A STUDY INTO HOW THE OCCUPANTS OF NATURALLY VENTILATED BUILDINGS USE ENVIRONMENTAL CONTROL STRATEGIES TO MODIFY THEIR INTERNAL ENVIRONMENT

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格物致知
(To attain knowledge by investigating things)

礼记 • 大学 (The Book of Rites • The Great Learning)

Ask, and it shall be given you; seek, and ye shall find; knock, and it shall be opened unto you.

Matthew 7:7 (KJV)

Summary

- **Title:** **A Study into How the Occupants of Naturally Ventilated Buildings Use Environmental Control Strategies to Modify Their Internal Environment**
- **Author:** Yufan Zhang
- **Keywords:** *built environment, comfort, occupant control, blind, window,*

Nowadays, issues regarding building stock are highly important in the quest to reduce overall UK energy consumption and finding prime targets for cuts in carbon emissions. Of all the main consumers of energy, the fact how occupants use and operate the building plays a crucial role. Therefore, it is necessary to have a thorough understanding of the occupant response to environmental controlling systems in buildings because the building should be designed not only to satisfy comfort requirements but also to be used with a low input of energy.

This research can be seen as an attempt to explore such issues. It examines various environmental issues such as motivating forces and influential effects related to the occupant control behaviour with special attention to the usage of those simple, easy-to-use and robust means that the occupant is able to see and almost immediately experience the results of the actions.

Two naturally ventilated buildings in Sheffield were selected as the study cases. Their architectural features were examined, including environmental situation, occupant identification and architectural speciality. Both buildings' blinds (shading rolls) and windows were recorded by photograph twice a day for 16 months continuously. At the same time, the outside hourly weather parameters and inside physical parameters were collected. A questionnaire survey and a face-to-face interview were also carried out in order to investigate the thermal, visual and acoustic comfort sensation and an indication of the motivating forces for manual control obtained.

From a sustainability perspective, the study has provided knowledge that enables designers to anticipate how a design encourages that the sustainable interaction between the occupant operation behaviour, building components and/or systems, and conversely, avoid built conditions where occupant interaction may cause sustainable penalties. This understanding may well lead to the building using less energy to maintain comfort. The study could also provide opportunities for decision makers to understand the current situations of the buildings that were selected as case studies. The result of this research may be used as a work-base for successful improvement and give confidence to embark on the design of naturally ventilated buildings.

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[redacted]

Yufan Zhang
Sheffield, UK
July 2007

Table of Content

List of Figures

List of Tables

Chapter One

Introduction

- Jason Evans: What's going to happen to us?
- Jack Hall: What do you mean?
- Jason Evans: I mean 'us'? Civilization? Everyone?
- Jack Hall: Mankind survived the last ice age. We're certainly capable of surviving this one. The only question is, will we be able to learn from our mistakes?

\- *[the Day after Tomorrow*] (Film 2004)

Chapter One
Introduction

1.1 Background of the Study

Today, all developed societies, including the UK are dependent on sources of energy both for their existence and in order to maintain people's high standards of living. However, the public has become aware of the fact that human society's deep reliance on oil, gas and other petroleum products is not built on a solid foundation. Shortages of these fossil fuels and rapidly rising energy costs have been apparent for years and are likely to continue to be a critical problem for the world [1]. Coupled with this problem, the mean surface temperature of the earth has been increasing due to the harmful emission of 'greenhouse gases' resulting from excessive energy consumption [2].

Of all the main consumers, the use of energy in buildings, both domestic and non-domestic, is responsible for about half of the nation's total consumption and about half of the total release of carbon [3]. Issues regarding building stock are, therefore, highly important in the quest to reduce overall UK energy consumption and finding prime targets for cuts in emissions. At present, much work has been done in the attempt to find potential solutions to the problems of energy efficiency and 'environmental friendliness' in building design.

The use of energy is not just a matter concerning the 'life-cycle' construction of buildings, and the efficiency of the various kinds of servicing system. Crucially, it also depends on how occupants operate buildings. Therefore it is important to have a thorough understanding of the occupant responses to environmental controlling systems in buildings.

This research can be seen as an attempt to push discussion of such issues in this direction. It begins by highlighting the scope of the study. Then the research problem is outlined in order to elaborate the central challenges of the study and to provide an overview of current knowledge about occupant responses to environmental control. The chapter goes on to present both the objective and the research hypothesis that is adopted for this study and concludes by detailing the organization of the thesis as a whole.

1.2 Scope of the Study

A large number of conventional energy sources are utilized to create a thermally, visually and acoustically comfortable indoor environment. There are many environmental strategies in the domain of architectural design for achieving degrees of indoor comfort that are as high as possible. Occupant responses, on the other hand, to these strategies are made according to their sensations. This is especially true when they are in a naturally ventilated environment, as the indoor environment normally follows the local prevailing climate and changeable weather variables. Thus, as shown in Figure 1.1 the indoor environment, occupant comfort, and control strategy affect and are affected by each other to a significant degree.

