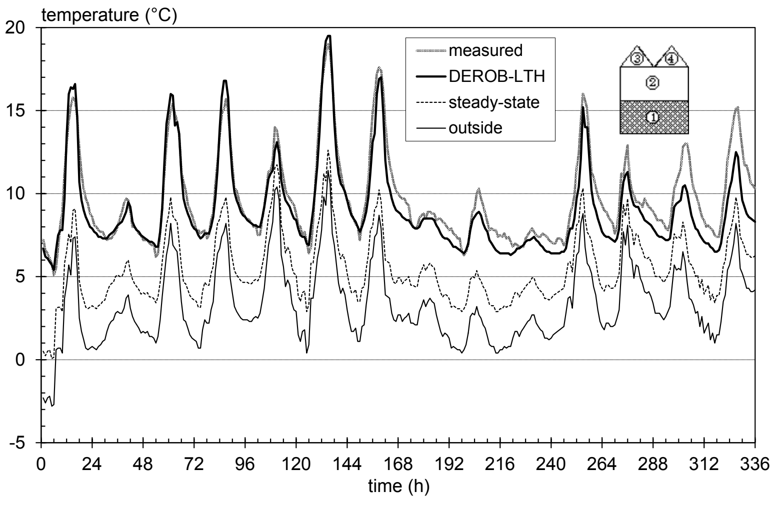


Figure 6.15 Calculated and measured temperature in the lower part of the glazed courtyard at Tärnan during two weeks in April 1987 (Wall, 1992a).

6.10 Long wave sky radiation

Long wave sky radiation can be of importance when the energy balance for buildings is calculated, especially when glazed spaces are involved. Field measurements in the glazed courtyard at Tärnan showed that the measured temperature just below the single glazed roof was at times even lower than the outside temperature. The measured temperature below the glazed roof, together with the outside temperature on four days in December 1987, is plotted in Figure 6.16. Figure 6.16 shows that, over periods of some hours, the temperature in the glazed space is lower than outside. Sky radiation evidently has an effect, and unless this is taken into account it is difficult to estimate accurately the temperature in the upper part of a glazed space and the energy requirement.

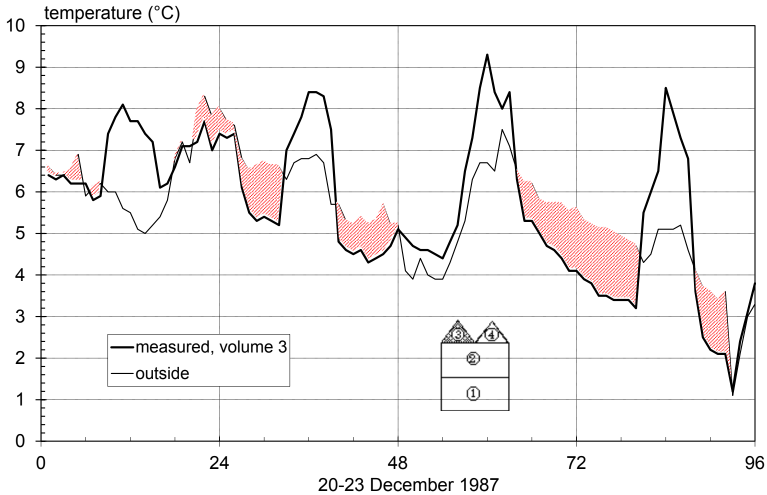


Figure 6.16 *Measured temperature in volume 3 and outside temperature during 20 - 23 December 1987. The shaded portions show when the temperature in volume 3 is lower than the outside temperature. The glazed courtyard at Tärnan (Wall, 1992a).*

In earlier versions of DEROB-LTH the sky temperature was assumed to be equal to the outside temperature. This can be true for an overcast sky. In DEROB version V9302, the sky temperature became a part of the input data in the climatic file, together with outside temperature and solar radiation.

The long wave sky radiation is measured by the Swedish Meteorological and Hydrological Institute (SMHI) at some places in Sweden. When field measurements are made it is advisable to measure the long wave sky radiation as a complement to the other normally measured climatic data (outside temperature, solar radiation, wind speed).

In many cases it is still necessary to have the capability to calculate the sky temperature and thus sky radiation. The aim is to find a way of calculating long wave sky radiation on the basis of "normal" climatic data. In this study, some methods of calculating the long wave sky radiation were tested and compared with measurements.

6.10.1 Calculation of long wave sky radiation and sky temperature

In order to calculate long wave sky radiation, the sky temperature and sky emissivity are required. These parameters are usually unknown but the following approach can be used. The long wave radiation can be calculated as

$$R = \sigma \cdot T_{sky}^4 \tag{6.2}$$

where

R = long wave sky radiation (wave length > 4 μm) (W/m²)
σ = 5.6696 · 10^{-8} (W/m²K⁴) (Stefan-Boltzmann Constant)
T_{sky} = sky temperature (K)

In Equation 6.2, the sky is considered to be a black body with the emissivity equal to 1.

The sky emissivity can instead be related to the air temperature at ground level and defined as

$$\varepsilon_{sky} = \frac{R}{\sigma \cdot T_o^4} \tag{6.3}$$

where

ε_{sky} = sky emissivity (-)
T_o = air temperature at ground level (K)

If the sky emissivity is known, the long wave radiation can then be calculated as

$$R = \varepsilon_{sky} \cdot \sigma \cdot T_o^4 \tag{6.4}$$

Combining Equations 6.2 and 6.4 results in

$$T_{sky} = \varepsilon_{sky}^{1/4} \cdot T_o \tag{6.5}$$

which is the sky temperature needed as input data for DEROB-LTH. The sky temperature is then used to calculate the long wave radiation between external surfaces and the sky.

6.10.2 Measurements of long wave sky radiation

The long wave sky radiation is measured by the Swedish Meteorological and Hydrological Institute [SMHI] at some places in Sweden. Measurements from five places were studied, from the town of Lund in the south of Sweden (latitude 56°N) to the town of Luleå in the north (latitude 66°N); see Figure 6.17.

The monthly mean sky temperature and the outside temperature in Lund during 1991 are shown in Figure 6.18. The sky temperature is calculated from Equation 6.2 and is based on measurements of long wave radiation. The mean sky temperature is approximately 10°C lower than the outside temperature. This difference can of course be much larger during shorter periods. The minimum radiation in Lund during 1991 was 178 W/m², measured on the 14th of February (during the night). It corresponds to a sky temperature of approx. -36°C. At the same time the outside temperature was -8°C. The maximum radiation during this year was 422 W/m² (corresponding to approx. 21°C) and the mean value was 303 W/m² (-3°C).

In Figures 6.19 - 6.21, the corresponding measurements are shown for Stockholm, Borlänge and Luleå. Both the outside temperature and the sky temperature are lower in the northern part of Sweden.

Figure 6.17 Places in Sweden where the long wave sky radiation is measured.

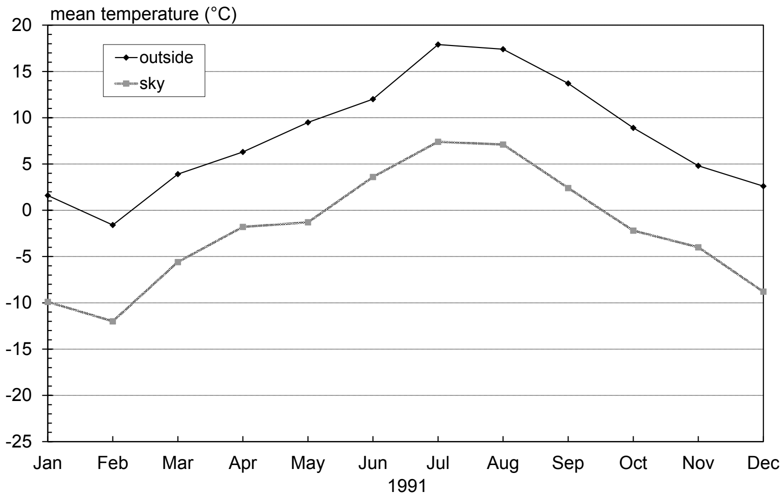


Figure 6.18 Monthly mean sky temperature and outside temperature in Lund, 1991.

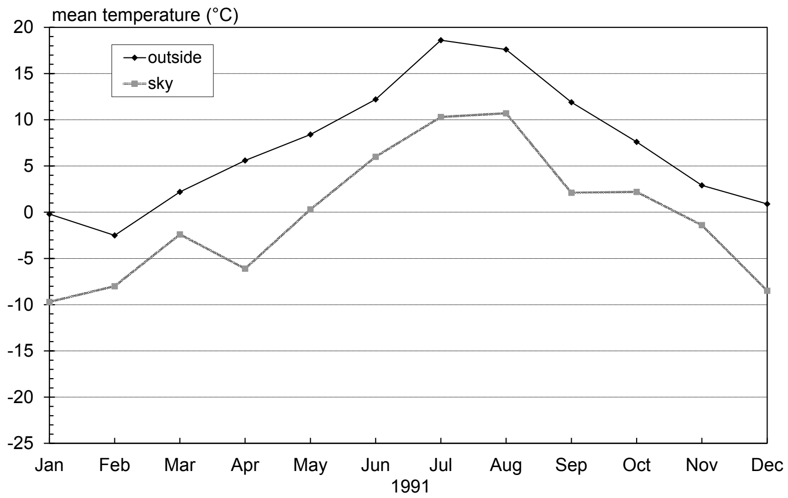


Figure 6.19 *Monthly mean sky temperature and outside temperature in Stockholm, 1991.*

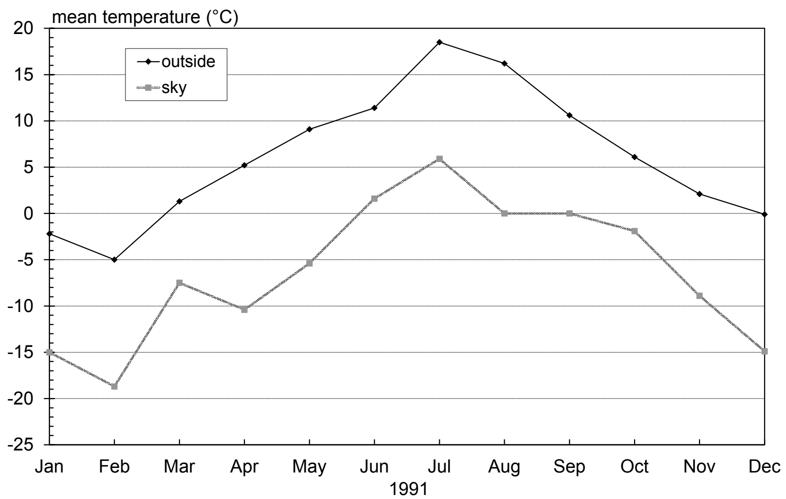


Figure 6.20 *Monthly mean sky temperature and outside temperature in Borlänge, 1991.*

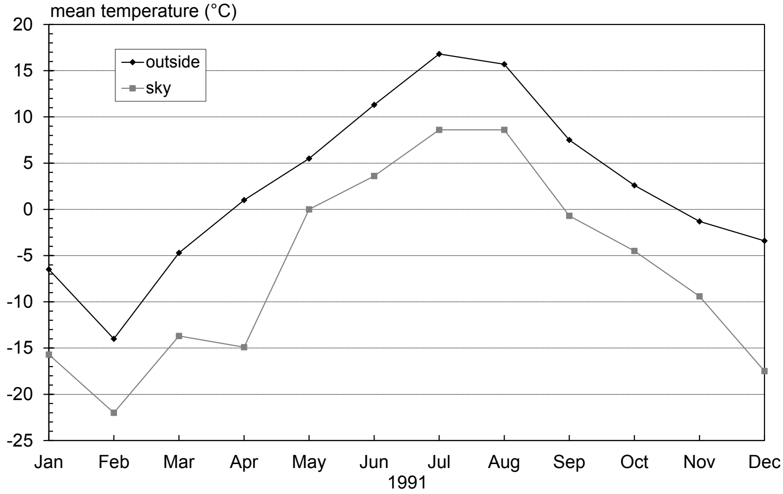


Figure 6.21 *Monthly mean sky temperature and outside temperature in Luleå, 1991.*

6.10.3 Algorithms for calculation of the sky emissivity

One study of the sky emissivity was made by Martin & Berdahl, Lawrence Berkeley Laboratory, University of California, Berkeley (1984). This work is based on an empirical and theoretical model of clouds, together with a correlation between the clear sky emissivity and the dew point temperature.

The *monthly* average *clear* sky emissivity is obtained from the relationship

$$\varepsilon_0 = 0.711 + 0.56 \cdot \left(\frac{T_{dp}}{100}\right) + 0.73 \cdot \left(\frac{T_{dp}}{100}\right)^2 \tag{6.6}$$

where

ε_0 = clear sky emissivity (-)
T_{dp} = dew point temperature (°C)

In order to predict *hourly* emissivities, the following correction is added

$$+0.013 \cdot \cos\left[2\pi \cdot \frac{h_D}{24}\right] \tag{6.7}$$

where

h_D = the hour of the day

A correction for the atmospheric pressure, p_{atm} (mbar) is also added

$$+ 0.00012\,(p_{atm} - 1000) \tag{6.8}$$

The sky emissivity during both *clear and cloudy* days is calculated as

$$\varepsilon_{sky} = \varepsilon_0 + (1 - \varepsilon_0) \cdot c_n \cdot \varepsilon_c \cdot e^{-c_h / c_{h0}} \tag{6.9}$$

where

ε_{sky} = sky emissivity (-)
ε_0 = clear sky emissivity (-)
c_n = fractional area of the sky covered by clouds (-)
ε_c = hemispherical cloud emissivity (=1)
c_h = actual cloud base height (km)
c_{h0} = 8.2 km

This algorithm was tested but first it was simplified to

$$\varepsilon_{sky} = \varepsilon_0 + (1 - \varepsilon_0) \cdot c_n \cdot e^{-0.5} \tag{6.10}$$

which means that the clouds are assumed to be at a medium height level. ε_{sky} was then put into Equation 6.4 in order to calculate the long wave sky radiation.

The problem with Equation 6.10 is to estimate the cloud cover. As one possibility, cloud observations from an airport about 30 km outside Lund were used. Another way to estimate the cloud factor c_n was to compare measured direct solar radiation of perpendicular incidence with the theoretical radiation on clear days (Brown & Isfält, 1974). The following relationship is then obtained

$$c_n = 1 - \frac{I_{D,m}}{I_{D,c}} \tag{6.11}$$

where

$I_{D,m}$ = direct solar radiation of perpendicular incidence, *measured* (W/m²)
$I_{D,c}$ = direct solar radiation of perpendicular incidence, *calculated* for clear days (W/m²)

This suggested method for calculating the cloud factor c_n is in no way perfect. It considers only the part of the sky where the sun is situated, and not the whole hemisphere. Another problem is the nights. The mean value of the last but one value in the evening and the second value in the morning was used for the whole night. By using this method, the only climatic data needed for calculations of the sky radiation are

- outside temperature
- relative humidity
- atmospheric pressure
- solar radiation

6.10.4 Comparisons between measurements and calculations

In order to compare the calculations with measurements, measured long wave radiation from Lund was used.

In Figure 6.22 the cloud factor c_n is shown for the first week in December 1986. The solid line is the cloud factor c_n from SMHI observations 30 km outside Lund. The other line is the cloud factor calculated according to Equation 6.11, using measured solar radiation from Lund. There is a certain similarity between the lines but the agreement is not very good.

Figure 6.23 shows the long wave sky radiation during the same period. The solid line represents measurements from Lund and the other line shows the calculated radiation for *clear days*. The clear sky emissivity was calculated according to Equations 6.6 - 6.8. The long wave radiation was then calculated from Equation 6.4. The measured radiation should not be less than the calculated radiation for clear days.

Figure 6.24 also shows the measured long wave radiation during the same week but compared with calculations which take the clouds into account (Equation 6.10). One of the curves is based on the measured cloud factor and the other on the calculated cloud factor. The agreement is rather good. One problem is that we do not really know how reliable the measurements are. A calibration method for instruments measuring long wave radiation did not exist at the time.

In Figures 6.25 - 6.27, the corresponding results from a week in May are presented. The calculated radiation with a clear sky is somewhat high; this may however be due to measurement errors. The agreement in Figure 6.27 is rather good but during periods of some hours there are large differences.

The tested algorithms for calculating the long wave sky radiation appear to provide a means of making an estimation based only on “normal“ climatic data. The agreement between measurements and calculations is quite good but at times there are large differences. In spite of this, the method described is a better solution than using the outside temperature as the sky temperature. Obviously, the best solution is to measure the long wave radiation.

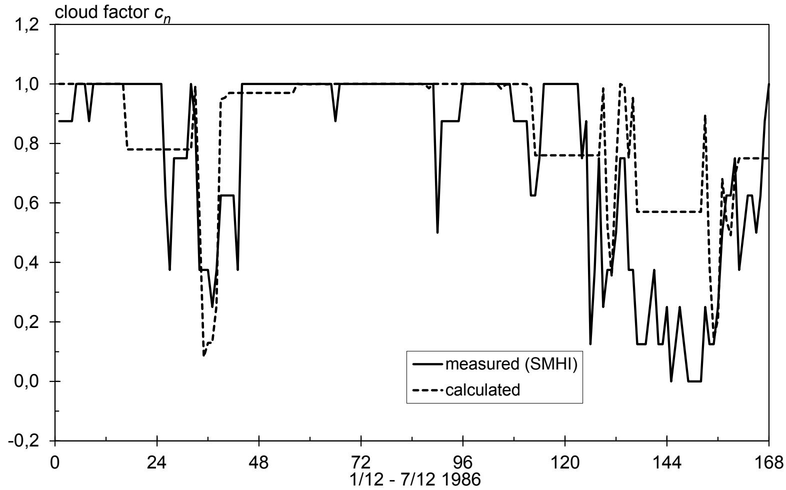


Figure 6.22 *Measured and calculated cloud factor during one week in December 1986, Lund.*

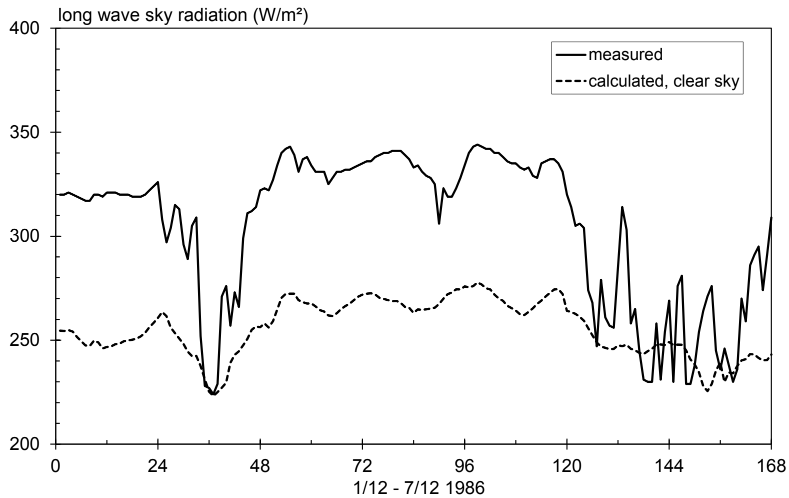


Figure 6.23 *Measured long wave radiation and calculated long wave radiation for a clear sky during one week in December 1986, Lund.*

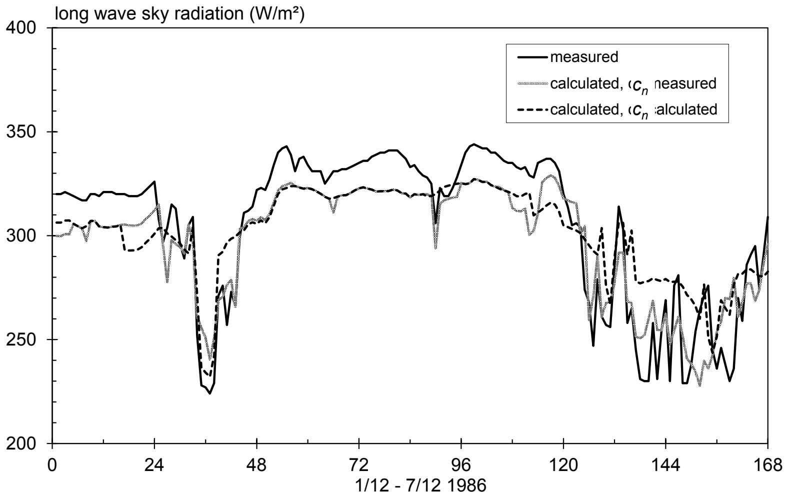


Figure 6.24 *Measured long wave radiation, calculated radiation based on measured cloud factor and calculated radiation based on calculated cloud factor. One week in December 1986, Lund.*

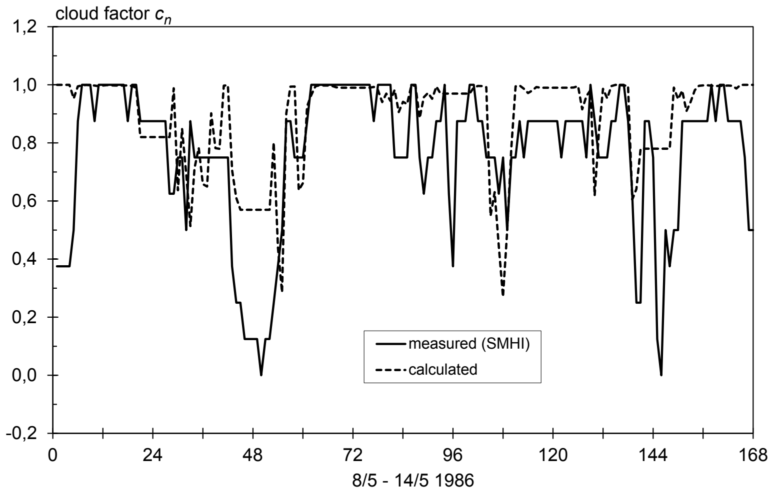


Figure 6.25 *Measured and calculated cloud factor during one week in May 1986, Lund.*

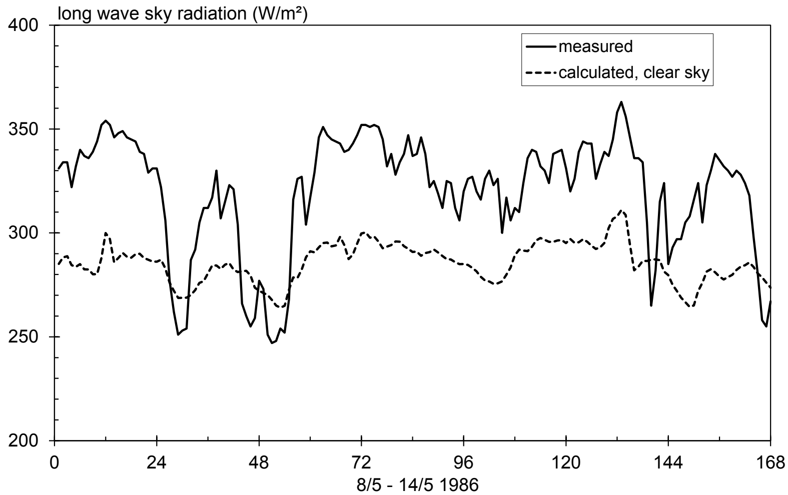


Figure 6.26 *Measured long wave radiation and calculated long wave radiation for a clear sky during one week in May 1986, Lund.*

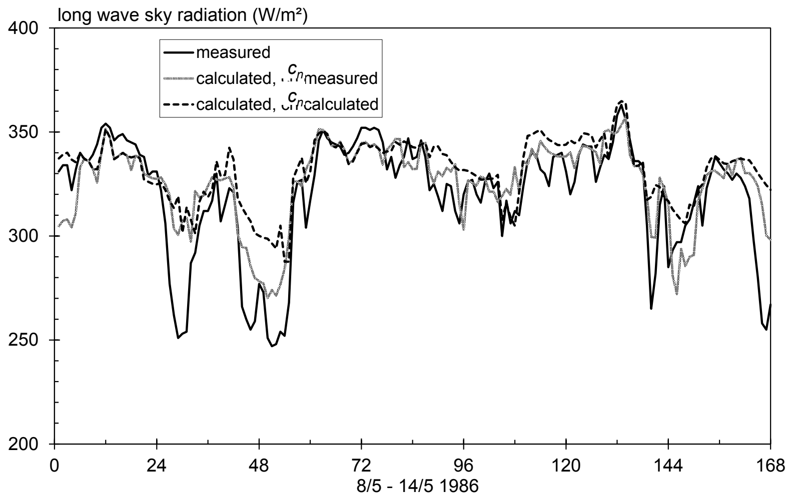


Figure 6.27 *Measured long wave radiation, calculated radiation based on measured cloud factor and calculated radiation based on calculated cloud factor. One week in May 1986, Lund.*

6.10.5 Calculated differences in energy requirement due to the sky radiation The abbey church ruins at Hamar

One example of how important the calculation of long wave sky radiation is for the estimation of energy requirements is the glazed roof over the abbey church ruins at Hamar. The first calculations were made by using the old DEROB-LTH version which assumed that the sky temperature was equal to the outside air temperature (Wall, 1990a). The energy required to maintain a temperature of 1°C in the glazed space, with single glazing without low emissivity coating, was then approx. 257 MWh for a standard year. A newer version of DEROB-LTH which took into account the sky temperature gave the corresponding energy requirement as 446 MWh. This is an increase of 74%. Of course, this glazed space is extraordinarily sensitive to sky radiation as it is single glazed and has very large surfaces facing the sky.

In this calculation the sky temperature was calculated by a very simple algorithm (Unsworth & Monteith, 1975). The calculated sky temperature was therefore probably too low on some cloudy days, which means that the difference between the above calculated energy requirements may be somewhat overestimated. The simple algorithm used was

$$T_{sky} = T_o - 25.0 + (25.0 - 3.5) \cdot c_n \tag{6.12}$$

where

T_{sky} = sky temperature (°C)
T_o = outside air temperature, ground level (°C)
c_n = cloud factor (-)

The cloud factor c_n was calculated according to Equation 6.11, using data for solar radiation once per day, at 12 noon. The calculated value of c_n was then used for the whole day.

6.11 A design tool for glazed spaces Example 1 – Glazed courtyard at Tärnan

This section provides examples of the ability of the manual calculation method described in Chapter 3 to assess temperatures and energy requirements in the glazed courtyard at Tärnan where an extensive body of measurement results is available. The measurement results and evaluations are described in Wall (1992a). The building is also described in Chapter 5.

6.11.1 Calculation of minimum temperature in the courtyard

In order to estimate the minimum temperature in the glazed courtyard, the general energy balance Equation 6.13 is used.

$$Q^t_{from} + Q^v_{from} = Q^t_{to} + Q^v_{to} + S \cdot P_{sun} + P_{heat} \tag{6.13}$$

where

Q^t_{from} = fabric losses of the glazed space (W)
Q^v_{from} = ventilation losses of the glazed space (W)
Q^t_{to} = fabric losses from the adjoining buildings to the glazed space (W)
Q^v_{to} = ventilation losses from the adjoining buildings to the glazed space (W)
S = the solar collection property of the glazed space (-)
P_{sun} = monthly mean of solar radiation transmitted to the glazed space (W)
P_{heat} = heat gain from the heating system (W)

Since the courtyard is not to be heated, the term P_{heat} is omitted. The term Q^v_{to} is also omitted as no exhaust air from the adjacent buildings is passed into the glazed space. For the calculation of the minimum temperature, a reasonable estimate is also obtained if solar radiation is not included as a gain in the energy balance, i.e. $P_{sun} = 0$. In reality, the lowest temperature in the courtyard, at a certain outside temperature, occurs when solar radiation is low.

Using the data relating to the glazed courtyard at Tärnan, the total losses are obtained as

$$Q_{from} = Q^t_{from} + Q^v_{from} = 2011 \cdot (T_g - T_o) \quad \text{(W)} \tag{6.14}$$

The ventilation losses, i.e. the leakage flow, are estimated using the measurements of the airtightness of the glazing (Wall, 1992a), and are equal to 0.6 ach.

The total gain in the courtyard is made up of the fabric losses from the surrounding buildings, and is given by

$$Q_{to} = Q_{to}^{t} = 264 \cdot (T_i - T_g) \quad \text{(W)} \tag{6.15}$$

From an energy balance which states that the losses according to Equation 6.14 are equal to the gains according to Equation 6.15, and using an assumed indoor temperature T_i = 20°C, the relationship for the minimum temperature in the courtyard is obtained as

$$T_{g,min} = 2.3 + 0.884 \cdot T_o \quad \text{(°C)} \tag{6.16}$$

Equation 6.16 has been plotted in Figure 6.28 together with measured hourly values over a whole year as a function of the outside temperature. As will be seen, the measured temperatures vary a lot depending, mainly, on solar radiation. What is important however is that the minimum temperature in the courtyard at a certain outside temperature is in very good agreement with the curve for Equation 6.16.

On the other hand, when the temperature is below freezing, the minimum temperature in the courtyard deviates from the curve for Equation 6.16. The reason for this is that, as an emergency measure, two 9 kW building driers were placed in the courtyard in order to keep the temperature above freezing, so that the plants in the courtyard should not be damaged.

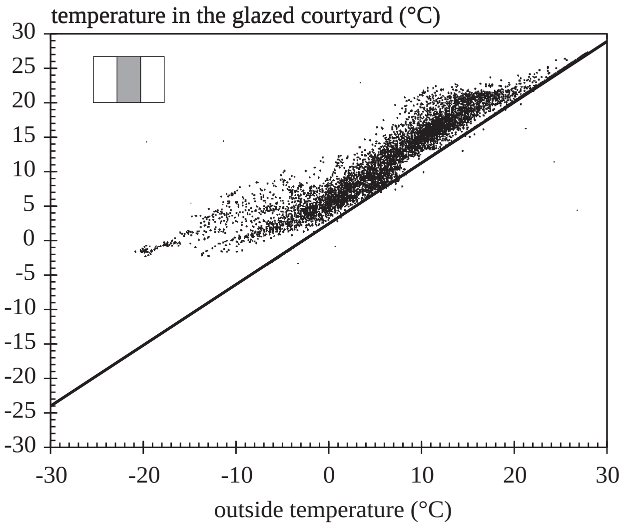


Figure 6.28 *Temperatures measured in the glazed courtyard at Tärnan in 1987 as a function of outside temperature. The points represent measured hourly values. The line shows the calculated minimum temperature in the glazed courtyard for passive climatic control (Wall, 1992a).*

6.11.2 Power required for heating

As will be seen from Section 6.11.1, the design of the glazed courtyard is not suitable for keeping the temperature above freezing by passive climatic control. The curve in Figure 6.28 indicates that when the outside temperature is about -3°C at night during a cloudy period, there is already a risk of frost in the glazed courtyard.

In order to calculate the power requirement, Equation 6.13 is used with $P_{sun} = 0$. Thus,

$$Q_{from} = Q_{to} + P_{heat} \tag{6.17}$$

Substituting the values of Q_{from} and Q_{to}, the design outside temperature $T_{o,min}$ = -15°C, the desired minimum temperature in the glazed courtyard $T_{g,min}$ = 0°C and the indoor temperature T_i = 20°C in the surrounding buildings,

$$2011 \cdot (0+15) = 264 \cdot (20-0) + P_{heat} \quad \text{(W)}$$

i.e.

$$P_{heat} = 24\,885 \text{ W}$$

The total heat losses are 30 kW. The surrounding buildings have contributed by about 5 kW. The net power requirement is thus about 25 kW.

6.11.3 Calculation of mean temperature in the courtyard

With the help of the energy balance Equation 6.13, the mean temperature of the glazed courtyard can be estimated with reference to the absorbed solar radiation. The solar collection property *S* and the transmitted solar radiation P_{sun} can be estimated with the help of the design data and the properties of the courtyard. As a first step, an illustration of how reasonable the estimates are will be given by making comparisons with the measurement results. In a second step, calculations will be set out for the reference year 1988 which was selected for the design data; see Chapter 3. The results of this latter calculation will then be used in Section 6.11.4 to estimate the energy requirement for heating.

In order to estimate the gain due to solar radiation, the absorptivity of the glazed courtyard must first be assessed. The dark brown floor of the courtyard and the white walls of the surrounding buildings have about the same area. In view of this and with regard to the solar control curtains, plants and furniture, absorptivity can be estimated as between 0.5 and 0.6. The value 0.55 will be used in the calculations below.

With the help of the design diagram and for the given configuration of the courtyard and the number of panes in the glazing, the solar collection property of the courtyard can be estimated. For this courtyard, Figure 6.29 applies, from which $S = 0.52$.

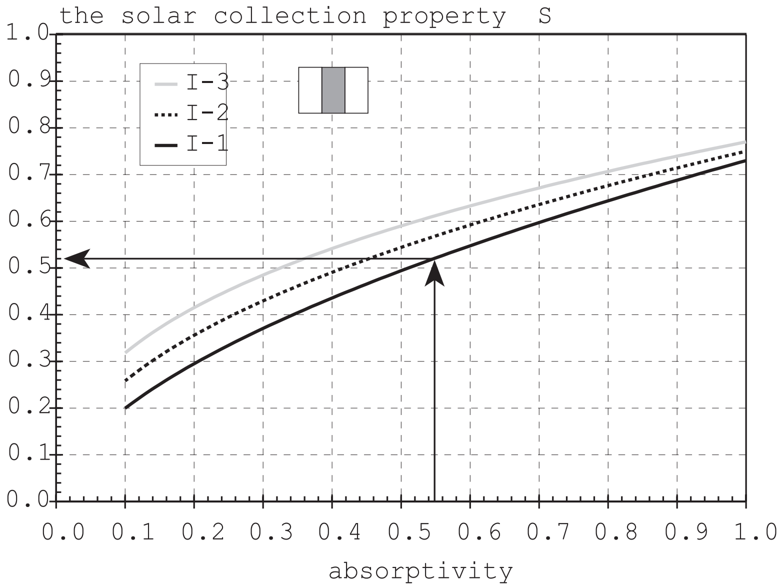


Figure 6.29 *Solar collection property as a function of the absorptivity of the glazed space with buildings on two sides (Wall, 1994b; Fredlund, 1995).*

In order to calculate the transmitted solar radiation P_{sun}, design data for the nearest location, Lund, and for single glazing, are selected. Tabulated values for vertical and horizontal surfaces and for surfaces at 30° inclination, are used in this example and are set out in Table 6.8.

Table 6.8 Solar radiation transmitted through single glazed windows in Lund in 1988 (Wall, 1994b; Fredlund, 1995).

month 1988	transmitted solar radiation vertical surfaces (W/m²)				surfaces at 30° inclination (W/m²)				horizontal surfaces (W/m²)
	north	east	south	west	north	east	south	west	
January	5	5	10	6	7	8	10	8	8
February	13	16	31	19	20	24	34	27	26
March	29	39	68	50	43	61	83	68	66
April	46	75	91	87	80	113	137	121	121
May	66	113	117	136	141	180	211	197	198
June	74	99	96	113	144	162	177	171	177
July	69	93	92	101	131	149	162	154	161
August	54	74	90	86	97	121	143	130	133
September	31	53	76	57	48	79	100	80	81
October	17	30	65	36	24	42	67	46	43
November	8	17	55	19	12	21	44	22	19
December	4	6	26	9	6	8	19	10	8
year	35	52	68	60	63	80	99	86	87

Using the information in Table 6.8 and the geometrical configuration of the courtyard, the solar radiation transmitted through the appropriate glazed surfaces is calculated and is summated monthly as shown in Table 6.9.