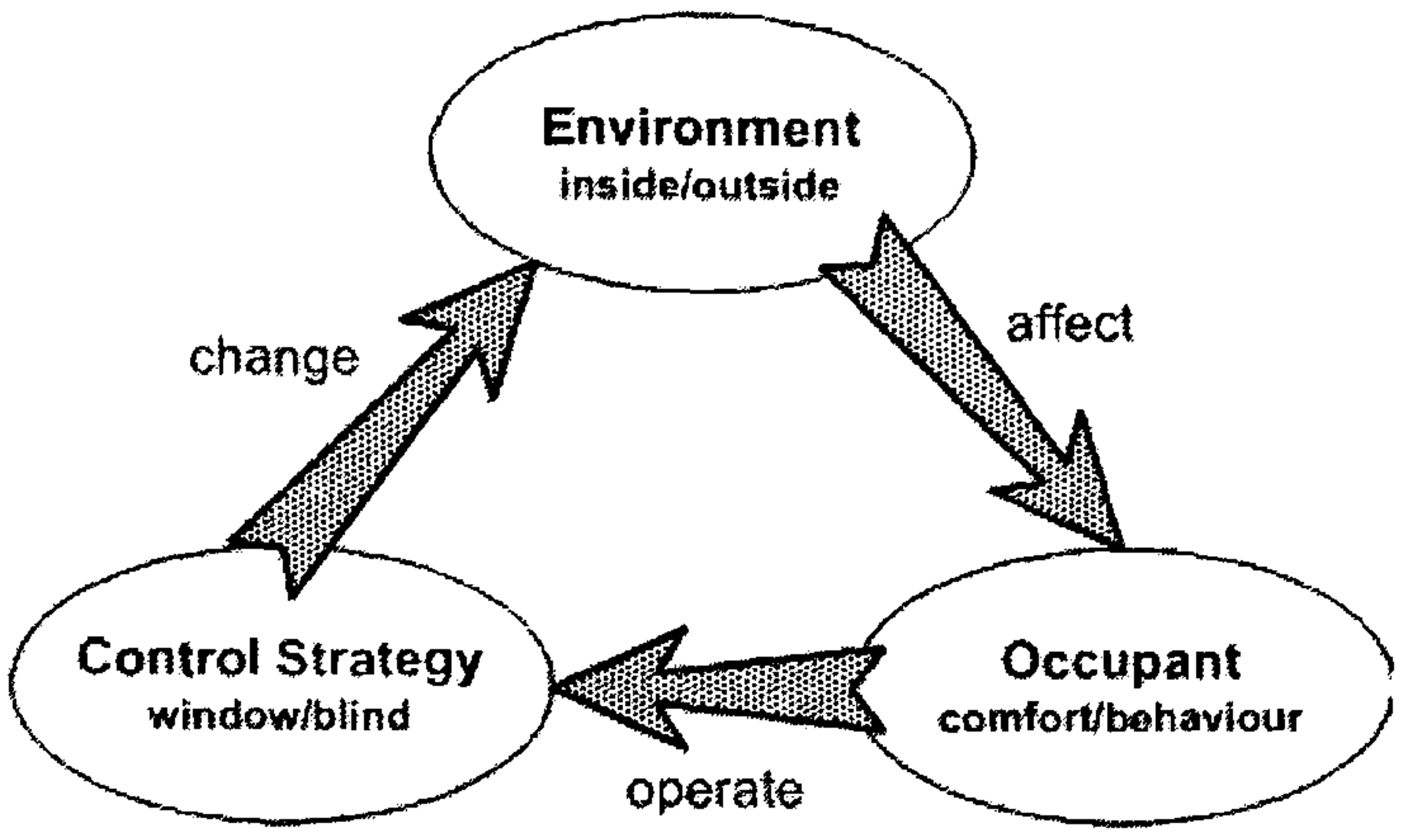

Figure 1.1 Scope of the research

This research is aimed at contributing to the understanding of the indoor environment, occupant sensation, environmental control and the interaction between these main issues especially with regard to naturally ventilated buildings. Therefore, this research is unique because it examines an important aspect of the impact of occupants' behaviour on the performance of buildings in use which previous studies have not investigated fully due to the predominantly segmented nature of earlier studies in examining either the comfort criteria of a built environment or environmental control systems. As suggested by the general scope, three areas are specified in detail in order to make sure that the study is not only clearly defined but also easily controlled.

1.2.1 Occupant Comfort in a Built Environment

With respect to the level of comfort inside the building, in the first place this is connected to the physical conditions in a room considered as a whole, and is primarily determined by four major factors: air temperature, mean radiant temperature, humidity and air velocity, all of which influence a person by way of heat loss and gain [4]. Later, this concept is extended to include some non-thermal factors: optical and acoustic requirements, electric particles, micro organisms, and so on, which are all important in evaluating a given indoor climate [5].

As of now, there are thousands of people active in this field and much work has been devoted to establishing a series of reliable quantitative comfort indices for the desired indoor climate related to all kinds of physical aspects. More recently, the concept of 'human comfort' has been developed further: it is no longer just about advocating an obsessive application of 'optimized' environmental parameters. Instead it defines a far more holistic experience of 'comfort', since the very concept is dependent on some subjective variables: the variability and options that the environment offers, the ability of occupant to determine those options, the perceived degree of control by the occupant (whether direct or indirect), management skill, and so on.[6]

This study tries to examine the concepts of occupant comfort in relation to the thermal, visual and noise effects which are primarily in the domain of architecture. It discusses the principles of heat, light and sound, the perceptions and preferences of occupants that are related to these issues. Based on the characteristics of these physical performances, how a building can provide a satisfactory indoor environment for satisfying the requirements of occupants are among the areas explored.

1.2.2 Building Environmental Control

Since the climate does not offer conditions that ensure comfort all of the time, it is necessary to correct it with the help of devices for lighting, heating and cooling etc. The entire history of shelter engineering reveals the unremitting effort by mankind to achieve as high a degree of indoor comfort as possible. With technological advances in the 1950s, when the compact heating and air-conditioning equipment was developed, a high degree of comfort in buildings became achievable even in adverse climates.

In terms of the effective distribution of heat and coolness, there are two basic building environmental systems employed: passive and active systems. The difference between them is that if the total energy consumed by the mechanical devices is negligible in comparison to the total energy needed for heating or cooling a building, it is called a passive system. Conversely, it is called an active system when it uses an appreciable amount of conventional energy [3]. However, it needs to be stressed that a good built environment control system can not be dependant on only one of these. Instead, they have to be regarded as complementary to each other, so that the advantages of both can be properly exploited at all times.

Broadly the active control type of system has two classifications: the Heating, Ventilation and Air Conditioning (HVAC) system and the Permanent Artificial Lighting (PAL) system. In this study they are discussed only in a general way due to this being primarily an engineering matter. In contrast, this study gives more attention to how landscape, envelope and fabric affect the built environment in a natural way. A wide range of environmental control strategies are examined and their basic principles, design aspects, performance are discussed and illustrated with reference to practical examples.

1.2.3 Occupant Control of the Built Environment

The manifestations of the environmental control strategy are varied. Some of them are static, or fixed in place; examples include site selection, layout arrangement, construction details, insulation materials, and glazing orientation in the building shell etc.

Some of the controls, however, are dynamic; these include operable window sash, movable window insulation covering, and a variety of adjustable sun-shading devices etc. The latter examples involve the inhabitants, who need to take an active role in the operation of buildings.

In this study, the main aim is to explore the occupant manual operation of the control strategies, especially those simple, easy-to-use, robust means that the user is able to see and almost immediately experience the results of their actions - e.g. the operation of doors, electrical lighting, windows, blinds, shading rolls - on the basis of the field evidence provided by existing building stocks. Of all these strategies, the window with internal shading covering is singled out because, by means of adjustment, it is one of the most important elements in the control of solar gain, day lighting and overheating at the disposal of occupants.

1.3 Statement of the Problem

It is difficult to investigate occupant manual control as this is an area that has to take account of the complexity of the physical built environment, the complexity of human experience and behaviour and the equally complex possible relationships between the two. Humphreys M.A [7] argues that *people are not inert recipients of the environment, but interact with it in order to optimise their own conditions and use various means at their disposal to improve their comfort position* thus indicating that research in this area involves observing the daily routines, practices and habits of building occupants in order to see how they modify and adjust their environments to achieve satisfactory built environments for themselves. This perhaps depends on many factors, some of which may have nothing to do with physical comfort e.g. privacy practices.

1.3.1 Review of Previous Work

Much work has been done on the relation between built environment and occupant comfort, and the built environmental control system. These two parts are discussed in a detailed way in Chapters Two and Three. However, there are few published studies on occupants' individual experiences of the physical environment and responses to the building control system. The following studies have focused on the premise that occupant operation occurs as a reaction to a series variables, e.g. season, air temperature, sun light and sun heat, time of the day and periods of presence in the building etc.

Diane Haigh [8] studies five schools in two seasons, monitoring both environmental conditions and the responses of staff and pupils to them. He concludes that this is an essential aspect of designing for energy conservation. The design challenge lies in integrating the users' priorities with energy efficient control, so that their happy and positive attitude is coincident with behaviour that conserves energy. Nicol [7, 9] does a survey on the use of simple controls – window, lighting, blind, heater and fan – in naturally ventilated buildings in several countries. His intention is to make realistic assumption about user behaviour that can be used later in simulations. He shows how the use of each control varies with outdoor temperature. As the temperature rises there is an increased probability that a window will be open.

These two simple surveys generally provide a theoretical background to this study while the following can establish what this study is proposing to examine and what has already been studied and help to refine the research methodology.

Rubin et al. [10] is found to be the earliest in pursuing research of occupant use of the window blind. He studies several buildings in Maryland and finds systematic differences in the occupants' blind positions depending upon the window orientation. Furthermore, they conclude that most occupants have preferred blind positions relatively independent of daily, seasonal, and, possibly, climatic condition. A rating system for evaluating the blind positions from the photographic slides is also developed. This method is maintained and employed by many future studies on occupant blind control although they all have their notable and distinct features as well.

Rea M.S. [11] performs a similar pilot study to test some simple hypotheses in light of the conclusions reached by the pioneering efforts and focuses the attention on the effect of blind occlusion on daylight factors. He concludes that the estimations of daylight factors should include assessment of window blind usage, because over half of the window area is usually occluded in some way by blinds. It appears that many occupants purposely use blinds to prevent sun light from penetrating their work space.

Inoue et al. [12] investigate four high-rise office buildings in Tokyo. They conclude that, on average, 60% of blinds are not moved at all during the day. Operation of blinds seems to be determined, not by the solar heat gain through windows but by the incident distance of direct solar radiation. It is not triggered when the intensity of direct solar radiation is under some threshold value. They also issue a questionnaire and find that the majority of occupants in offices prefer a space near the window. Glazing needs to be transparent while shading is indispensable to the thermal and luminous environment.

Lindsay et al. [13] concludes from a study involving five separate surveys that there is some link between the amount of sunshine, the position of the sun, orientation and blind use. They can not establish or confirm a connection as to whether it is the sun's heat or glare that causes the blind to be moved, but assume it is likely that glare rather than heat is the overriding motivating factor.