Table 6.9 Solar radiation transmitted to the glazed courtyard at Tärnan in 1988 (Wall, 1994b; Fredlund, 1995).

month 1988	transmitted solar radiation (W) west	east	north 30°	south 30°	ΣP_{sun}
January	252	255	707	1 010	2 224
February	798	816	2 020	3 434	7 068
March	2 100	1 989	4 343	8 383	16 815
April	3 654	3 825	8 080	13 837	29 396
May	5 712	5 763	14 241	21 311	47 027
June	4 746	5 049	14 544	17 877	42 216
July	4 242	4 743	13 231	16 362	38 578
August	3 612	3 774	9 797	14 443	31 626
September	2 394	2 703	4 848	10 100	20 045
October	1 512	1 530	2 424	6 767	12 233
November	798	867	1 212	4 444	7 321
December	378	306	606	1 919	3 209

With the values of *S* and P_{sun} known, the monthly mean temperature of the glazed courtyard can now be calculated from the energy balance Equation 6.13 for given values of the outside temperature T_o and the indoor temperature T_i in the surrounding buildings.

In order to test the possibilities of the method, outside temperatures for 1987 are chosen. For this year, measured values of the temperature in the glazed courtyard are available. In the calculation, T_i is put equal to 20°C and P_{heat} equal to 0.

Calculations were made with solar radiation from two different years. At first, calculations were based on solar radiation data for 1988 according to Table 6.9. Calculations were then made using solar data for 1987 which is the year measurements from Tärnan are available.

The results of calculations using solar radiation data for 1988 are plotted in Figure 6.30. It is seen that the calculation method yields good agreement in the spring and autumn. In the summer, the estimated temperatures are about 5°C higher, the reason being that in the model no account has been taken of the fact that, in practice, both solar control curtains and vents were used.

If the value of the solar collection property *S* had been put at 0.95 (which means a building with ordinary sized windows) instead of 0.52, the mean temperature would have been much higher. In the summer, the calculated mean temperature would have been approx. 7 - 9°C higher and in the spring approx. 3 - 7°C higher. During the winter, the difference would have been smaller, approx. 1 - 2°C due to low solar radiation (Wall, 1994b).

The solar radiation in the summer of 1987 was less powerful than during the summer of 1988. If solar radiation data from 1987 are used, the estimated temperatures in the summer are only about 3.5°C higher than the measured temperatures, see Figure 6.31. In addition, the previously mentioned building driers were also used to some extent in the winter, which explains the underestimate in January. When the use and properties of the solar control curtains are known, the value of transmitted solar radiation in the summer can be adjusted so that the temperature in the glazed courtyard may be better estimated.

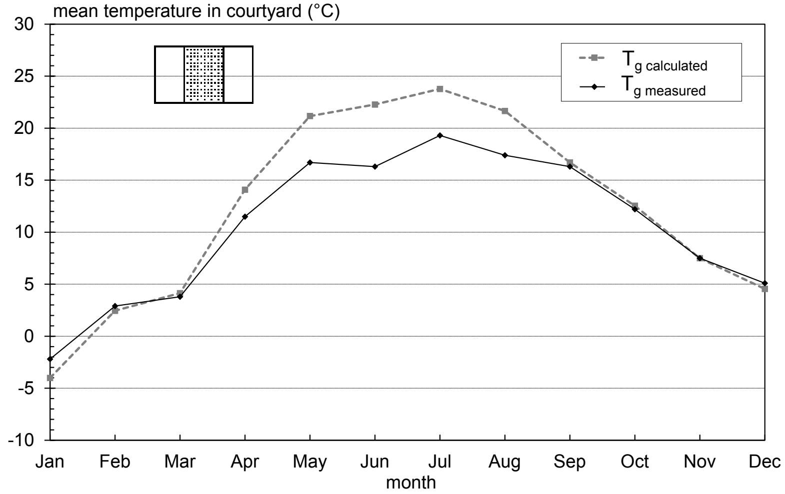


Figure 6.30 *Comparison of calculated and measured monthly mean temperatures in the glazed courtyard in 1987 with solar radiation in 1988 and with outside temperatures measured in 1987 (Fredlund, 1995).*

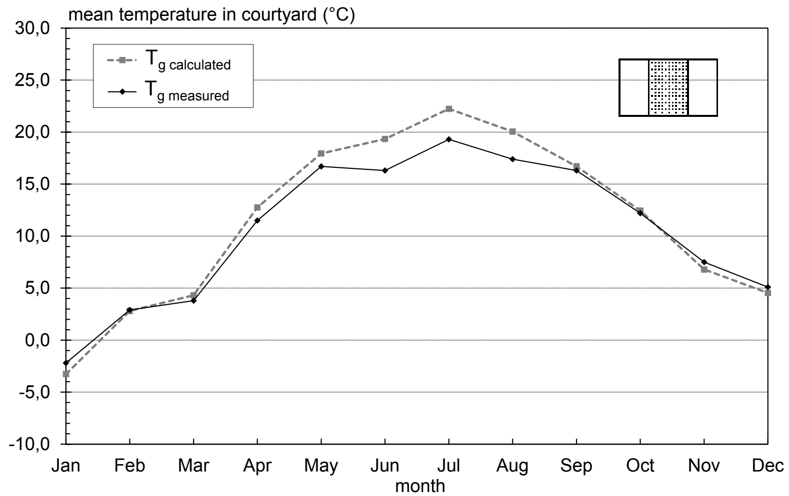


Figure 6.31 *Comparison of calculated and measured monthly mean temperatures in the glazed courtyard with solar radiation, and outside temperatures measured in 1987 (Wall, 1994b).*

6.11.4 Energy requirement for heating

If the glazed courtyard at Tärnan is to be heated to a certain least mean temperature, an approximate energy requirement can be estimated by the calculation method. Since, in its present form, the method is for practical reasons based on monthly means, it must be realised that this may result in both under and overestimates of the heating requirement. For instance, temperatures overnight may very well be lower than what is acceptable, even though the monthly mean temperature in the courtyard is sufficiently high for heating not to be required.

Obviously, the method can be improved in this respect by a resolution better than monthly design tables. The easiest way of doing this is to produce a computerised design method. In this simple version, however, the method is sufficiently accurate for comparisons of different glazed space configurations to be easily carried out.

In Table 6.10, the heating requirement for the glazed courtyard has been calculated using climatic data for the representative year 1988. The table sets out two required levels of least acceptable mean temperature, 10°C and 20°C. As seen from Table 6.10, the energy required to maintain the mean temperature at 10°C is about 35 MWh. If the solar collection property is 0.95 instead of 0.52, the energy requirement is underestimated by about 10%.

When the glazed space is heated to 20°C, the energy required is about 144 MWh. If in this case it had been assumed that 95% of the transmitted solar radiation was retained in the glazed space (S = 0.95) instead of 52% (S = 0.52), the energy requirement would have been estimated at about 117 MWh, which is an underestimate of the heating requirement by about 23%. The more powerful the solar radiation during the period, the greater is the significance of the solar collection property. When the required temperature level is high, heating will be required even when solar radiation is considerable, i.e. during spring and autumn. It is then very important to bear in mind that, in actual fact, a large proportion of the transmitted solar radiation is not retained in the glazed space.

Table 6.10 *Heating requirement in the glazed courtyard in 1988 when the specified mean temperature is 10°C and 20°C respectively (Wall, 1994b; Fredlund, 1995).*

month 1988	hour (h)	outside temperature (°C)	mean power +10°C (W)	energy requirement +10°C (kWh)	mean power +20°C (W)	energy requirement +20°C (kWh)
January	744	2.8	10 783	8 023	33 533	24 949
February	696	1.7	10 396	7 236	33 146	23 070
March	744	0.8	7 077	5 265	29 827	22 191
April	720	5.4	0	0	14 115	10 163
May	744	12.5	0	0	0	0
June	720	16.5	0	0	0	0
July	744	16.9	0	0	0	0
August	744	15.8	0	0	0	0
September	720	13.4	0	0	2 869	2 066
October	744	7.9	0	0	18 012	13 401
November	720	2.5	8 736	6 290	31 486	22 670
December	744	2.4	10 975	8 165	33 725	25 091
year				34 979		143 601

6.11.5 Other studies of the thermal properties of the glazed space

It is easy to make a number of other studies of the thermal properties of the glazed space using the developed design data and the energy balance set up in Equation 6.13.

Examples of relevant studies which may be mentioned are

- Investigation of ventilation requirements when temperatures are excessive.
- Energy requirements for cooling.
- The influence of the glazed space on the energy requirements in surrounding buildings.
- The possibility of reducing the insulation standard of surrounding buildings without increasing their energy requirements, since the glazed space can be regarded as supplementary insulation.

Examples of how this can be done are given in Wall (1994b).

6.12 A design tool for glazed spaces Example 2 - Glazed verandas, Taberg

This section provides examples of the ability of the manual calculation method described in Chapter 3 to assess temperatures and energy requirements in the glazed verandas at Taberg where an extensive body of measurement results is available. The measurement results and evaluations are described in Fredlund (1989). The buildings are also described in Chapter 5. The following comparison between measurements and calculations with the manual method is described in Fredlund (1995).

6.12.1 Calculation of minimum temperature in the veranda

Theoretical overall heat transfer coefficients have been calculated for the components of the building. The calculations are based on design drawings. The calculations were made in accordance with the Swedish Building Code 1980.

A summary of the calculated specific losses from the verandas to the outside is given in Table 6.11. The table also gives the loss between a flat and a glazed veranda. This is a measure of the possibility of making use of the energy from the veranda at a given veranda temperature. It can also be related to the losses of the veranda overnight or in cloudy periods, and gives then an energy balance under steady conditions, from which the veranda temperature can be easily calculated.

Table 6.11 Calculated specific losses for the glazed verandas (Fredlund, 1995).

veranda type	fabric loss veranda-outside (W/°C)	ventilation loss veranda-outside (W/°C)	total specific losses veranda-outside (W/°C)	fabric loss flat-veranda (W/°C)
2 r+k	141.0	25.8	166.8	9.8
2.5 r+k	137.1	24.1	161.2	9.7
4 r+k	232.1	61.4	293.5	18.4
whole building	1 484	345	1 830	112

The verandas are constructed in accordance with greenhouse technology. This means, inter alia, that the panes of glass overlap and their airtightness is therefore relatively low. At the junctions with the building also, there are large gaps. The large number of openings in the verandas give rise to further leakage paths. Owing to the large leakage paths, the air change rate in the veranda will also probably vary considerably as a function of wind speed and direction. The summary in Table 6.11

has been based on the measured average air change rate of 3.0 h^{-1} in the veranda, with the openings and doors closed.

If the verandas are analysed on the assumption that they are in equilibrium at a given temperature and that solar radiation does not contribute to the energy increment, the veranda temperature is determined only by the relationship between the fabric losses from the flat concerned and the losses from the veranda to the outside air. The temperature of the verandas can then be obtained from the energy balance Equation 6.13. With the specific losses of each veranda as given in Table 6.11 (on the assumption that the air change rate in the veranda is 3 h^{-1}), we have

for a veranda for a flat of 2 rooms and kitchen,

$$T_g = 0.9434 \cdot T_o + 0.0544 \cdot T_i \;; \tag{6.18}$$

for a veranda for a flat of 2 ½ rooms and kitchen,

$$T_g = 0.9432 \cdot T_o + 0.0568 \cdot T_i \;; \tag{6.19}$$

and for a veranda for a flat of 4 rooms and kitchen,

$$T_g = 0.9410 \cdot T_o + 0.0590 \cdot T_i \tag{6.20}$$

It is seen from the above expressions that during the night and the darker part of the year, the veranda temperatures will be very near the outside temperature owing to the relationship between the contribution from the flats and the losses from the verandas (according to Table 6.11, this relationship varies from 1:16 to 1:17, i.e. G is approx. 16 - 17). For instance, for a 4 rooms and kitchen flat, the veranda temperature is -17.6°C when the outside temperature is -20°C and the temperature in the flat is +20°C.

The temperatures according to Equations 6.18 - 6.20 are the lowest temperatures that can be expected in the verandas under the given temperature conditions. These calculated temperatures are compared with the measured veranda temperatures, see Table 6.12.

As will be seen from Table 6.12, there is good agreement between calculated and measured minimum temperatures in the three types of verandas.

Table 6.12 Comparison of calculated and measured minimum temperatures in the verandas (Fredlund, 1995).

veranda type	calculated temperature (°C) T_o = -20°C	T_o = -10°C	measured temperature (°C) T_o = -20°C	T_o = -10°C
2 r+k	-17.8	-8.4	-17.7	-8.7
2.5 r+k	-17.7	-8.3	-17.0	-8.0
4 r+k	-17.6	-8.2	-16.8	-7.5

6.12.2 Calculation of mean temperature in the veranda

In this section the veranda for a flat with 2 rooms and kitchen will be analysed. For purposes of evaluation, a flat is selected which for measurement reasons was unoccupied during the whole of the measurement period concerned. This means, inter alia, that we have had full control over ventilation in the veranda and that no solar control curtains have been used.

With the help of the energy balance Equation 6.13 and input data from Table 6.11,

$$Q_{from} = Q_{to} + S \cdot P_{sun} \qquad (6.21)$$

i.e.

$$166.8 \cdot (T_g - T_o) = 9.8 \cdot (T_i - T_g) + S \cdot P_{sun} \quad \text{(W)} \qquad (6.22)$$

On the basis of the properties of the surface finishes, the absorptivity for short wave radiation is estimated at 0.55. Using this value of absorptivity and the design data for determination of the solar collection properties of a glazed space with a building on one side, as in Figure 6.32, we have that S = 0.42.

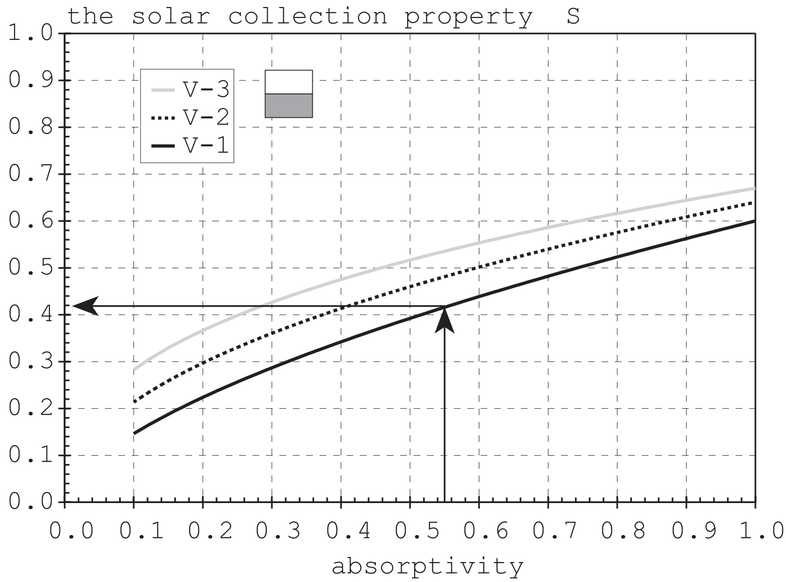


Figure 6.32 *Solar collection property as a function of the absorptivity of the glazed space with a building on one side (Wall, 1994b; Fredlund, 1995).*

The next step in the calculation is to estimate the transmitted solar radiation P_{sun}. For this purpose the design data produced for the alternative of single glazing and the nearest location, which is Göteborg, is used; 55.72°N, 13.22°E, altitude 5 m. Taberg is situated at 57.40°N, 14.05°E, and its altitude is 230 m.

The areas of glazed surfaces are:

glazed roof to the south 4.7 m², inclination 35° to the horizontal
glazed wall to the west 5.9 m²
glazed wall to the east 5.9 m²
glazed wall to the south 7.0 m².

For the glazed roof, the tabulated values given in the design data for surfaces of 30° inclination are used as an approximation.

Using the information in Table 6.13 and the geometrical configuration of the veranda, the solar radiation transmitted through each glazed surface is calculated and summated monthly as in Table 6.14.

Table 6.13 *Solar radiation transmitted through single glazed windows in Göteborg in 1988 (Wall, 1994b; Fredlund, 1995).*

month 1988	transmitted solar radiation vertical surfaces (W/m²)				surfaces at 30° inclination (W/m²)				horizontal surfaces (W/m²)
	north	east	south	west	north	east	south	west	
January	4	4	8	5	6	6	9	7	6
February	13	13	21	17	20	21	26	24	23
March	24	31	54	42	36	47	65	55	52
April	40	69	93	86	68	105	135	116	114
May	65	109	118	127	132	171	203	185	188
June	75	106	110	134	154	175	205	198	199
July	63	87	86	86	117	137	148	135	145
August	54	65	86	95	94	108	135	132	126
September	31	48	79	65	47	73	101	86	81
October	16	27	69	33	23	39	66	42	40
November	8	13	53	20	11	17	41	21	17
December	4	6	30	9	6	8	21	10	8
year	33	48	67	60	59	75	96	84	83

Table 6.14 *Solar radiation transmitted to veranda in 1988 (Fredlund, 1995).*

month 1988	transmitted solar radiation (W)				
	west	east	south vertical	south 30°	ΣP_{sun}
January	30	24	56	42	151
February	100	77	147	122	446
March	248	183	378	306	1 114
April	507	407	651	634	2 200
May	749	643	826	954	3 172
June	791	625	770	963	3 150
July	507	513	602	696	2 318
August	560	384	608	634	2 186
September	384	284	553	475	1 695
October	195	159	483	310	1 147
November	118	77	371	193	758
December	53	35	210	99	397

With the values of S and P_{sun} known, the monthly mean temperature of the veranda can now be calculated from the energy balance Equation 6.13 using the given values of outside temperature T_o and the temperature in the flat T_i .

In order to test the ability of the method to estimate solar gain, the outside temperatures measured during the measurement period in 1982 and the indoor temperature in the flat, T_i = 20°C, are selected as input values in the calculations.

In Figure 6.33 the calculation results are compared with the measured veranda temperatures. The mean outside temperature during 1982 is also shown. It is seen that the calculation method produces good agreement during the whole year, and that the maximum difference is less than 2°C. The differences vary over the year, but this is natural since the variation in solar radiation during 1982 obviously does not fully agree with that in the reference year 1988. However, for design purposes and studies of alternative configurations of the veranda, the results are sufficiently good.