Forster M et al. [14] examines the current assumptions in occupant use of the blind and then compares the assumed use with actual use from monitored data in two seasons with three buildings. In particular the impact of façade orientation, sunshine and electric lighting on blind use is investigated. It confirms that on average 40% of a building's façade is obscured by blinds. Occupant's use of blinds is predominantly not affected by solar availability as often modelled due to a low correlation coefficient.

Hunt D.G. [15] studies how people in their normal working environment use artificial lighting. He discovers that usually either all or none of the lighting is in use without part of lighting on situation. The crucial factor is the cycle of occupation of the space, with continuous and intermittent occupation clearly affecting people's operation of the light and determining the frequency with which people switch lights on and off.

Warren et al. [16] conducts a study in five naturally ventilated office buildings in the UK over a period of 3 months during the heating season. They find window opening is strongly related to outdoor temperature, followed by solar gain and wind speed. Slight opening of windows is to satisfy indoor air quality requirements whereas wide opening of windows strongly corresponds to temperature. In addition, the glazed area, orientation, the type of heating system and its control all affect window control. They also reveal that once the window is opened, it is rarely closed until the room is finally vacated.

Fritsch et al. [17] undertake a study of four office rooms over a complete heating season. They reveal that the outside temperature acts as a driving variable for window opening or closing. However, the strong relationship between the window angle and the outdoor temperature in winter does not exist during the summer. They develop a model to predict the window operation but it is only valid for the winter period.

Herkel S. et al. [18] produce a field study of the manual control of windows which is carried out in 21 individual office rooms in Germany over a period of one year. They conclude that user behaviour reveals a strong correlation between the percentage of opened windows and the time of year, outdoor temperature and building occupancy patterns. Based on the results, a preliminary user model is proposed to simulate and predict window status in office buildings with varying outdoor temperatures and occupancy.

The above studies provides a solid basis for conducting this study although they are all have their own limitations such as the complexity involved in monitoring blind movement, or the difficulty in obtaining large enough samples. Furthermore, none of them combines the occupant operation with their perception and opinion on the built environment they experience and neither is the effect of building design features addressed.

1.3.2 Statement of Problem

There are several reasons that may make study in this field of limited value and/or experimentally impractical. The first lies in the pattern of occupancy. As mentioned from previous work review, time-lapse photography of the façade is an efficient way to observe the window and blind position and record the variation day by day, time by time. However, it ignores the information that lies behind these windows. Even if the observation focuses on one type of a building e.g. office there are still lots of occupancy patterns that correspond to different room usages. The nature of the occupation of a space plays an important role in affecting occupant behaviour but this variable is very flexible even if the period of office day is fixed with standard starting and finishing time. The usage pattern of each room during that period is unpredictable. Therefore the room usage which represents different occupancy cycle, time, density and user features may imply that a major factor in the balance of the environment is changeable.

Furthermore, the interior environment condition can have a great impact on the occupant perception with respect to the requirement for a satisfactory and comfortable built environment. This includes not only room orientation but also room volume. Fundamentally the former determines what time and how long the amount of global radiation both solar and diffused is received. The latter determines the internal surface to the volume ratio which has a great impact on both ventilation rate and daylight illuminance distribution. As a result, the occupant operation behaviour in response to the natural physical environment may lead to differences as well.

In addition, the weather as opposed to climate becomes another important problematic aspect that environmental response studies may overlook. Broad seasonal differences can be fairly easily accommodated by changes in clothing, heating systems etc. But the weather is ever changing, even hour by hour. The occupant of a naturally ventilated building can be very sensitive to the temperature. And the visual environment varies with each passing cloud. Therefore it is these short term fluctuations that make the internal environment of a building affect the individual occupant's perception and response to the built environment in the form of different operations and adjustments [8].

Broadly this study builds on the previous method and specifically seeks to identify the relation between these highly variable factors which impinge on the internal environment and occupant sensation/operation behaviour. Therefore this research can be seen as an attempt to resolve the problem below:

How occupants attempt to control and balance their thermal, visual and acoustic comfort in a naturally ventilated environment?

1.4 Objective of the Study

Theoretically, from a sustainability perspective the study can provide knowledge that enables designers to anticipate how a design that encourages the sustainable interaction between the occupant operation behaviour, building components and/or systems, and conversely, avoid built conditions where occupant interaction may cause sustainable penalties e.g. greater energy expenditure. Practically, it can provide opportunities for decision makers to understand the current situation of the buildings that were selected as case studies. The result of this research may be used as a work-base for successful improvement and give confidence to embark on the design of naturally ventilated buildings.

It is set out to bridge the gap between the occupant operation behaviour and the built environment with special attention on windows with internal shading covering systems. The main purpose of this research is to examine the various environmental issues e.g. motivating forces and/or influential effects related to occupant control based on their own perception and experience in a naturally ventilated environment. Hopefully they can be brought to the attention of designers, researchers and decision makers who are involved in delivering, planning, implementing, monitoring and evaluating the indoor environment and/or computer simulation.

One of the buildings (Arts Tower) which is selected as the case study is going to have a thorough refurbishment with regard to its service system and building plan very soon. The current research on occupant window and blind operation can make a great contribution to better façade design as these two issues affect the thermal and visual environment very much. In addition the survey on the perception and comfort level of the individual indoor environment etc. can provide beneficial information people concerned about understanding the current building situation. All the results from this investigation may be used as a work-base for successful refurbishment.

On the other hand, the other example studied (ICOSS Building) is considered to be very successful and energy efficient in which sustainability is a fundamental aspect of the architectural concept. Its advanced stack-natural-ventilated system has the potential to consume much less energy for space conditioning than typical mechanically ventilated or air-conditioned buildings. This post occupancy observation and survey can reveal the occupant evaluation and opinion on this building and the operation of windows with internal shading roll systems. Hopefully this study will give architects and environmental design consultants the confidence to embark on the design of advanced naturally ventilated buildings.

More specifically, the following are the details of the objectives this study hopes to achieve:

- To review the fundamental issues on the interaction between indoor environment and occupant sensation – thermal, luminous and acoustic comfort by specifying how the human being responds to all kinds of heat, light and sound and how the building characteristics affect these indoor environments.

- To review a wide range of environmental control systems such as landscape, envelope and fabric design strategies by outlining their basic principles, design aspects, levels of performance, and giving practical examples to reveal how they affect the built environment in a natural way.
- To identify a number of specific methods such as building simulation, questionnaire survey, field observation etc., by putting in place the necessary strategy to support the conduct of study and to collect the required data.
- To study the basic background information of two investigated buildings by exploring the issues with regard to their macro and microclimate, environment, architectural and occupant features.
- To examine the occupant's sensation and experience across the indoor environment of the investigated naturally ventilated buildings by analyzing fundamental issues that relate to his/her response to the environmental control system, both generally and specifically.
- To examine the occupant's actual operation of the window with internal shading covering by illustrating the impact of several main effects and the combinations of each interaction between them.

1.5 Hypothesis of the Study

Based on the discussion of the study scope, central problem and core objective, the aim of this thesis is to explore what is indicated by the motivating forces for occupant environmental manual control in naturally ventilated buildings. The following hypotheses are formulated and tested in this research:

> The way in which occupants attempt to control their thermal, visual and acoustic comfort in a naturally ventilated environment depends not only on the prevailing external climate but also a complex function between climate, orientation and size of the room etc.

1.6 Organization of the Thesis

This thesis begins with an Introduction, which presents the basic information about this study as *Chapter One*. The following is divided into two parts. The first one is a literature review. Previous studies which may be incorporated with this project are introduced and discussed, including:

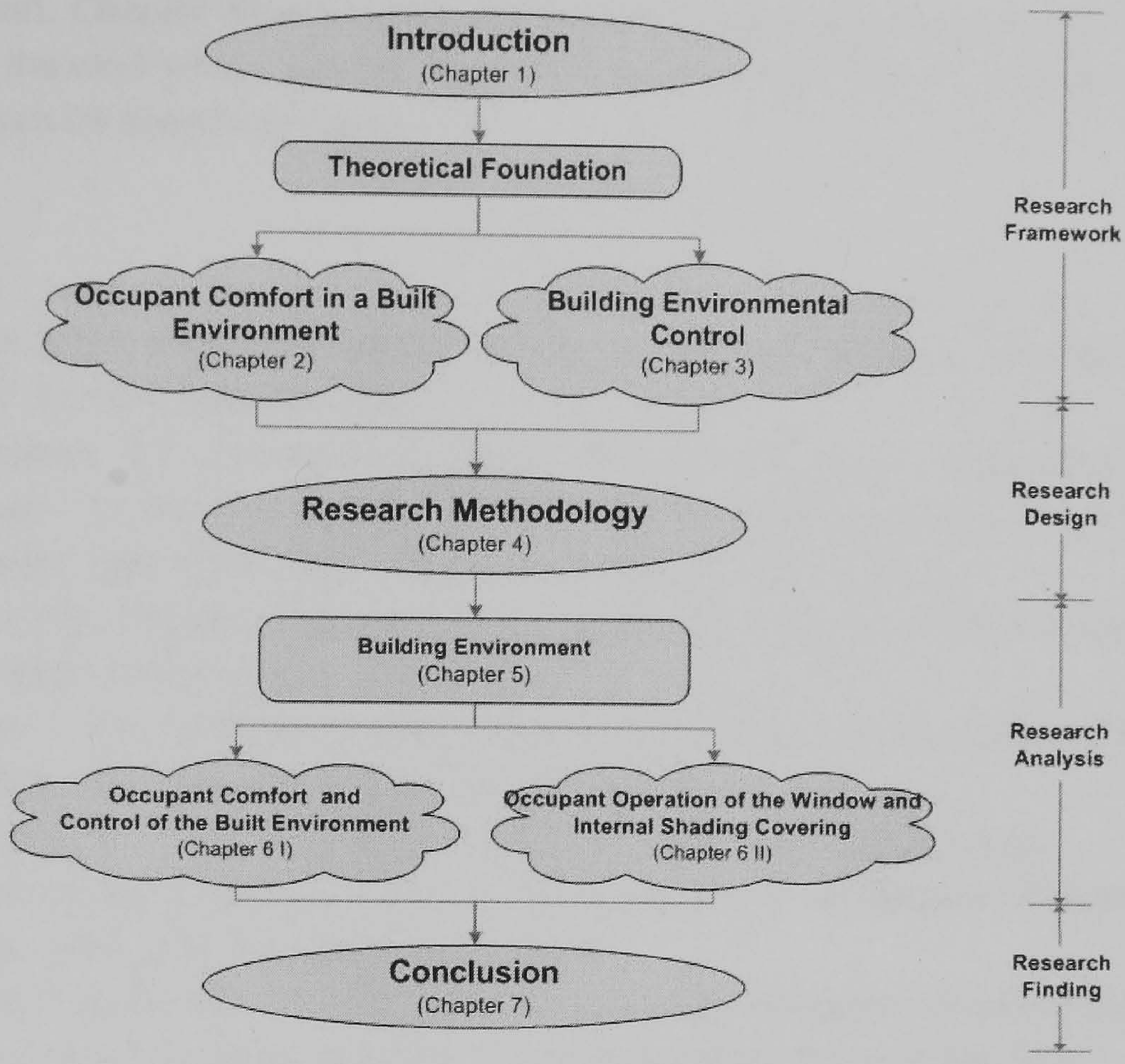

Figure 1.2 Organization of the thesis

- Occupant comfort in a built environment (*Chapter Two*): fundamental information on the interaction between indoor environment and occupant sensation – thermal, luminous and acoustic comfort - is presented.