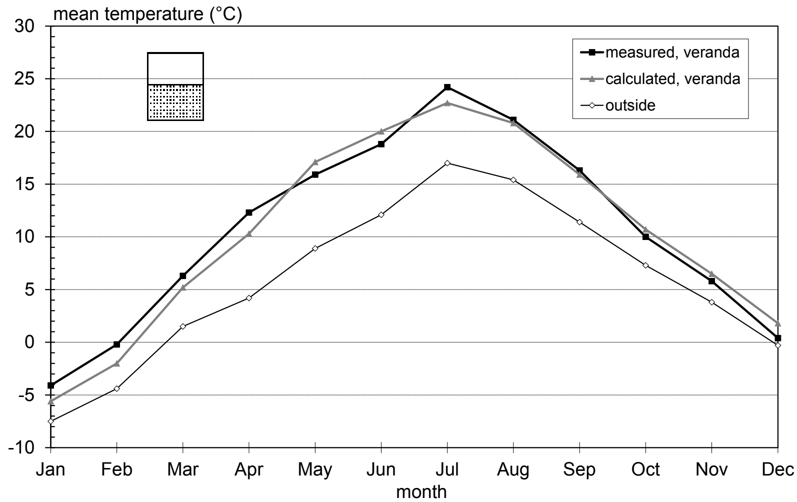


Figure 6.33 *Comparison of calculated and measured monthly mean temperatures. The measurement results refer to 1982. The calculations are based on outside temperatures in 1982 but relate to solar radiation data for the reference year, 1988, of the calculation method (Fredlund, 1995).*

6.12.3 Energy requirement for heating

In the following section, the consequences of trying to heat the veranda to at least keep it free of frost are studied. In order to guarantee this, the minimum temperature in the veranda is assumed to be 5°C. The term P_{heat} shall thus be estimated in the energy balance Equation 6.13, and its value is obtained from

$$P_{heat} = 687 - 166.8 \cdot T_o - 0.42 \cdot P_{sun} \quad \text{(W)} \tag{6.23}$$

In Equation 6.23 it has been assumed that T_i is constant and equals 20°C and that the veranda temperature is at least 5°C. Outside temperatures measured in 1982 are substituted as outside temperatures, and monthly values of P_{sun} are taken from Table 6.14. The calculated energy requirement for each month is given in Table 6.15.

Table 6.15 Heating load for the veranda of the two rooms + kitchen flat in 1982 when the required mean temperature is 5°C (Fredlund, 1995).

month 1988	hours (h)	outside temperature (°C)	veranda temperature (°C)	power (W)	energy (kWh)
January	744	-7.5	5.0	1 874	1 395
February	672	-4.4	5.0	1 234	829
March	744	1.5	5.2	0	0
April	720	4.2	10.3	0	0
May	744	8.9	17.1	0	0
June	720	12.1	20.0	0	0
July	744	17.0	22.7	0	0
August	744	15.4	20.8	0	0
September	720	11.4	15.9	0	0
October	744	7.3	10.7	0	0
November	720	3.8	6.5	0	0
December	744	-0.3	5.0	570	424
year					2 648

As will be seen from the calculations set out in Table 6.15, the annual energy requirement for the year, to maintain at least 5°C in the veranda, is approx. 2 600 kWh. This may appear to be a relatively low energy consumption. If, however, this result is related to the energy consumption for heating the flat as a whole, which is about 3 600 kWh, heating the veranda is seen to be very wasteful in energy. It is 73% of the energy requirement of the flat. It is therefore unrealistic to heat the veranda in its present configuration.

It is precisely in this way that the calculation model is intended to be used, i.e. to provide an easy means of making realistic assessments at an early stage, so that there are no excessive expectations regarding the thermal properties of glazed spaces. In the foregoing example, if the temperature requirement cannot be changed, consideration will obviously have to be given to altering the construction in order to reduce the energy requirement.

6.12.4 Discussion and conclusions

By using this calculation method, an estimate can be made of temperatures and energy requirements in the glazed space and the surrounding buildings. Perhaps the principal advantage of such a method is not that exact results can be produced, but that it is possible to get a feel, right at the preliminary design stage, of how the configuration of the glazed space will affect temperatures and energy requirements. If the design of the space in combination with the surrounding buildings is determined in view of these and other aspects simultaneously, the prospects that the glazed space will perform satisfactorily are greatly enhanced.

The application of the method has been illustrated in the two example calculations shown. When a comparison is made with measurements, the method is seen to give a good idea of the minimum and mean temperature in the glazed space in conjunction with passive climatic control, i.e. when the temperature in the glazed space is principally determined by heat losses from the surrounding buildings and by solar radiation. Assessment of the energy required for heating or cooling is more uncertain since the method is based on monthly mean values. This implies that shorter periods during the month or day when there is a heating or cooling load are not taken into account. Development in this respect can be envisaged using computerised methods.

An important goal in developing the calculation method is to be able to estimate the maximum temperature in a glazed space. When this is possible, the design of vents, solar control curtains and cooling loads can be estimated. Such a development also necessitates that the thermal storage capacity of the glazed space is taken into consideration, and that the effect of solar control curtains in combination with the glazed roof and glazed facades is determined. And, naturally, a study of thermal comfort is also of interest for the utilisation of glazed spaces.

6.13 Summary

In this chapter, the influence of different factors on actual buildings has been illustrated and the practical experiences gained in the different buildings, which had been introduced in Chapter 5, have been discussed.

The factors discussed are

- type of glazed space (geometry)
- the thermal properties of the glazed structure
- orientation
- heat storage capacity
- airtightness and ventilation

- curtains as solar protection and/or insulation
- the glazed space as part of the ventilation of the building as a whole
- heating and cooling
- solar radiation
- long wave sky radiation

The geometrical configuration of the studied buildings has varied greatly. The glazed roof over the abbey ruins at Hamar is the most extreme case since it has no adjacent buildings and its only energy gain under passive climatic control is obtained from the sun. This glazed structure will however be heated.

The glazed verandas at Taberg have adjacent buildings on one side, and all their outside walls and also the roof are single glazed. The glazed balconies at Sätuna also have a building on one side only, but they have smaller glazed surfaces in contact with the external air and have no glazed roof.

The glazed courtyard at Tärnan in Landskrona has buildings on two sides and is ca 6 m high. The same applies for the glazed street at Gårdsåkra in Eslöv. The atrium at the Scandinavian Center also has buildings along both long sides, but the buildings here are much taller. The height of this atrium is ca 22 m. The atrium at the Kabi Pharmacia buildings is cruciform in shape. There are buildings along the long sides, and in the atrium which is ca 13 m high both the roof and gables are glazed.

Two of the buildings studied have a U shape, which means that the glazed courtyard is surrounded by buildings on three sides. This applies for the glazed courtyard at Piggvaren in Malmö which is ca 10 m high, and for the atrium at the Oncological Clinic in Lund which is ca 12 m high to the ridge.

The atrium at Siriushuset in Malmö has buildings on all four sides and only its roof is glazed. This atrium is ca 23 m high.

With passive climatic control, the fundamental temperature level in the glazed space depends to a high degree on the geometrical configuration. Of the studied glazed spaces, some are wholly or in part under passive climatic control. This applies for the glazed roof over the abbey ruins at Hamar, the glazed verandas at Taberg, the glazed courtyard at Tärnan, the glazed street at Gårdsåkra and the glazed courtyard at Piggvaren. Of these, the glazed courtyard at Piggvaren has the highest temperature level with passive climatic control. The glazed balconies at Sätuna may also be considered to have passive climatic control. However, since the supply air for the flat is admitted through the glazed balcony, this has an appreciably higher ventilation rate than would otherwise have been the case. During the dark parts of the day and the year, the supply air is not preheated in the solar collector. The temperature in the glazed balcony, which at such times is low, is to a high degree dependent on the temperature of the supply air.

Since it is the geometrical configuration which largely governs the temperature level under passive climatic control, this means that the fundamental temperature level in the glazed space is to a high degree determined at an early stage of design, perhaps without the architect being aware of this. With passive climatic control, a low temperature level also implies that a large amount of energy will be required if it is decided to heat the space in order to raise the temperature level in the winter.

The number of panes of glass and the type of glass also influence the temperature in the glazed space. However, this applies primarily for glazed spaces where the geometry is such that the value of the factor *G* is relatively low. Calculations of the temperature in the glazed courtyard at Tärnan and the glazed verandas at Taberg showed that the temperature level would not have been raised by more than ca 1-2°C if double or triple glazing had been used instead of single glazing. Both these types of glazed space, verandas and a glazed courtyard with buildings on only two sides, have such large glazed surfaces in contact with the external air that fabric losses would be high even if a glass with a better U value were used. Naturally, this also applies for the glazed roof at the abbey ruins at Hamar. The significance of the choice of glass also diminishes if the glazed space is leaky and if it is shaded by surrounding buildings or natural features. On the other hand, if the glazed space is heated, the choice of glass is of great significance for the energy requirement irrespective of the value of the factor *G*.

Apart from the geometry of the building and the thermal characteristics of the glass, the amount of solar radiation which can be utilised by the glazed space also depends on the *orientation* of the glazed surfaces. The surrounding buildings also cast shadows to different extents depending on the direction in which they face. Calculations according to Fredlund (1989) showed that the maximum temperature in a glazed veranda at Taberg could be delayed by ca 2 hours if the veranda was oriented to the south-west instead of due south. The maximum temperature also increased by ca 2-3°C. In the evening, however, when the occupants have a greater opportunity to use the veranda, the difference in temperature is marginal. If the glazed space is ventilated and sunshades are used, the difference between orientations decreases. Studies of the glazed courtyard at Tärnan also showed that if another orientation had been chosen the effect on temperature would have been only marginal, which is naturally due to the shadows cast by the surrounding buildings on the vertical glazed surfaces. It was also seen in Chapter 4 that not even an unshaded and unventilated glazed courtyard is affected a lot by a choice of orientation between west, south or east. Other factors have greater significance.

Heat storage capacity influences the range over which temperatures fluctuate during the day when the temperature is allowed to vary. It also affects the power requirement for heating and cooling and, to a certain extent, the energy requirement also. The glazed spaces studied have different capacities to store heat. Small glazed spaces such as the glazed verandas at Taberg have very little capacity to store heat over the day. The temperature in the veranda drops rapidly in the afternoon and evening when the sun has gone down. The losses in this type of glazed space are too high for heat storage capacity to have any significance for the climate in the space. The surfaces which absorb and emit heat are limited in size. The glazed courtyard at Tärnan also has little capacity to store heat from the day to the evening. The smaller the value of the factor *G* for the glazed space, the greater is the significance of the heat storage capacity. However, in spite of a very high value of the factor *G* (= ∞), the glazed roof over the abbey ruins at Hamar has a significant heat storage capacity due to the extremely large quantities of stone which the ruins consist of.

It is also important to bear in mind that heat storage capacity can only have a major effect when the temperature in the glazed space is allowed to vary over the day. The atrium at the Oncological Clinic in Lund has a very high heat storage capacity. However, since the requirement is that the temperature in the atrium must be constant, the heat storage capacity is not made use of effectively.

The heat storage capacity of a building can be analysed through studies of its time constant. The time constant is a measure of how quickly the temperature indoors changes when the temperature outdoors suddenly changes. This time constant is calculated for the building when there is no heating and there are also no other energy gains. Use of the concept of time constant for a glazed space is not quite so self evident. The time constant can obviously be calculated for a glazed space when this and adjacent buildings are not heated at all. The temperature in the glazed space and the adjacent buildings will then drop if the outside temperature is suddenly lowered. A value of the time constant is then obtained and can be compared with that for other glazed spaces. In actual fact, however, this time constant bears no relationship to reality. After all, in actual conditions in a glazed space with passive climatic control, a change in outside temperature will give rise to a change in temperature in the glazed space while, in principle, the temperature in the adjacent buildings remains the same due to the fact that they are heated. This means that if the outside temperature suddenly drops, the temperature in the glazed space will also drop, but this will be compensated for to a certain extent by an increased energy increment from the adjacent buildings.

The *airtightness* of a glazed space can have great significance for the temperature level and the energy requirement. Calculations of the heating requirement to maintain a temperature of 22°C in the atrium at the Oncological Clinic showed that at air leakage corresponding to 1 ach the energy needed was almost 3 times higher than if the atrium had been completely airtight. During the construction period the airtightness was measured and gaps were sealed, with the result that the atrium was less leaky.

In order that the airtightness of different glazed spaces may be compared, measurements were made using the fan pressurisation method. Measurements were made in six glazed courtyards. These showed that at a differential pressure of 50 Pa air leakage varied between 2 and 64 m^3 per hour per m^2 of glazed area in contact with the external air (m^3/m^2h). The atrium at the Scandinavian Center was most airtight while air leakage was greatest at Piggvaren, owing to large gaps in the glazed roof.

The airtightness of the atria at Kabi Pharmacia, Scandinavian Center, Siriushuset and the Oncological Clinic did not exceed 6 m^3/m^2h at 50 Pa. Swedish building regulations have no special requirements for the airtightness of glazed spaces. For dwellings the requirement is 3 m^3/m^2h at 50 Pa pressure difference, and for other premises 6 m^3/m^2h. If the glazed spaces can be defined as "other premises", then these four more recent glazed spaces would satisfy the requirement. Since, in principle, these four glazed spaces must be maintained at indoor temperature and are therefore both heated and cooled, it is obviously open to question whether the airtightness requirement should not be stricter under these conditions.

Airtightness is often substandard at the junction between a glazed roof or glazed facade and the adjacent buildings. The airtightness tests performed in laboratories check only the airtightness of the actual glazed component, which is naturally also important. The total airtightness of the glazed space may however be completely different. Airtightness measurements for glazed spaces as a whole indicate that less than half of the air leakage would have been predicted from the results of tests on isolated glazed components.

By calculations with the air flow program MOVECOMP, a rough estimate of the magnitude of air flow rates was made for the atria at Kabi Pharmacia and Scandinavian Center. With the help of this computer program, an estimate was made of air flow rates between the atrium and outside, between the atrium and adjacent buildings, and between the buildings and outside, for different outdoor climates. The results showed that these air flow rates may be high and may give rise to a significant energy requirement. When people will be present in the atrium, it is also important to bear in mind that this air leakage should not give rise to a reduced standard of comfort due to draughts.

Ventilation in the summer, in order to reduce the temperature, is achieved in some glazed spaces by opening vents in the glazed roof and at a lower level in the glazed space. This can be sufficient so long as the temperature outside is appreciably lower than that in the glazed space. Obviously, if the space is actively cooled, the vents must be closed during periods when it is warmer outside than in the glazed space.

In some glazed spaces curtains are used as *solar control*. External sunshades are most effective since they prevent entry of solar radiation into the glazed space. Internal sunshades can however also be effective if solar radiation is retained high up in the glazed space and the heat is removed through vents in the roof before it reaches the occupied zone. The glazed courtyard at Tärnan makes use of this method of combining solar control and vents to maintain a low temperature level in the summer, and this works well. The vents and curtains are automatically controlled. The glazed street at Gårdsåkra and the glazed courtyard at Piggvaren have similar systems.

Solar control curtains can also be used as *overnight insulation*. The glazed courtyard at Tärnan has horizontal curtains below the roof which can be drawn in a double layer during the night. Measurements show that the insulation effect of the single glazed roof in combination with the curtains is equal to that of a double glazed construction. This requires however that the curtains leave no gaps along the edges.

It is usual for sunshades to be installed at a later stage, i.e. during the first summer. One reason for this may be that it is difficult to assess the influence which the sunshade will have on temperatures, energy requirements and comfort. Not enough is known of the thermal characteristics of different sunshades and the way they function in combination with a glazed surface depending on whether they are installed on the inside, between the panes of glass or on the outside. It is therefore difficult to calculate total cost and the pay-off period, and it is therefore also difficult to justify the installation of a sunshade at the preliminary design stage, which means that the need must be demonstrated during the first summer. Unfortunately, the result of this is that total cost increases and the cooling plant is designed incorrectly.

The glazed space can be used as part of the *ventilation system* of the building as a whole. In order to reduce ventilation losses in the adjacent buildings, the glazed space can be used to preheat the supply air for these buildings. If the temperature level in the glazed space is to be higher than what is possible with passive climatic control, air exhausted from the adjacent buildings can be passed into the glazed space. By combining the ventilation system for the glazed space and the adjacent buildings, the energy requirement can be reduced and a higher temperature level can at the same time be provided in the glazed space. The buildings studied have different types of systems. In Chapter 4, there is also an analysis of different ventilation systems for three types of glazed courtyard.

The glazed balconies at Sätuna are used to preheat the supply air for the flats. Solar collectors are in addition installed to preheat the supply air for the glazed balconies. It was found that the energy gain due to preheating the supply air for the flats amounted to ca 7% of the heating requirement of the flat. Only 20% of the gain is due to the solar collector, the remainder of the gain is due to the glazed balcony. The solar collectors are therefore not justified. One difficulty with this type of ventilation system is that there is no alternative way in which supply air can be provided in the summer. Both the glazed balcony and the flat therefore receive preheated supply air in the summer, which is not desirable. During the dark part of the day and the year the air is not preheated at all, which means that unsuitable siting of the supply air terminal inside the flat may easily give rise to a cold downdraught and to unpleasant draughts.

The glazed courtyard at Tärnan and the glazed street at Gårdsåkra are both used to preheat the supply air for the adjacent buildings. Since both these glazed spaces have a high value of the factor G, this does not have much effect on the temperature level in the glazed space which in this way receives a larger volume of supply air from the outside than it would otherwise have had. This also implies, however, that the amount of energy saved due to preheating is small. During a standard year, the contribution of the glazed courtyard as the preheater of the supply air at Tärnan was estimated at just over 3% of the heating requirement of the adjacent buildings.

At the atrium at Siriushuset, only the roof is glazed, and the temperature level in the atrium would therefore have been relatively high even if it had passive climatic control. In this case also the ventilation system is a combined one. Supply air for the surrounding buildings is preheated by passing the extract air from the atrium through a heat exchanger. Supply air for the atrium is taken both directly from the outside and from the surrounding buildings without passing through a heat exchanger. The outside air can be either heated or cooled as required. Through this ventilation system, the possibility of maintaining a high temperature level in the atrium during the winter months, without giving rise to high ventilation losses, is well utilised.

The glazed spaces which are used not only as circulation spaces, such as those in office buildings, hotels and hospitals, often have a *heating and cooling system*. Glazed spaces which have a high value of the factor G and are only single glazed should not be heated continuously, since otherwise the energy needed for heating may be very high. One example where heating is required in spite of the fact that the glazed space has high losses is the glazed roof over the abbey ruins at Hamar. This glazed roof is to serve as climatic protection for the ruins, and the temperature in the glazed space must therefore be at least 1°C in order to prevent freezing. This low temperature requirement nevertheless gives rise to a very high energy requirement since the roof must be single glazed. This is stipulated so that the glazed construction may be as transparent as possible, since it is the ruins which must be seen, not the glazed roof. If the temperature requirement were increased from 1°C to 5°C, the energy requirement would be almost doubled. And if the requirement were raised to 9°C, the energy requirement would be almost three times as high.

When a glazed space is heated, the energy needed to heat the adjacent buildings is at the same time reduced. The energy needed to heat the glazed space cannot however be compensated for by a reduced energy requirement in the adjacent buildings, especially not when the glazed space has a high value of the factor G and the glazed construction has low insulation capacity.

In the glazed spaces which have high comfort requirements and are also cooled in the summer, it should nevertheless be possible to provide ventilation by opening vents. Above all, active cooling does not imply that solar control curtains can be omitted. These can reduce the cooling requirement and at the same time enhance comfort by reducing the risk of glare and by screening off solar radiation, so that those in the glazed space need not be exposed to direct solar radiation.

Naturally, *solar radiation* is of great importance for the temperature in a glazed space and also for the heating and cooling requirement. How important it is depends on the number of panes of glass and the type of glass. A glazed courtyard with buildings on three sides, with a glazed roof and glazed gables to the south, east or west, is greatly influenced by solar radiation. This type of glazed space transmits a lot of solar radiation and at the same time utilises a high proportion of the transmitted solar radiation. The solar collection property *S* is a good measure of how effective a glazed space is in utilising solar radiation. This property is defined as that proportion of the transmitted solar radiation which is retained in the glazed space and is thus an energy gain. Since solar radiation is of great significance for a glazed space, it is important that the energy gain due to solar radiation is calculated accurately when the climate and energy requirement are being assessed.

Long wave sky radiation may also have great significance for the temperature in the glazed space and for the energy requirement. Glazed spaces often have glazed roofs which also have a higher U value than an ordinary building. The glazed space may therefore be affected by long wave sky radiation to a greater extent than an ordinary building. The sky temperature may be considerably lower than the outside air temperature, especially when the weather is clear. Measurements in the glazed courtyard at Tärnan showed that the temperature below the glazed roof was at times even lower than the outside air temperature.

A method of calculating long wave sky radiation, based on normally measured climatic data, has been tested and compared with measurements. Agreement was relatively good, but during certain periods there were large differences. Calculation of the long wave sky radiation by such a method is in any case much better than the usual method applied in calculation programs which assumes that the sky temperature is equal to the outside air temperature. If the sky temperature is put equal to the outside air temperature, the energy needed for heating a glazed space can be appreciably underestimated.

The simplified calculation method for glazed spaces, described in Chapter 3, has been tested and compared with measurements in two glazed spaces. Studies have been made in the glazed verandas at Taberg and in the glazed courtyard at Tärnan.

Comparisons show good agreement between measured and calculated temperatures. The calculated minimum temperature is in very good agreement with measurements. The greatest amount by which the calculated monthly mean temperature in the glazed courtyard at Tärnan exceeded the measured mean temperature was ca 3.5°C. This occurred in the summer when, in actual fact, solar control curtains were used and the vents were open. The calculations took no account of this; they apply to an unshaded and unventilated glazed courtyard where the infiltration is put at a constant 0.6 ach for the year. For the glazed veranda at Taberg, the difference between the calculated and measured monthly mean temperature was less than 2°C.

Estimation of the energy needed for heating or cooling, if any, is less reliable since the method is based on monthly mean values. The method can however be used to compare different designs. The calculation method can be made more accurate if it is developed into a computer program.

7 Thermal comfort

The degree of thermal comfort achieved is influenced by the air temperature, radiant temperature, solar radiation, clothing, physical activity, local air velocity, draught and humidity. Thus, the air temperature alone is not a sufficient parameter of how people will experience the thermal environment. As can be seen in this chapter, in glazed spaces there may be extreme variations in the degree of thermal comfort or discomfort, to a much higher extent than in buildings with ordinary window sizes.

This chapter briefly describes thermal comfort in three types of glazed spaces in order to show the importance of studying thermal comfort, and not only air temperatures, when glazed spaces are designed. The study is based on calculations with the dynamic energy simulation program DEROB-LTH together with a post processor which calculates the thermal comfort.

7.1 The COMFORT program

The COMFORT program was developed at the Department of Building Science, Lund University (Källblad, 1996). The program calculates the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) according to International Standard ISO 7730. COMFORT also calculates the operative temperature.

The COMFORT program uses data from the energy simulation program DEROB-LTH. The geometrical description of the building together with hourly values of air and surface temperatures and distributed solar radiation is read from a file produced by DEROB-LTH.

The calculations with DEROB-LTH are based on a geometrical description of the building which is utilised to give a detailed calculation of the distribution of short wave and long wave radiation to different surfaces and volumes. Output data from DEROB-LTH is therefore well suited as input to the COMFORT program in order to calculate e.g. the operative temperature.

The calculations with COMFORT are carried out using a grid of observation points each approximated with a differential cube. Results can thus be obtained for the whole volume. Solar radiation is taken into account in the calculations.

Output data from the COMFORT program are:

Operative temperature

International Standard ISO 7730 defines the operative temperature as follows:

> The operative temperature is the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

The operative temperature is thus a combination of the surface temperatures and the air temperature.

The COMFORT program calculates the global operative temperature as well as the directed operative temperatures in six main directions.

PMV

The PMV index is based on the heat balance of the human body. Man is in thermal balance when the internal heat production of the body is equal to the heat losses to the environment. The heat balance consists of parameters regarding clothing, activity (metabolic rate), air temperature, mean radiant temperature, relative air velocity and partial water vapour pressure. See ISO 7730 (1994). The PMV index predicts the mean value of the votes of a large group of persons on a 7-point thermal sensation scale. The scale is between -3 and +3 where -3 is defined as cold, +3 as hot and 0 as neutral.

PPD

The PPD index predicts the percentage of people likely to feel uncomfortably warm or cold. The rest of the group will feel thermally neutral, slightly warm or slightly cool. The calculation of the PPD index is based on the PMV index. In ISO 7730 it is recommended that the PPD index should be lower than 10%. This is equivalent to a PMV index of ± 0.5.

7.2 Basic information and limitations

The studies of thermal comfort were confined to the three building types described in Section 4.1. These three building types each consist of a glazed courtyard with buildings on two, three and four sides respectively. The type of glazing has been limited to single and triple clear glazing. The thermal inertia in the walls between the glazed space and adjacent buildings is also varied. These walls consist of plasterboard or concrete plus insulation. Adjacent buildings were allowed to have a temperature between 20°C and 25°C.

Climatic data from Lund were used (Wall, 1994b). Two days were chosen from the year 1988 in Lund. The first day was the coldest day during the year, the 15th of March; see Figure 7.1. The minimum temperature during this day was -7.7°C. The solar radiation during the day was moderate; see Figure 7.2.

The second day, the 9th of June, was the warmest day during the year; see Figure 7.3. During this day, the maximum temperature was 27°C. It was a rather clear summer day with high solar radiation; see Figure 7.4.

This study of thermal comfort has been limited to comparisons of the PMV index. No comparison has been made regarding the directed operative temperatures which can be used in order to examine the asymmetry of the thermal environment.

In order to estimate local air velocity, which is necessary for the comfort calculations, calculation terms developed by Heiselberg (1994) were used. Heiselberg examined the flow conditions in a room with a cold wall surface, such as a glass wall, by laboratory tests. Results from these measurements were described in expressions showing the relation between the maximum air velocity and the wall height, the distance from the wall and the temperature difference between the wall surface and room air. For a distance larger than 2 m from the wall, the following expression is given by Heiselberg:

$$v_{max} = 0.028 \cdot \sqrt{d \cdot \Delta t} \qquad (7.1)$$

where

v_{max} = maximum air velocity (m/s)
d = distance from wall (m)
Δt = temperature difference between wall surface and air (°C).

When a cold downdraught may occur, the maximum air velocity is calculated according to Equation 7.1. This velocity is then used as the local air velocity in order to calculate thermal comfort. The surface temperature of the wall and the air temperature are output from the DEROB-LTH program. The mean temperature difference during the day in question is used in Equation 7.1.

Draught is also a factor which can influence thermal comfort. In ISO 7730, draught is described as an unwanted local cooling of the body caused by air movement. In this standard, the following equation is given in order to calculate the draught rating:

$$DR = (34 - T_{local}) \cdot (v - 0.05)^{0.62} \cdot (0.37 \cdot v \cdot TU + 3.14) \qquad (7.2)$$

where

DR = the draught rating, i.e. the percentage of people dissatisfied due to draught (%)
T_{local} = the local air temperature (°C)
v = the local mean air velocity (m/s)
TU = the local turbulence intensity, defined as the ratio of the standard deviation of the local air velocity to the local mean air velocity (%).

According to Heiselberg (1994), the turbulence intensity more than 2 m from a glass wall can be estimated as 20%.

The ISO 7730 model of draught rating applies to people at light, mainly sedentary activity, with a thermal sensation close to neutral. The model is based on studies of people exposed to air temperatures of 20°C to 26°C, mean air velocities of 0.05 m/s to 0.4 m/s and turbulence intensities of 0% to 70%.

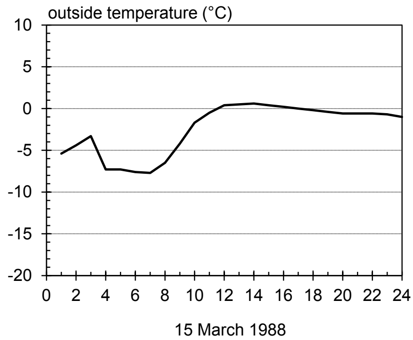


Figure 7.1 *Outside temperature in Lund, 15 March 1988.*

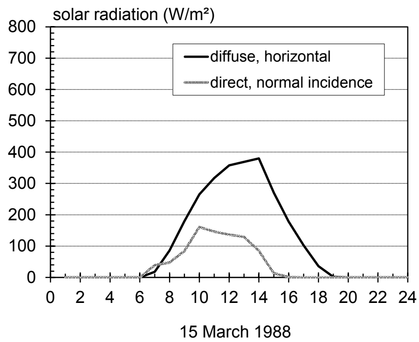


Figure 7.2 *Diffuse insolation on a horizontal surface and direct insolation at normal incidence in Lund, 15 March 1988.*

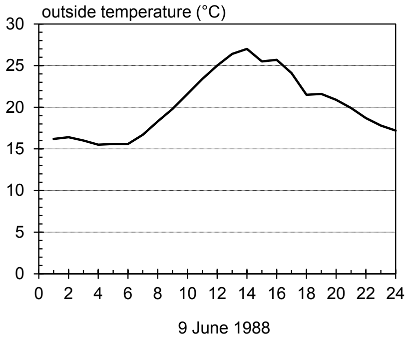


Figure 7.3 *Outside temperature in Lund, 9 June 1988.*

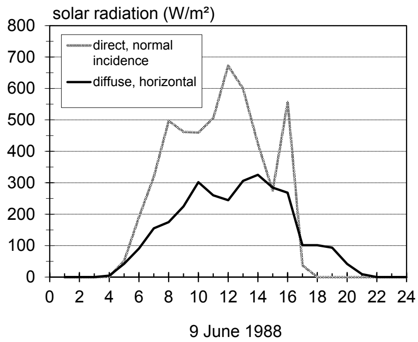


Figure 7.4 *Diffuse insolation on a horizontal surface and direct insolation at normal incidence in Lund, 9 June 1988.*

7.3 Calculation of thermal comfort in three types of glazed spaces

Dynamic simulations with the computer program DEROB-LTH were first made in order to obtain the necessary data for the COMFORT program. In Figure 7.5, the calculated air temperature during the 15th of March, obtained from DEROB-LTH, is shown for the type of glazed courtyard with buildings on three sides. The glazed gable is oriented towards south. Results are shown for both a single glazed and a triple glazed courtyard. In addition, the thermal inertia is varied in the walls between adjacent buildings and the courtyard. The glazed courtyards are in this case unheated, and if the temperature rises above 22°C the courtyards are assumed to be ventilated. During this particular day, only the triple glazed courtyard with plasterboard walls has to be ventilated for a few hours in the middle of the day. Air leakage to the outside is in all four cases assumed to be equivalent to 0.3 ach.

The results in Figure 7.5 show that there are large differences in air temperature between the four variants of courtyards. The single and triple glazed courtyards have different temperature levels. In addition, solar radiation in combination with available thermal inertia causes a difference in temperature between plasterboard and concrete walls. This indicates that thermal comfort also will vary. If the comparison is limited to the air temperatures, it seems that people will be too cold for most of the time this day. This seems to apply especially in the case of the single glazed courtyard with concrete walls, in which the maximum air temperature is only 10°C.

However, solar radiation together with long wave radiation between different surfaces can give rise to a different experience of the thermal environment. In Figure 7.6, the predicted mean vote is shown at 2 pm on 15 March for the single glazed courtyard with buildings on three sides and with concrete walls. The PMV index is shown at the level of 1.5 m. The relative humidity is assumed to be 70%. The person is walking at the rate of 2 km/h which is equivalent to a metabolic rate of 1.9 met. The clothing insulation is in this case 1.1 clo, which, according to ISO 7730, may mean panties, stockings, blouse, long skirt, jacket and shoes. The absorptivity of the cloths is set to 0.60 in all calculations. The maximum air velocity according to Equation 7.1 is used as the local air velocity in order to calculate thermal comfort. In this example, the maximum air velocity is calculated as 0.22 m/s at a distance of over 2 m from the wall. However, in the results shown in Figure 7.6, this air velocity is assumed at all points. The surface in question, causing the cold downdraught, is the glass wall towards south.

In Figure 7.6, it can be seen that the PMV index varies between approx. -0.2 and 0. This means that the slowly walking person is fairly comfortable, maybe slightly cool. The air temperature is only 10°C. However, this is the warmest hour during the day, and the person is therefore likely to be colder during the rest of the day. The level of comfort is higher in places where the sun is shining.

In Figure 7.7, the predicted mean vote is shown for the corresponding triple glazed courtyard. In this courtyard the air temperature at 2 pm is 17.3°C. The local air velocity is 0.15 m/s calculated according to Equation 7.1. The same person who visited the single glazed courtyard will here feel slightly warm instead, according to the PMV index which varies between 0.8 and 1.0.

In this way the thermal comfort can be studied for different places in the glazed space so that the best position may be chosen for a reception, a cafeteria etc. The results from Figures 7.6 and 7.7 could not have been predicted merely by studying the air temperature in Figure 7.5. Of course, studies have to be made for more than one single hour.

In Figures 7.8 - 7.11 hourly values of the PMV index on the 15th of March are shown for the four variants of the glazed courtyard with buildings on three sides. One specific point is selected, 3 metres from the glazed gable, in the middle of the glass wall at the level of 1.5 m. This observation point is marked in Figures 7.6 and 7.7. The local air velocity during the whole day, calculated according to Equation 7.1, is set to 0.22 m/s in the single glazed courtyard and to 0.15 m/s in the triple glazed courtyard. For each case, the physical activity and clothing are changed. As mentioned earlier, 1.9 met is equivalent to slow walking. The value 1.2 met is equivalent to sedentary activity, such as in an office. A person dressed in underpants, shirt and trousers has a clothing insulation of 0.75 clo. If the person also has a singlet with short sleeves and a jacket, this will be equivalent to 1.1 clo.

The warmest example of clothing is underwear with short sleeves and legs, shirt, trousers, waistcoat, jacket, coat, and of course socks and shoes. According to ISO 7730 this clothing is equal to 1.5 clo.

According to ISO 7730, an acceptable predicted mean vote is ± 0.5 which is equivalent to 10% dissatisfied people. In Figure 7.8, it can be seen that sedentary activity will be too cold in the single glazed courtyard with concrete walls, even if the person has a jacket on. However, walking through the glazed space can be quite comfortable during the day, at least if the person has a jacket on.

In the single glazed courtyard with plasterboard walls, the PMV index varies greatly between day and night; see Figure 7.9. The low thermal inertia will give rise to a higher air temperature during the day but a lower temperature during the night. A person walking through the courtyard would probably take off his or her jacket to feel comfortable during the day. Sedentary activity is possible in this part of the glazed space during a few hours in the middle of the day.

In the triple glazed courtyard with concrete walls, temperature fluctuations are dampened most and the temperature level is also highest here. In this courtyard, an acceptable level of comfort can be achieved in the evening as well as during the day. See Figure 7.10. However, if this courtyard has plasterboard walls instead, see Figure 7.11, the person will feel slightly warm or warm in the middle of the day irrespective of the chosen clothing and activity.

The corresponding courtyards with buildings on two sides and on all four sides will give similar results as shown in Figures 7.8 -7.11. Figure 7.12 shows an example from the triple glazed courtyard with buildings on two sides and concrete walls. The glazed gables are oriented towards south and north. The same observation point in the courtyard is chosen as in the previous examples. The local air velocity, calculated according to Equation 7.1, is set to 0.10 m/s. In Figure 7.13, the corresponding results are shown for the triple glazed courtyard with buildings on all four sides. The local air velocity in this case also is set to 0.10 m/s.