- Building environmental control strategy (*Chapter Three*): the natural effect of landscape, envelope and fabric on the built environment is discussed.

Then the main part of the research is presented, including:

- Research methodology (*Chapter Four*): the research procedure and the method of collecting the data and processing it are introduced.

- Background of the investigated buildings (*Chapter Five*): information about the investigated buildings is explored such as environmental, architectural and occupancy features.

- Results and analysis concerning the investigated buildings (*Chapter Six*): the results and analyses produced by the whole research study are presented so that the hypothesis which will be generated in Chapter One may be tested.

The final part, *Chapter Seven* shows the main findings drawn from this study and also introduces the work which may be carried out in the near future. The whole structure of the thesis can be seen from Figure 1.2.

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Chapter Two

Occupant Comfort in a Built Environment

The task of designer is to create the best possible indoor environment. It is a challenge for the designer to strive toward the optimum of total comfort, which may be defined as the sensation of complete physical and mental well-beings.

- Koenigsberger 1974

Chapter Two
Occupant Comfort in a Built Environment

2.1 Introduction

This chapter mainly deals with the fundamental information on occupant sensation in a built environment: thermal, luminous and acoustic comfort. In each section, building physics is firstly introduced then followed by a discussion of the basics of occupant comfort, that is to say, how humans respond to all kinds of heat, light and sound. Lastly, the building characteristics that affect these indoor environments are specified and pursued.

2.1.1 Occupant Comfort

The main function of architecture is to provide a quite complicated multi-purpose mechanism, providing a recognizable boundary between the outside and the inside. This boundary creates an enclosed environment and initially ensures the physiological and psychological well-being of its occupants. It is considered to be a selective filter not only to exclude unwanted influences such as extreme cold or heat, rain, wind, noise, damp and intruders, but also to admit the desirable and useful ones like daylight, solar radiation, controlled ventilation, outside views and access to friendly visitors (Figure 2.1) [1, P39]. This becomes one of the main objectives of architecture: to ensure the provision of continuous comfort for occupants in spite of variable external conditions.