As can be expected, the variations in PMV between day and night are largest in the courtyard with buildings on only two sides and smallest in the courtyard with buildings on all four sides. This can be seen when Figures 7.10, 7.12 and 7.13 are compared. However, during the day there is no significant difference between the courtyard with buildings on two sides and the corresponding courtyard with buildings on three sides. In the courtyard with only the roof glazed, it is easier to achieve an acceptable thermal comfort during the whole day; see Figure 7.13.

In conclusion, it can be said that it is possible to achieve a reasonable level of comfort in these types of glazed courtyards on a winter day with passive climatic control if they are mainly used for circulation.

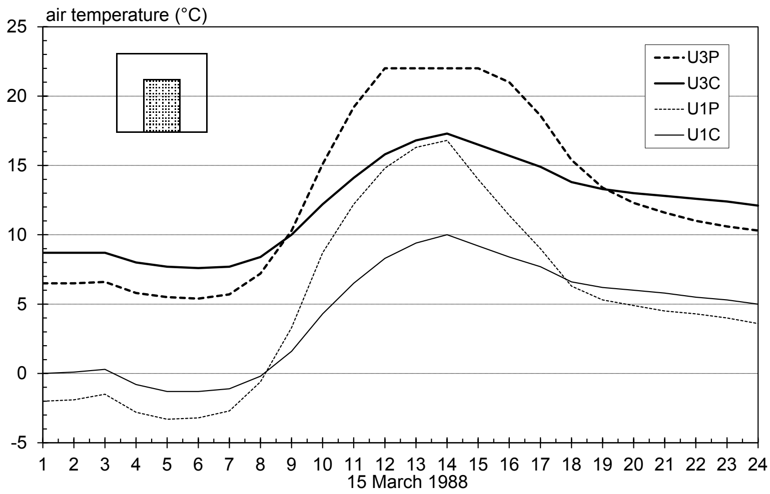
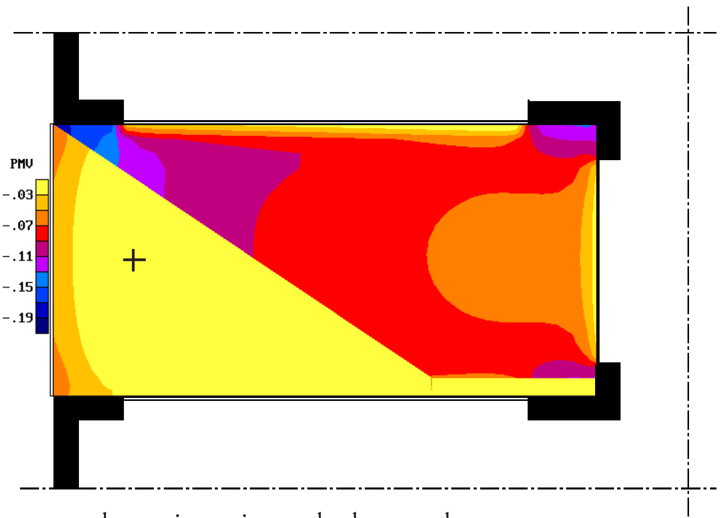
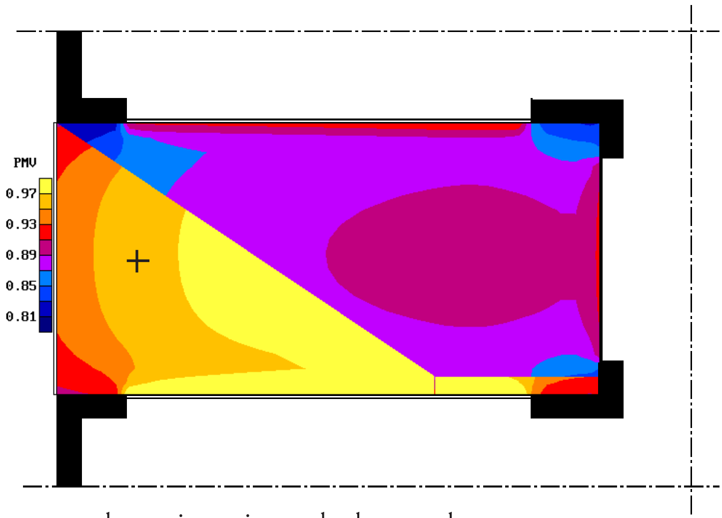


Figure 7.5 *Air temperature in the single glazed and triple glazed courtyards with buildings on three sides on the 15th of March 1988 in Lund.*
U = U shape (buildings on three sides of the courtyard)
1 = single glazing and 3 = triple glazing
P = plasterboard walls and C = concrete walls.



+ observation point used subsequently

Figure 7.6 *The predicted mean vote in the single glazed courtyard with buildings on three sides and concrete walls at the level of 1.5 m. The 15th of March 1988 at 2 pm in Lund.*



+ observation point used subsequently

Figure 7.7 *The predicted mean vote in the triple glazed courtyard with buildings on three sides and concrete walls at the level of 1.5 m. The 15th of March 1988 at 2 pm in Lund.*

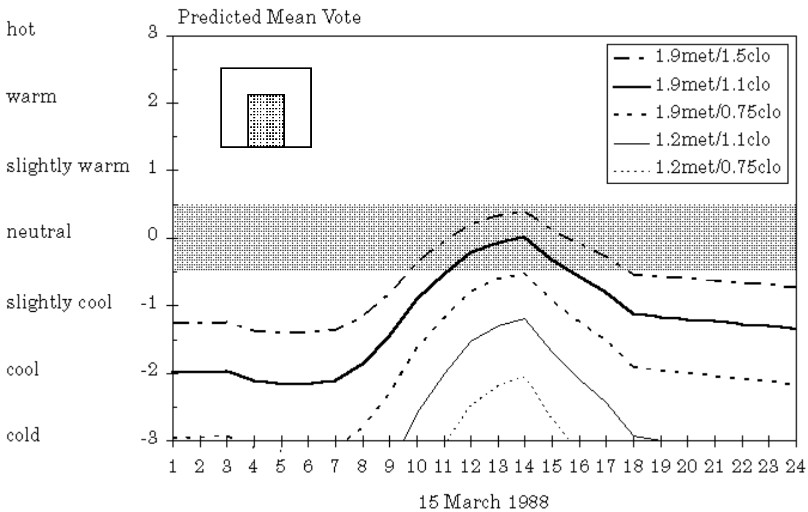


Figure 7.8 *The predicted mean vote in the single glazed courtyard with buildings on three sides and concrete walls at the level of 1.5 m, 3 m from the glazed gable. Results for different clothing and activities. The 15th of March 1988 in Lund. The glazed space is unheated.*

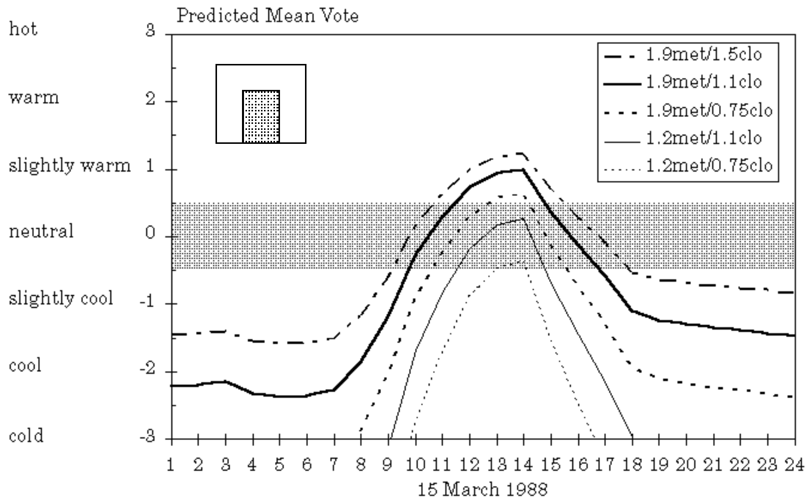


Figure 7.9 *The predicted mean vote in the single glazed courtyard with buildings on three sides and plasterboard walls at the level of 1.5 m, 3 m from the glazed gable. Results for different clothing and activities. The 15th of March 1988 in Lund. The glazed space is unheated.*

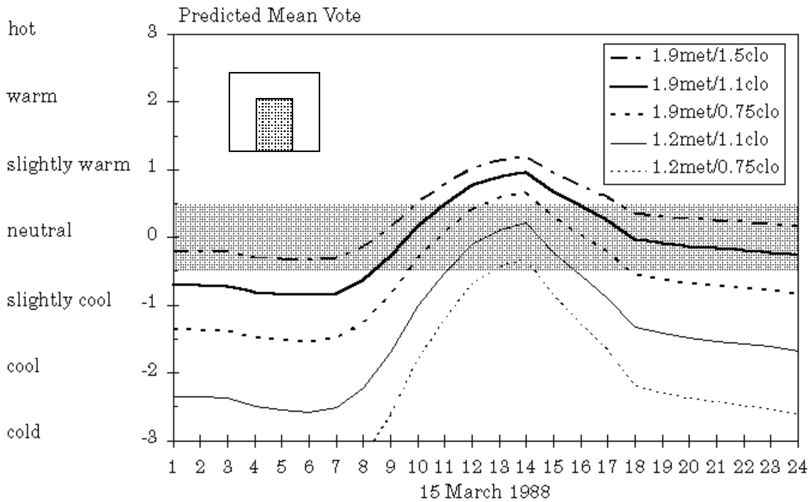


Figure 7.10 *The predicted mean vote in the triple glazed courtyard with buildings on three sides and concrete walls at the level of 1.5 m, 3 m from the glazed gable. Results for different clothing and activities. The 15th of March 1988 in Lund. The glazed space is unheated.*

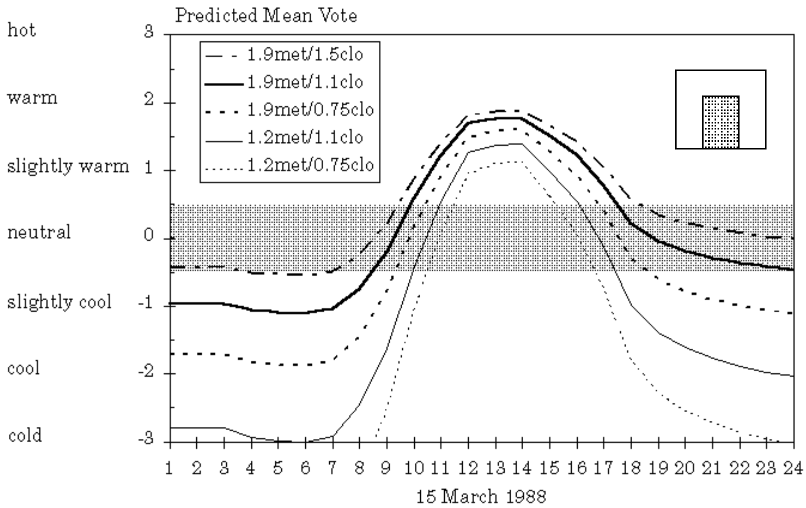


Figure 7.11 *The predicted mean vote in the triple glazed courtyard with buildings on three sides and plasterboard walls at the level of 1.5 m, 3 m from the glazed gable. Results for different clothing and activities. The 15th of March 1988 in Lund. The glazed space is unheated.*

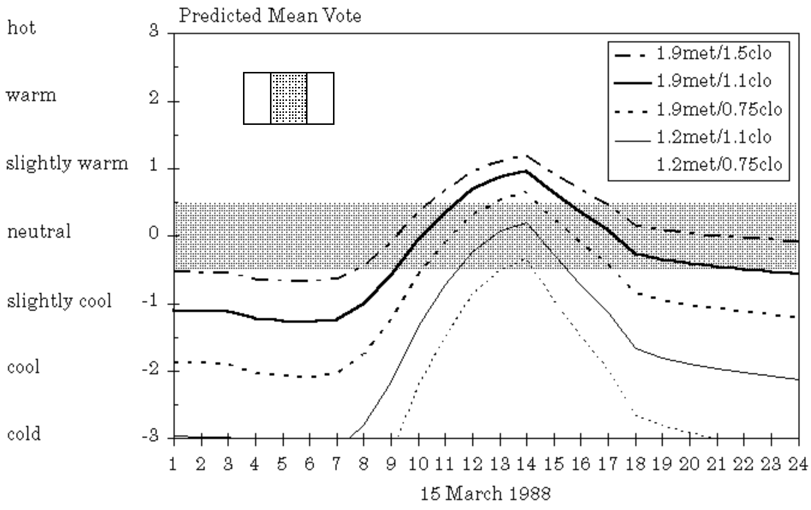


Figure 7.12 *The predicted mean vote in the triple glazed courtyard with buildings on two sides and concrete walls at the level of 1.5 m, 3 m from the glazed gable towards south. Results for different clothing and activities. The 15th of March 1988 in Lund. The glazed space is unheated.*

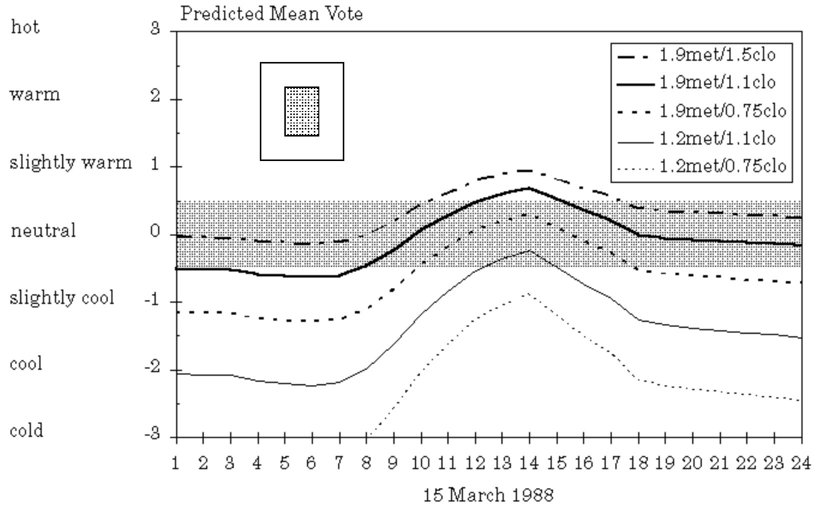


Figure 7.13 *The predicted mean vote in the triple glazed courtyard with buildings on all four sides and concrete walls at the level of 1.5 m, 3 m from the end wall. Results for different clothing and activities. The 15th of March 1988 in Lund. The glazed space is unheated.*

On the other hand, if the glazed space is to be used by a person on a more permanent basis, for example if a reception is placed in the courtyard, heat must be supplied during the winter. In order to study thermal comfort under these conditions, calculations were made in which the different courtyards were heated to 20°C. The courtyards were still assumed to be ventilated if the temperature rose above 22°C. The relative humidity was set to 30%.

In Figure 7.14, the predicted mean vote is shown for a person wearing underpants, shirt, trousers, socks and shoes (0.75 clo). Sedentary activity is assumed, such as in an office (1.2 met). Results are shown for the courtyards with buildings on three sides, at the same observation point as in earlier examples. The local air velocity, calculated according to Equation 7.1, is set to 0.30 m/s in the single glazed courtyards and to 0.16 m/s in the triple glazed courtyards.

In Figure 7.14, it can be seen that the person will feel comfortable between 10 am and 3 pm in the single glazed courtyard with plasterboard walls. This can also almost be accomplished in the single glazed courtyard with concrete walls. In the triple glazed courtyards, the same person will probably feel slightly warm in the middle of the day. Calculations for the courtyards with buildings on only two sides give approximately the same results.

The corresponding results for the courtyard with only the roof glazed are shown in Figure 7.15. The local air velocity is assumed to be 0.10 m/s. As can be seen, the difference between single and triple glazing is not as large as in the other two types of courtyards. According to the PMV index, the thermal comfort is acceptable from 8 am to 6 pm in the single glazed courtyard with concrete walls.

However, to heat the glazed space to 20°C will not automatically give an acceptable thermal comfort. In the evening, all three types of glazed spaces will feel too cool, except maybe the triple glazed courtyard with only the roof glazed.

Another question which arises is whether there is a risk of draught in these glazed spaces. The risk of draught was examined on the 15th of March during the hours when the studied person is close to a neutral thermal sensation (PMV = 0). According to the draught model in Equation 7.2, approx. 20% would be dissatisfied due to draught in the glazed courtyard with buildings on three sides. This is based on the calculations shown in Figure 7.14. The local mean air velocity was then assumed to be 0.2 m/s and the turbulence intensity 20%. Similar results are obtained for the courtyard with buildings on two sides.

The results of calculations shown in Figure 7.15 indicate that approx. 8% would be dissatisfied due to draught during the hours when thermal sensation is close to neutral in the glazed courtyard with only the roof glazed. The local mean air velocity is then assumed to be 0.1 m/s and the turbulence intensity 20%.

In ISO 7730 it is recommended that not more than 15% of the occupants should be bothered by draught. The type of courtyard with only the roof glazed would be the easiest to design so as to satisfy these recommendations.

In conclusion, high thermal comfort is not achieved automatically by heating a glazed space to indoor temperature. Solar radiation, long wave radiation and draught will strongly influence the experience of the thermal environment.