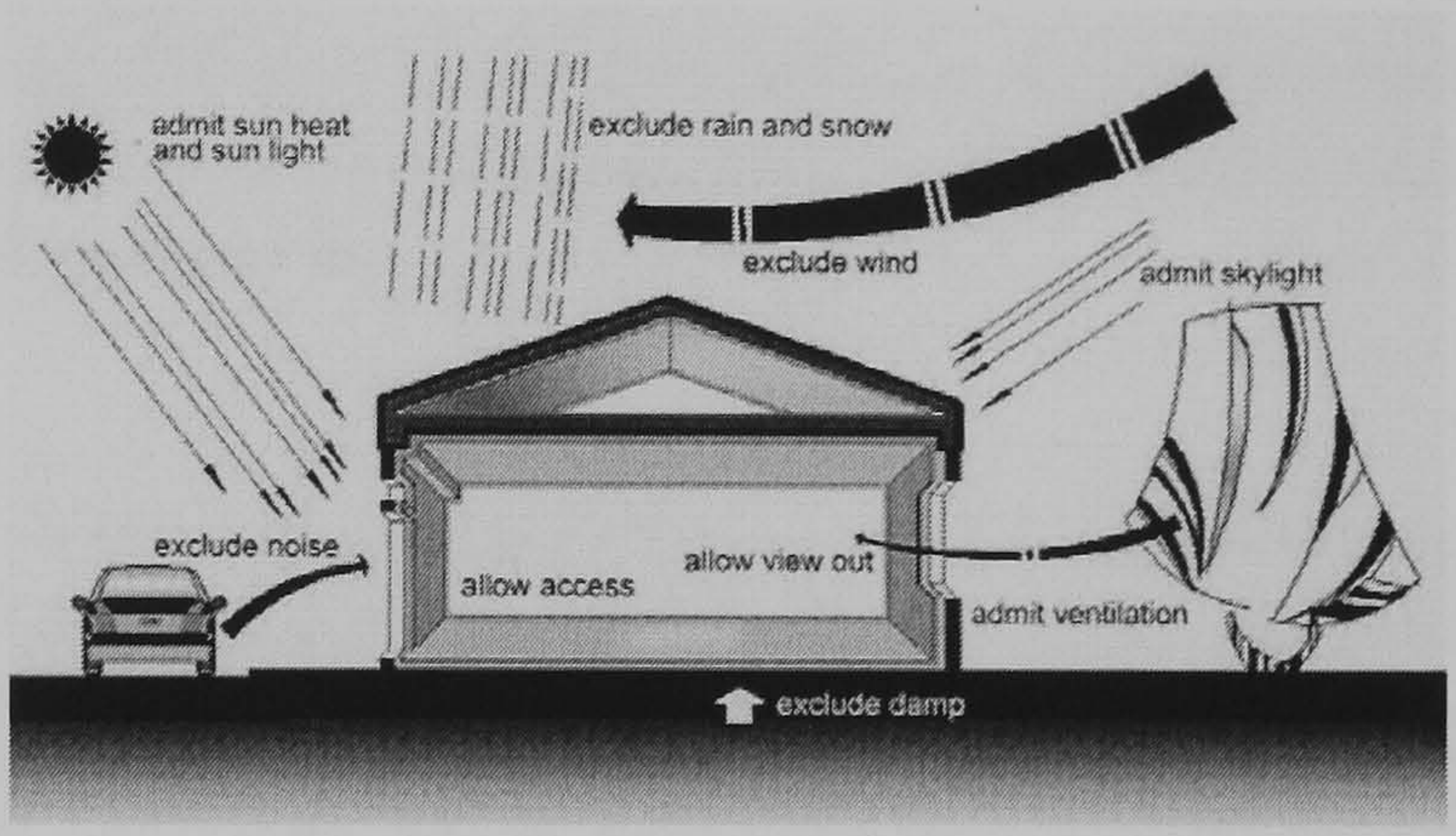

Figure 2.1 Building enclosure: a barrier and filter

The occupants' perception of comfort in a building room changes constantly as their needs change. For example a hard-working young athlete's perception of the comfort level of a sports hall would be quite different from that of an old and sedentary audience. In fact there are many elements involved in the perception of occupant comfort which are shown in Figure 2.2. It is a very broad field that comprises physical as well as physiological and psychological factors [2, P13]. Of these factors, the built environment can affect occupant comfort primarily via the following:

- the body: it is easy to maintain the balance of heat gain and loss;
- the eye: the sense of vision ensures visual comfort and facilitates visual performance;
- the ear: hearing is an appropriate condition for listening to wanted sounds and eliminate noise.

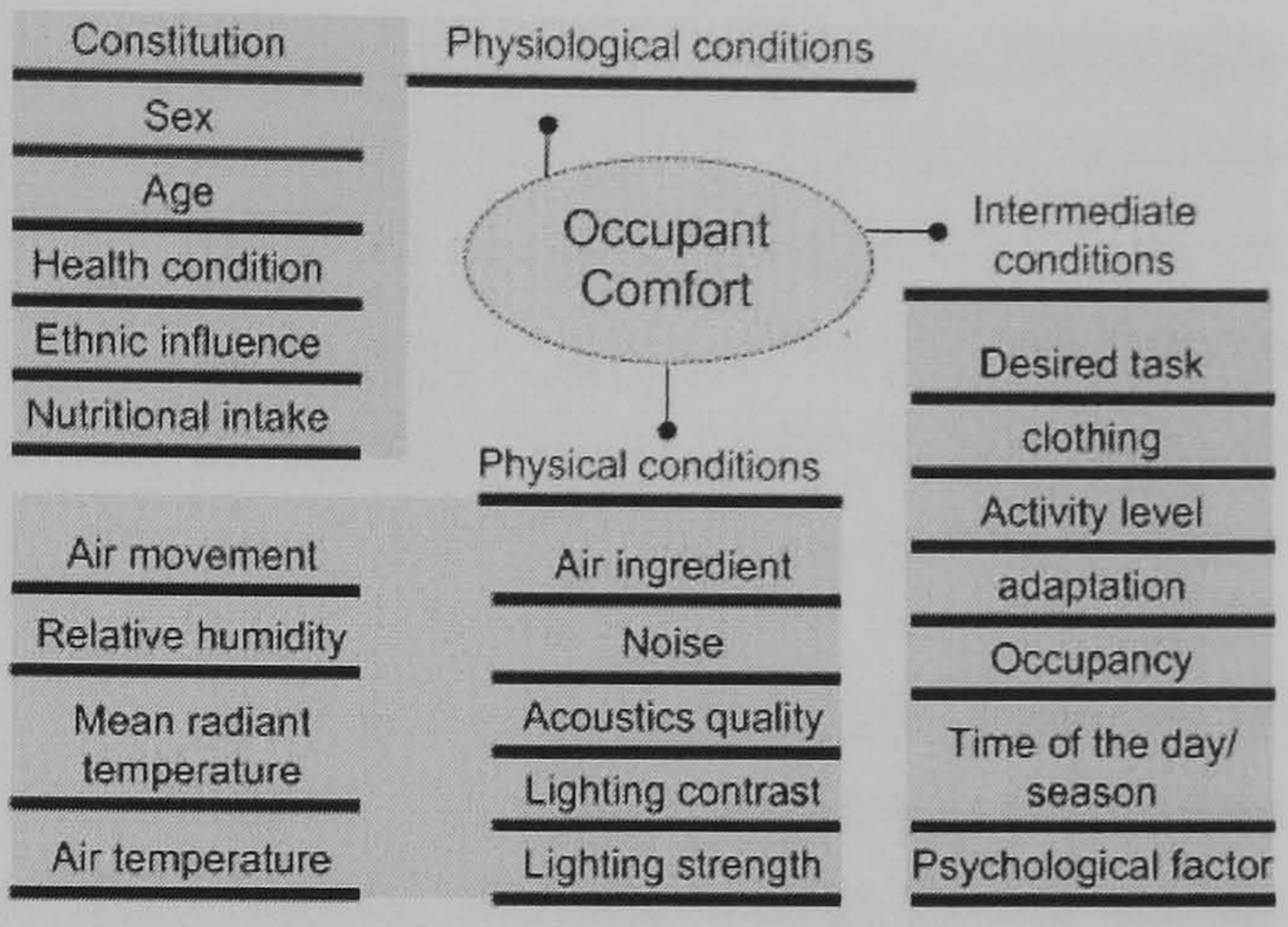

Figure 2.2 Factors for the state of occupant comfort

These human senses serve as a life support and constitute a vital link between environment, comfort and behaviour. Aside from these physical issues, psychological factors such as having a pleasing view and having some control over their environment are also to be satisfied through the built environment.