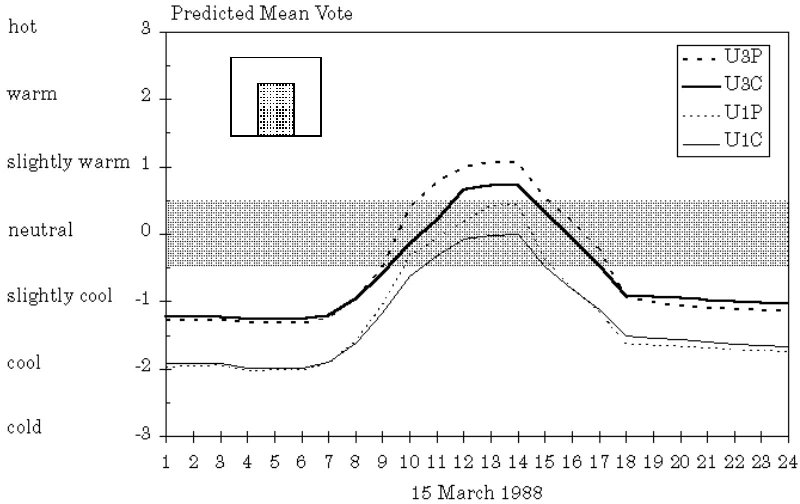


Figure 7.14 *The predicted mean vote in the glazed courtyards with buildings on three sides at the level of 1.5 m, 3 m from the glazed gable. Sedentary activity (1.2 met) and the person is wearing shirt and trousers (0.75 clo). The 15th of March 1988 in Lund. The glazed space is heated to 20°C.*
U = U shape (buildings on three sides of the courtyard)
1 = single glazing and 3 = triple glazing
P = plasterboard walls and C = concrete walls.

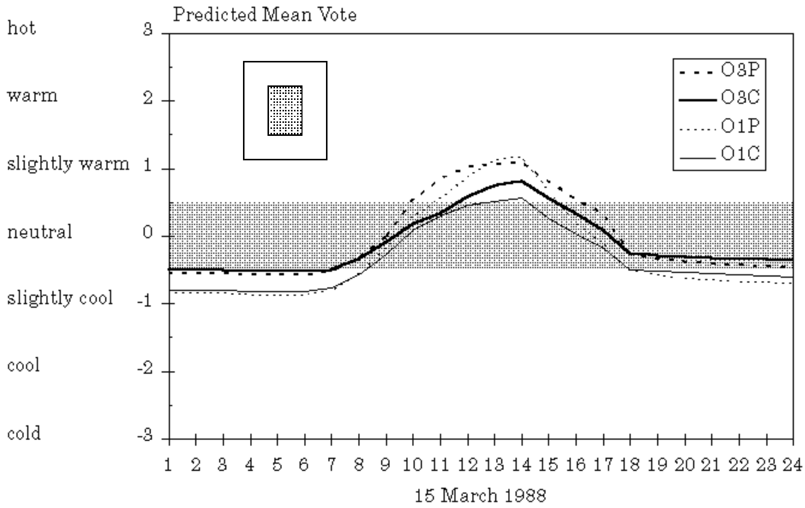


Figure 7.15 *The predicted mean vote in the glazed courtyards with buildings on all four sides at the level of 1.5 m, 3 m from the end wall. Sedentary activity (1.2 met) and the person is wearing shirt and trousers (0.75 clo). The 15th of March 1988 in Lund. The glazed space is heated to 20°C.*
O = O shape (buildings on four sides of the courtyard)
1 = single glazing and 3 = triple glazing
P = plasterboard walls and C = concrete walls.

In order to study thermal comfort on a warm summer day, calculations were made for the 9th of June 1988 in Lund. The studied courtyards were then cooled to 20°C, which can be achieved by supplying cooled air to the courtyard and by opening vents during times when the outside temperature is below 20°C.

Even when the courtyard is cooled to 20°C, radiation will strongly influence the space. The operative temperature in the single glazed courtyard with buildings on three sides and with concrete walls is plotted in Figure 7.16. The observation point is the same as in earlier examples. The air temperature and the surface temperature of the glazed gable are also plotted. The operative temperature is almost 40°C at noon, even if the air temperature is not more than 20°C. At the same time, the glazed wall has a surface temperature of 28°C. Such an environment is quite extreme, and very far from the situation in an ordinary room. How will people feel in an environment like this?

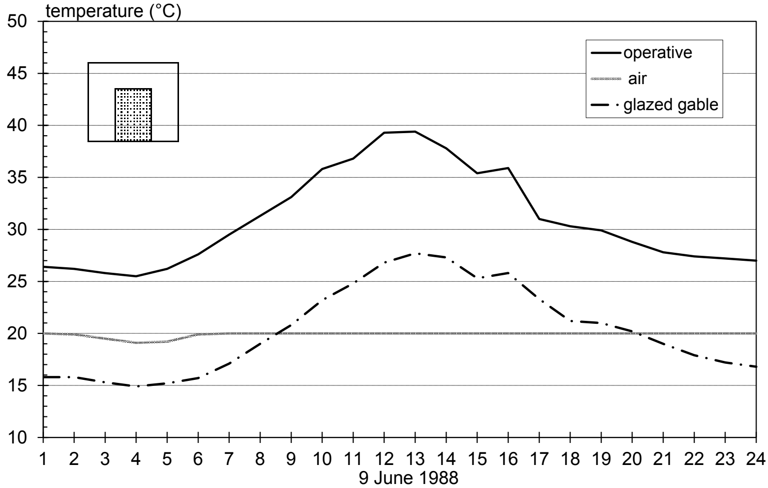


Figure 7.16 *Air temperature, surface temperature of the glazed gable and operative temperature 3 m from the glazed gable at the level of 1.5 m. The courtyard is single glazed with concrete walls and surrounded by buildings on three sides. The glazed space is cooled to 20°C. The 9th of June 1988 in Lund.*

In Figure 7.17, the predicted mean vote is shown for the variants of courtyards with buildings on three sides, at the same observation point as in earlier examples. The local air velocity is assumed to be 0.3 m/s and the relative humidity is set to 50%. The air temperature, as previously noted, is not more than 20°C. The person is now only dressed in panties, T-shirt, shorts, light socks and sandals (0.3 clo). The activity is sedentary (1.2 met).

In Figure 7.17, it can be seen that the space will feel too warm during most of the day, irrespective of single glazing, triple glazing, concrete walls or plasterboard walls. Very similar results are obtained for the type of courtyard with buildings on only two sides. Unfortunately, less clothing is probably not possible.

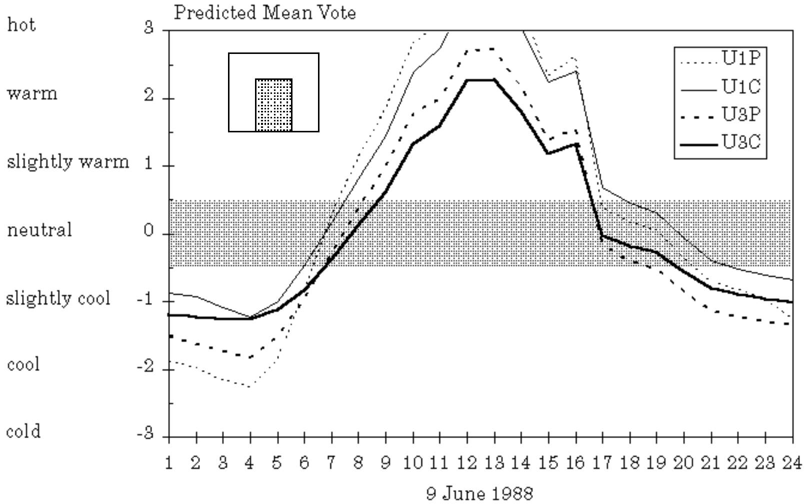


Figure 7.17 *The predicted mean vote in the glazed courtyards with buildings on three sides at the level of 1.5 m, 3 m from the glazed gable. Sedentary activity (1.2 met) and the person is wearing T-shirt and shorts (0.3 clo). The glazed space is cooled to 20°C. The 9th of June 1988 in Lund.*
U = U shape (buildings on three sides of the courtyard)
1 = single glazing and 3 = triple glazing
P = plasterboard walls and C = concrete walls.

In Figure 7.18, the corresponding results are given for the courtyard with only the roof glazed. The person will in this type of glazed space feel slightly cool to slightly warm during the day, which is a lot better than in the previous examples. However, during the night the space is too cold.

In conclusion, it is not easy to obtain a high degree of thermal comfort by merely reducing the air temperature to 20°C on a warm summer day. Solar radiation and long wave radiation have a strong influence on the way the thermal environment will be perceived.

One way to increase thermal comfort is to use solar shadings. The effect of solar shadings placed on the outside of the glazed courtyard can be seen in Figure 7.19. In this figure, the predicted mean vote is shown for the single glazed courtyard with buildings on three sides and with concrete walls. As a reference, the result for an unshaded courtyard is shown, which is the same as shown in Figure 7.17. Thus, the same activity and clothing are used in the calculations as in Figure 7.17. The transmission of solar radiation is 20% for the shading device. In Figure 7.19, the PMV index is shown for a shaded roof during the day and also for both a shaded roof and a shaded glazed gable. As can be seen, solar shadings can significantly increase thermal comfort.

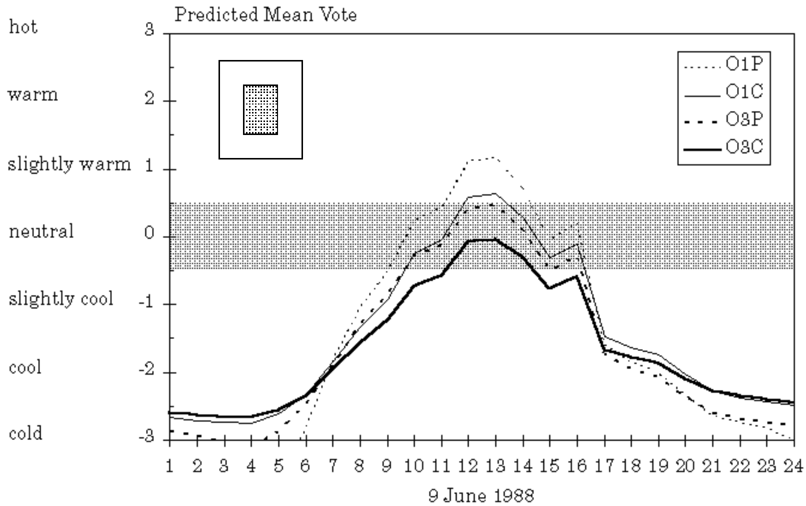


Figure 7.18 *The predicted mean vote in the glazed courtyards with buildings on all four sides at the level of 1.5 m, 3 m from the end wall. Sedentary activity (1.2 met) and the person is wearing T-shirt and shorts (0.3 clo). The glazed space is cooled to 20°C. The 9th of June 1988 in Lund.*
O = O shape (buildings on all four sides of the courtyard)
1 = single glazing and 3 = triple glazing
P = plasterboard walls and C = concrete walls.

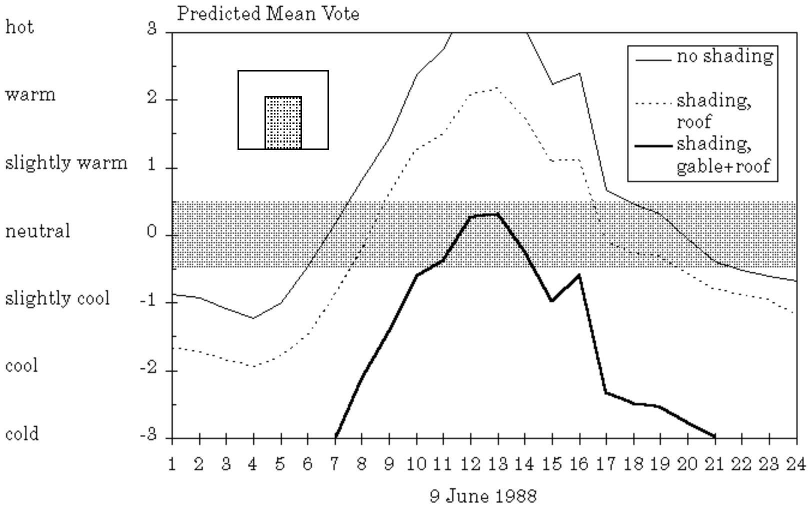


Figure 7.19 *The predicted mean vote in the single glazed courtyard with buildings on three sides and concrete walls. Results without solar shadings, with shadings outside the roof and with shadings both outside the roof and outside the glazed gable. Sedentary activity (1.2 met) and the person is wearing T-shirt and shorts (0.3 clo). The glazed space is cooled to 20°C. The 9th of June 1988 in Lund.*

7.4 Summary

The level of thermal comfort achieved is influenced by the air temperature, radiant temperature, solar radiation, clothing, physical activity, local air velocity, draught and humidity. Thus, the air temperature alone is not a sufficient parameter to indicate how people will experience the thermal environment.

Thermal comfort in glazed spaces should be studied at the design stage in order to choose the best positions in the space for different activities. These types of studies can also be helpful in deciding the required air temperature in the glazed space. This decision is necessary for sizing the heating and cooling equipment.

Studies of three types of glazed courtyards show that it is possible to achieve an acceptable level of comfort during the winter with passive climatic control if the glazed spaces are mainly used for circulation.

If the glazed space is to be used by a person on a more permanent basis, for example if a reception is placed in the courtyard, heat must be supplied during the winter. However, an acceptable thermal comfort is not achieved automatically by heating a glazed space to indoor temperature. Solar radiation, long wave radiation and draught will strongly influence the experience of the thermal environment. Local radiant heating in seating areas can be one way to increase comfort.

In the summer, it is not easy to achieve high thermal comfort merely by reducing the air temperature to 20°C in the glazed space. Nor is ventilation alone sufficient to increase thermal comfort. One way to increase thermal comfort is to use solar shadings.

8 Discussion and conclusions

Introduction

The theoretical studies together with the case studies have provided general knowledge regarding the performance of different types of glazed spaces. Parameters such as the geometry of the building, type of glazing, orientation, thermal inertia, airtightness, ventilation system, sunshades and the outside climate obviously affect climate and thermal comfort in the glazed space and energy requirements for heating and cooling. These parameters are of different importance for each specific type of glazed space. In addition, the significance of each of these parameters varies for different types of glazed spaces. Some of these parameters are determined early in the design stage which means that the climate in the glazed space and energy requirements will also be indirectly determined at an early stage, without any proper analysis.

Verification of the simulation program DEROB-LTH

Comprehensive calculations have been made with the dynamic building energy simulation program DEROB-LTH. Comparisons between calculations and measurements from the case studies have been made in order to verify the simulation program. The results of these comparisons show good agreement between calculations with DEROB-LTH and temperatures measured in glazed spaces with passive climatic control.

Geometry

The geometry of the building is of great importance for the climate in the glazed space as well as for heating and cooling requirements. It is the geometric relation between the glazed space and adjacent buildings that determines how well solar radiation and also the heat losses from adjacent buildings can be utilised. For example, a glazed veranda will hold a lower temperature level with passive climatic control than a glazed courtyard with buildings on two, three or four sides.

What mainly determines the temperature level in a glazed space with passive climatic control is the relationship between the specific losses and the specific gains. This relationship is denoted *G*. For each glazed space, the value of *G* may be calculated and in this way a direct assessment of the temperature level may be made. Solar radiation is then not included. The smaller the value of *G*, the higher the temperature level in the glazed space.

The results of the case studies show that in a glazed veranda with a building on only one side, with passive climatic control, the minimum temperature during the winter will be very close to the outside temperature. The same applies to a glazed space without any adjacent buildings. Assuming that any adjacent building is heated to 20°C, these types of glazed spaces have a value of *G* which is typically higher than 12.

Even in glazed courtyards with buildings on two sides it is difficult to keep the temperature above 0°C during winter nights in Northern Europe. Auxiliary heat is then necessary in order to keep plants from freezing. This type of glazed space has a value of *G* which typically lies between 2 and 10.

However, in Northern Europe glazed courtyards with buildings on three or four sides may have a minimum temperature that is above the freezing point. At least, this is possible if the glazing has a low U-value, or if, for example, the exhaust air from adjacent buildings is used as supply air to the glazed space. In order to obtain a minimum temperature higher than 0°C in the glazed space with passive climatic control, the value of *G* should not exceed 1 if the minimum outside temperature is -20°C.

Parametric studies show that heating requirements in buildings adjacent to a glazed courtyard vary depending on whether the courtyard is surrounded by buildings on two, three or four sides. A glazed courtyard surrounded by buildings on three sides with a glazed wall towards south utilise solar radiation better than a glazed courtyard with buildings on only two sides or a courtyard with only the roof glazed. A glazed courtyard with buildings on three sides will therefore have a higher temperature level and, because of this, the heating requirement in adjacent buildings may be reduced.

The results of the case studies show that the energy contribution from the glazed spaces is rather small when they are used as buffer zones or to preheat the supply air to the buildings. This reduction in energy for space heating in adjacent buildings has been less than 10%. The main reason for this is that because of the unfavourable design of these glazed spaces heat losses are much higher than heat gains. It can also be seen that solar gain can be significantly reduced if air leakage is high. A high air leakage will reduce the temperature level and also increase heating requirements.

What must not be forgotten is that one benefit of glazed spaces is that the space can be used for activities which would otherwise have to be located in adjacent buildings. The glazed space may include staircases, lifts, cafeterias, restaurants etc.

In addition, as the glazed space is a climatic shield, the facades abutting on the glazed space may have a lower technical standard.

Type of glazing

The type of glazing also influences the temperature level in the glazed space. This is especially true for a glazed space with a geometry which gives a relatively low value of the factor *G*. In the case studies, calculations showed that the temperature level in a glazed veranda would only have been 1-2°C higher with double or triple glazing than with the existing single glazing. The same result was obtained for a single glazed courtyard with buildings on two sides. Both these types of glazed space have very large areas of glass towards the outside which means that heat losses would still be very high even if glazing with a lower U value were chosen. The choice of glass of higher insulation capacity to obtain a slightly higher temperature will then be a costly measure. However, if the glazed space is heated, the U value of the glazing has a large influence on energy requirements regardless of the value of *G*.

Orientation

The temperature in the glazed space is less sensitive to the orientation of the building, as long as north is avoided as the main orientation of the glazed surfaces. If solar shadings are to be used, the orientation may obviously affect the type of shading that should be installed and the surfaces that have to be shaded.

Thermal inertia

The lower the value of *G* is for the glazed space, the greater is the influence of thermal inertia on the temperature fluctuations in the glazed space. However, during the winter, the thermal inertia has no appreciable significance for the temperature fluctuations. This is due to the fact that solar radiation in the winter is very low in Northern Europe.

Thermal inertia may to some extent influence the energy requirements in a glazed space. Power requirements may also be influenced. On the other hand, the thermal inertia available in the glazed space has no significant effect on the energy requirements of adjacent buildings. Thermal inertia is utilised best if the glazed space has passive climatic control. A high thermal inertia may also increase thermal comfort in the glazed space.

Thermal inertia has a greater influence on the heating requirements in a glazed courtyard with glazing of *low* U value than in a courtyard with glazing of high U value. However, thermal inertia has a greater influence on the cooling requirements in a glazed courtyard with glazing of *high* U value than in a similar courtyard with glazing of low U value. If solar shadings are used or if the glazed space is ventilated, the influence of the thermal inertia will be reduced.

Heating and cooling requirements

Heating requirements are much higher for a single than for a triple glazed courtyard. On the other hand, cooling requirements in order to obtain 20-22°C in the glazed space are not significantly higher for a single glazed courtyard than for a triple glazed one.

When a glazed space is heated, heating requirements for adjacent buildings will at the same time be reduced. However, the energy needed to heat a glazed space cannot be compensated for by a reduced heating requirement in adjacent buildings, especially not when the glazed space has a high value of *G*.

Airtightness

The lower the value of *G* is for the glazed space, the more sensitive is the glazed space to ventilation and air leakage. Glazed spaces with a low value of *G* in particular should therefore have an airtight climatic envelope so that ventilation can be controlled on the basis of existing need. Unintended ventilation during the winter may otherwise have drastic consequences for the temperature in the glazed space.

Measurements of airtightness in six glazed courtyards showed that the four atria built in recent years were much more airtight than the two older courtyards. If the requirement concerning air leakage is assumed to be that according to Swedish building regulations for premises other than dwellings, viz. 6 m^3/m^2h, then all four newer atria would satisfy this requirement. However, since these atria are in principle heated to indoor temperature and cooled in the summer, it may be appropriate to impose higher airtightness requirements in order to reduce the energy need in such spaces.

Moreover, the airtightness regulations for dwellings are different from those for other premises. It would be more appropriate to have higher airtightness requirements for fully (to 20°C) heated buildings than for unheated or partially heated buildings. A glazed space would then be automatically included and not forgotten in the regulations. It seems rather strange that we in Sweden have high demands in order to make buildings energy efficient and yet glazed spaces are allowed to be both heated and cooled to indoor temperatures.

Solar shadings

Solar shadings are used in some of the glazed spaces in order to reduce the temperature during the summer. External shadings are the most effective type as they prevent solar radiation from even being transmitted into the glazed space. Internal shadings may however also be effective if the solar radiation is blocked high up in the glazed space and the heat is ventilated out through vents in the glazed roof before it reaches the occupancy level. Solar curtains may also be used as night insulation.

The results of the case studies show that a combination of solar curtains and opening vents is an effective means of reducing the temperature in the glazed space in the summer. However, if the outside temperature during the day is close to the temperature in the glazed space, ventilation by opening vents obviously has a limited effect.

It is not unusual for solar shadings to be installed in glazed spaces *after* the building has been completed, i.e. during the first summer. A reason for this is insufficient knowledge on the part of consultants of how to estimate the influence of solar shadings on temperature, energy requirements and thermal comfort.

Generally, there is insufficient knowledge of the physical properties of different types of shadings. There is also a lack of knowledge regarding the performance of different shadings in combination with a glazing system. The performance varies depending on whether the shading is placed on the outside, between the panes or on the inside.

The lack of knowledge regarding solar shadings causes difficulties in estimating total costs and the pay-off period. It is then difficult to justify solar shadings already during the design stage, which means that the first summer will have to demonstrate the need. Unfortunately, the consequence of this may be that the total costs will be higher and that cooling plants may be wrongly sized.

Ventilation systems

Different ventilation systems can be used in order to achieve a higher temperature in the glazed space and/or lower energy requirements. A reduction in energy requirements can be achieved by using the glazed space as a preheater for the supply air to the adjacent buildings. The exhaust air from the buildings can also be used as supply air to the glazed space in order to obtain a higher temperature level.

A good ventilation system design is to use the exhaust air from the buildings as supply air to the courtyard and at the same time to use a heat exchanger to transfer heat from the exhaust air from the courtyard to the supply air to the buildings. In this way a high temperature level in the glazed courtyard is obtained in combination with low fabric and ventilation losses in adjacent buildings. However, heat exchangers should not be used in the summer.

Long wave sky radiation

Long wave sky radiation may have a large influence on the temperature in the glazed space and on heating requirements. Glazed spaces often have the roof glazed which in addition has a high U value compared with an ordinary insulated opaque roof. A glazed space is therefore influenced more by the long wave sky radiation than an ordinary building.

The sky temperature may be considerably lower than the outside air temperature. Because of this, the temperature just below a glazed roof may sometimes even be lower than the outside air temperature.

If long wave sky radiation is not taken into account, energy requirements for heating a glazed space may be strongly underestimated, especially if the glazing has a high U value. In building energy simulation programs, the sky temperature is often put equal to the outside air temperature.

Solar radiation

Solar radiation has a major influence on the climate in a glazed space and may of course be utilised in more or less efficient ways. Care should be taken to ensure that the solar gains are calculated accurately when the climate in the glazed space and energy requirements are estimated during the design stage. The result may otherwise be a poor climate, high energy requirements and disappointed building users.

Comparisons of four simulation programs show very large differences in the calculated distribution of solar radiation. The simpler methods overestimate the utilisation of solar radiation. This means that the temperature in the glazed space will be overestimated and the energy requirements for heating will be underestimated. Energy requirements for cooling the glazed space will be overestimated.

This investigation shows that simulations of atrium buildings or other types of glazed spaces must be based on a geometrical description of the buildings, with transmission through windows, reflection and absorption taken into account. Consequently, energy simulation programs which assume that all transmitted solar radiation is utilised should only be used for buildings with ordinary window sizes.

Thermal comfort

Thermal comfort in glazed spaces should be studied at the design stage in order to choose the best positions in the space for different activities. These types of studies may also be helpful in deciding the required air temperature in the glazed space. This decision is necessary for the design of heating and cooling systems.

Studies of three types of glazed courtyards show that it is possible to obtain an acceptable level of comfort with passive climatic control during the winter if the glazed spaces are mainly used for circulation.

If the glazed space is to be used by a person on a more permanent basis, for example if a reception is placed in the courtyard, heat must be supplied during the winter. However, acceptable thermal comfort is not achieved automatically by heating a glazed space to indoor temperature. Solar radiation, long wave radiation and draught will strongly influence the experience of the thermal environment. Local radiant heating in seating areas may be one way to increase comfort.

During the summer, it is not easy to achieve a high standard of thermal comfort merely by reducing the air temperature to 20°C in the glazed space. Nor is ventilation alone sufficient to increase thermal comfort. Solar shadings are one way of increasing thermal comfort.

Simplified calculation method

Experiences from the case studies show that the expectations of architects and others during the design process are sometimes too high regarding the temperature level in glazed spaces during the winter that can be achieved by passive climatic control. These expectations may of course be easily communicated to the building owners and the future building users. This may lead to disappointed tenants and high energy requirements.

It is therefore a very important goal to produce design guidelines and simple calculation methods which may be used early in the design stage. These design tools should make it possible to understand how the building design will affect the climate and energy requirements in a glazed space and adjacent buildings.

A simple manual calculation method has therefore been produced for the assessment of the temperature and energy requirement in glazed spaces. The effect of the glazed space on the energy requirements of the surrounding buildings can also be estimated.

It is intended that the method should be applied as early as during the preliminary design stage so that the effect which the design of the building will have on climate and energy requirement may be determined. The calculation method does not provide exact answers, but shall be used to get an idea of the difference between alternative configurations and to see which parameters are significant for climate and energy. It is hoped that the use of this method right at the preliminary design stage will prevent energy demanding solutions and a poor standard of comfort. It is also hoped that the method will provide an insight into how glazed spaces behave with regard to climate and energy.

The calculation method has been tested on two of the case studies. Field measurements were made in both these projects. Bearing in mind the simplicity of the method, good agreement between calculated and measured temperatures has been obtained in both examples.

The method is not yet complete. A way must be found to calculate the maximum temperature in the glazed space. In such a case it will be necessary to take account of the thermal storage capacity. In connection with this, the effect of different types of solar control will also have to be studied to see how much they can reduce solar radiation. Thermal comfort should also be treated.

Future work

More research and development regarding glazed spaces are still necessary. Further work is suggested on calculation methods for estimating air stratification in tall glazed spaces. Note that it is then also necessary to calculate the distribution of solar radiation accurately.

Not a lot is known about the performance of solar shadings. Solar shadings should be further studied as they may be used to reduce temperatures and cooling requirements and may also be used to increase thermal and visual comfort.

Thermal comfort should also be further studied. People may be more tolerant when they visit a glazed space than when they enter an ordinary room. Expectations are perhaps not so high, which could mean that the acceptable level of thermal comfort is lower than for an ordinary building. However, if a person is working in a glazed space over longer periods, the comfort criteria are presumably the same as for ordinary premises.

The most important goal should be the production of useful guidelines on how to design glazed spaces. Significant results concerning glazed spaces from both theoretical research work and studies of the performance of buildings in practice have been reported in several countries. This knowledge should be brought together into guidelines and calculation methods which should preferably be common to several countries which are situated in the same climatic zone.

9 Summary

Glazed spaces are not a new feature in architecture. At first, glazed spaces were used as greenhouses in botanic gardens in order to create a suitable climate for exotic plants. Then, in the 19th century, large spaces were built in glass and iron as exhibition halls, as the central parts of railway stations and also as atrium buildings. The glazed space had then become attached to ordinary buildings.

Glazed spaces ranging from small verandas to large atrium buildings have again become popular during the last fifteen to twenty years. This time, one of the main reasons for their construction was to save energy. It was the energy crisis in 1973 which provided the main impetus for the creation of low energy buildings.

Glazed spaces were then built, promising large energy savings as solar collectors. However, experiences from these buildings show that it is not self evident that energy will be saved in this way. Merely providing a glazed roof for a space does not mean that the climate will automatically become just right.

In Northern Europe, the climate is rather cold and unpleasant during the winter and a glazed space can therefore function as a climatic shield. Some of the glazed spaces are used only when the climate inside them is suitable, i.e. they have passive climatic control, while others are required to have more extensive use. Such a requirement often implies that energy must be supplied during the winter months to obtain an acceptable temperature. During the summer also, energy is sometimes used in order to cool the glazed space. It is obviously desirable that the climatic requirements should be satisfied as far as possible without any additional heating or cooling having to be supplied.

The goal of this research work has therefore been to elucidate the relationship between building design and the climate and the thermal comfort in different types of glazed spaces together with the en-ergy performance of the whole building. The studies of energy performance have been limited to requirements for heating and cooling.

Another goal has been to develop a design tool for glazed spaces for the calculation of temperatures and energy requirements. The aim has been to develop at least a calculation method, even if a complete design tool ready for use by consultants is not yet available. The development of a complete design tool is the next step and must be a collaboration between researchers, architects and other consultants involved in the design process.

The research work has mainly comprised case studies of existing buildings with glazed spaces and energy balance calculations using both the developed steady-state method and a dynamic building energy simulation program.

Parameters such as the geometry of the building, type of glazing, orientation, thermal inertia, airtightness, ventilation system and sunshades affect climate and thermal comfort in the glazed space and the energy required for heating and cooling. In addition, the outside climate is an important parameter, especially the short wave solar radiation but also the long wave sky radiation and of course the outside temperature. These parameters have therefore been studied.

All these parameters are of different importance for each specific type of glazed space. In addition, the significance of each of these parameters varies for different types of glazed spaces. Some of these parameters are determined early in the design stage which means that the climate in the glazed space and energy requirements will also be indirectly determined at an early stage, without any proper analysis.

Parametric studies show that heating requirements in buildings adjacent to a glazed courtyard vary depending on whether the courtyard is surrounded by buildings on two, three or four sides. A glazed courtyard surrounded by buildings on three sides with a glazed wall towards the south utilise solar radiation better than a glazed courtyard with buildings on only two sides or a courtyard with only the roof glazed. A glazed courtyard with buildings on three sides will therefore achieve a higher temperature level and, because of this, the heating requirement in adjacent buildings may be reduced.

In addition, the temperature level in a glazed courtyard with passive climatic control will be higher when the glazing has a low U value. Furthermore, if a glazed courtyard is to have a high temperature level, it is essential to keep the climatic envelope airtight.

Thermal inertia may to some extent influence the energy requirements in a glazed space. Power requirements may also be influenced. On the other hand, the thermal inertia available in the glazed space has no significant effect on the energy requirements of adjacent buildings. Thermal inertia is utilised best if the glazed space has passive climatic control. A high thermal inertia may also increase thermal comfort in the glazed space.

A good ventilation system design is to use the exhaust air from the buildings as supply air to the courtyard, and at the same time to use a heat exchanger to transfer heat from the exhaust air from the courtyard to the supply air to the buildings. In this way a high temperature level in the glazed courtyard is obtained in combination with low fabric and ventilation losses in adjacent buildings. However, heat exchangers should not be used in the summer.

The ten case studies which are described all contain glazed spaces of varying sizes. The sizes vary between 10 and 5 000 m^2, corresponding to 25 - 30 000 m^3.

The buildings in the case studies were built between 1981 and 1992. One of the buildings has not yet been constructed, but this will probably be done in 1997.

The results of the case studies show that the energy contribution from the glazed spaces is rather small when they are used as buffer zones or to preheat the supply air to the buildings. This reduction in energy for space heating in adjacent buildings has been less than 10%. The main reason for this is that because of the unfavourable design of these glazed spaces heat losses are much higher than heat gains. It can also be seen that solar gain can be significantly reduced if air leakage is high. A high air leakage will reduce the temperature level and also increase heating requirements.

What must not be forgotten is that one benefit of glazed spaces is that the space can be used for activities which would otherwise have to be located in adjacent buildings. The glazed space may include staircases, lifts, cafeterias, restaurants etc. In addition, as the glazed space is a climatic shield, the facades abutting on the glazed space can have a lower technical standard.

Measurements of airtightness in six glazed courtyards showed that the four atria built in recent years were much more airtight than the two older courtyards. If the requirement concerning air leakage is assumed to be that according to Swedish building regulations for premises other than dwellings, then all four newer atria would satisfy this requirement. However, since these atria are in principle heated to indoor temperature and cooled in the summer, it may be appropriate to impose higher airtightness requirements in order to reduce the energy need for such spaces.

The results of the case studies also show that a combination of solar curtains and opening vents is an effective means of reducing the temperature in the glazed space in the summer. However, if the outside temperature during the day is close to the temperature in the glazed space, ventilation by opening vents obviously has a limited effect.

It is not unusual for solar shadings to be installed in glazed spaces *after* the building has been completed, i.e. during the first summer. A reason for this is insufficient knowledge on the part of consultants of how to estimate the influence of solar shadings on temperature, energy requirements and thermal comfort.

Furthermore, the comfort calculations show the great importance of studying thermal comfort in glazed spaces already during the design stage. Such studies may be used in order to choose the best positions in the space for different activities. These types of studies may also be helpful in deciding the required air temperature in the glazed space. This decision is necessary for the design of heating and cooling systems.

Solar radiation has a major influence on the climate in a glazed space, and may of course be utilised in more or less efficient ways. Care should be taken to ensure that the solar gains are calculated accurately when the climate in the glazed space and energy requirements are estimated during the design stage. The result may otherwise be a poor climate, high energy requirements and disappointed building users.

Comparisons of four simulation programs were carried out for a sunspace with an adjacent room. The distribution of solar radiation between the glazed space and the adjacent room as well as the proportion of short wave radiation lost to the outside were studied.

The programs show very large differences in the calculated distribution of solar radiation. The simpler methods overestimate the utilisation of solar radiation. This means that the temperature in the glazed space will be overestimated and the energy requirements for heating will be underestimated. Energy requirements for cooling the glazed space will be overestimated.

This investigation shows that simulations of atrium buildings or other types of glazed spaces must be based on a geometrical description of the buildings, with transmission through windows, reflection and absorption taken into account. Consequently, energy simulation programs which assume that all transmitted solar radiation is utilised should only be used for buildings with ordinary window sizes.

Within this research work, a simple manual calculation method has also been produced for the assessment of the temperature and energy requirement in glazed spaces. The effect of the glazed space on the energy requirements of the surrounding buildings may also be estimated.

It is intended that the method should be applied as early as during the preliminary design stage so that the effect which the design of the building will have on climate and energy requirement may be determined. The calculation method does not provide exact answers, but shall be used to get an idea of the difference between alternative configurations and to see which parameters are significant for climate and energy. It is hoped that the use of this method right at the preliminary design stage will prevent energy demanding solutions and a poor standard of comfort. It is also hoped that the method will provide an insight into how glazed spaces behave with regard to climate and energy.

The calculation method has been tested on two of the case studies. Field measurements were made in both these projects. Bearing in mind the simplicity of the method, good agreement between calculated and measured temperatures has been obtained in both examples.

The method is not yet complete. A way must be found to calculate the maximum temperature in the glazed space. In such a case it will be necessary to take account of the thermal storage capacity. In connection with this, the effect of different types of solar control will also have to be studied to see how much they can reduce solar radiation. Thermal comfort should also be treated.

Further research is suggested regarding the performance of solar shadings, calculation methods for estimating air stratification in tall glazed spaces and also research concerning thermal comfort in glazed spaces.

The most important goal should be the production of useful guidelines on how to design glazed spaces. Significant results concerning glazed spaces from both theoretical research work and studies on the performance of buildings in practice have been reported in several countries. This knowledge should be brought together into guidelines and calculation methods which should preferably be common to several countries which are situated in the same climatic zone.

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ISSN 1103-4467
ISRN LUTADL/TABK--1009--SE