2.2 Thermal Comfort in a Built Environment

This is a very important factor to be considered in the building design process because thermal comfort is a fundamental condition for providing a liveable, healthy and productive environment for the building's occupant.

2.2.1 Physics of Heat

Heat and Temperature In physics, heat, symbolized by 'Q', is defined as energy in transit. Generally, heat is a form of energy transfer associated with the different motions of atoms, molecules and other particles that comprise matter. Temperature is a physical property of a system that underlies the common notions of hot and cold. The scientific field measures temperature using the Celsius scale, while thermodynamic temperature is expressed using the Kelvin scale. The Celsius scale is based on water: its freezing point is taken as 0°C and its boiling point at normal atmospheric pressure as 100°C. The Kelvin scale starts with 'absolute zero', the total absence of heat (0°C=273K) [3]. The concept of 'specific heat capacity' provides a connection between heat and temperature. This is the quantity of heat required to raise the temperature of a unit of mass of a substance by one degree, thus it is measured in units of J/kg·K. Table 2.1 shows some materials with their 'specific heat capacities'. Normally, the specific heat of masonry is higher than metallic materials, whilst water has the highest value of all common substances: 4176 J/kg·K [4, P248].

Material	Specific heat (J/Kg·K)
Stainless steel	510
Brickwork	800
Concrete block	1000
Hardwood	1200
Water	4176

Table 2.1 Specific heat of some architectural materials with water

Heat Flow Heat tends to flow from a higher temperature zone to a lower temperature in three specific ways - conduction, convection and radiation. Each one has a predominant material property which influences how fast heat will transfer. The three determine the location, direction and timing of all movements of heat within any thermal condition. In the building space, these three modes will contribute to conducting the heat exchange between an entity and its local surroundings, producing a unique indoor condition in every single room anywhere in the world.

Conduction is the mode concerned with a body or bodies in contact, and the transfer of heat by means of the 'spread' of molecular movement. Conduction always takes the shortest path possible, so the distance between the two temperatures becomes an important design variable. For any given thickness, then, the material property of thermal conductivity is the determinant of rate [5, P57]. Normally less dense materials such as styrofoam or fibreglass have low conductivity, while denser materials such as steel or glass have high thermal conductivities [6, P11].

Convection is the mode by which heat is transferred as a consequence of the motion of liquid and gas. Two types of convection are commonly distinguished, free convection, in which gravity and buoyancy forces drive the fluid movement, and forced convection, where a fan, stirrer, or other means is used to move the fluid. In general terms, heat transfer by convection typically occurs in a room when air passes over a solid surface with different temperature or when warmer air moves to a position where colder air exists. Apart from the temperature difference, air pressure and air density are also two state variables to determine the convection magnitude.

Radiation is the mode by which heat is transferred by electromagnetic waves in the absence of any form of medium, thus it is the only means that heat can be transferred through a vacuum. It can travel enormous distances, and will continue to do so until it is interrupted by a surface. In this case, temperature is the only state variable. The primary radiation sources that affect the indoor environment are the sun's radiation and the thermal radiation of architectural surfaces.

2.2.2 Thermal Comfort

For building design and engineering purpose, human thermal comfort has been defined as 'a condition of satisfaction expressed by occupants within a building with regard to their thermal environment' according to Limb (1992). The emphasis here, then, is on the state of mind of the occupants. It is therefore a psychological phenomenon rather than a physiological state. Evidence shows that it is influenced by factors such as mood, personality, culture and other individual, organizational and social factors [7, Pxiii]. Usually the term 'thermal neutrality' is preferred over 'thermal comfort' in order to emphasize the qualification that the subject feels neither too hot nor too cold, nor experiences any local discomfort.

2.2.2.1 Body and Thermal Comfort

The human body is a complex thermodynamic machine susceptible to slight changes in the environment. The mechanisms that are inside the body can function only within a fairly narrow range of temperatures, and only an even narrower range is perceived as comfortable. On the inside, the human body maintains a very stable core temperature of 37°C. This is the normal body temperature but the skin temperature is not constant, varying from 15 to 42°C when exposed to hot or cold environment without any ill effects when experienced for a short period of time. If the body manages to control its temperature and maintain the heat balance without much effort, a feeling of thermal comfort will result. Conversely, if a great deal of effort is required, discomfort and unhealthy conditions will result [7].

Body temperature is determined by certain processes. Amounts of heat are transferred from the core of the body to the skin and then from the skin to the surrounding environment on the basis of two basic mechanisms of body heat control. The internal mechanism is generally called metabolism, where the human body constantly produces heat for all kinds of functions and activities. The second mechanism is the environmental temperature heat exchange that takes place in order to maintain thermal balance. In this way comfort is achieved through radiation, conduction, convection and evaporation from the body to the surrounding environment (Figure 2.3). For example, heat is dissipated by a normally clothed person not engaged in physical activity in still air and an air temperature of 20°C in the following way: radiation 45%, convection 35% and evaporation 20% and conduction <1% [8, P29].

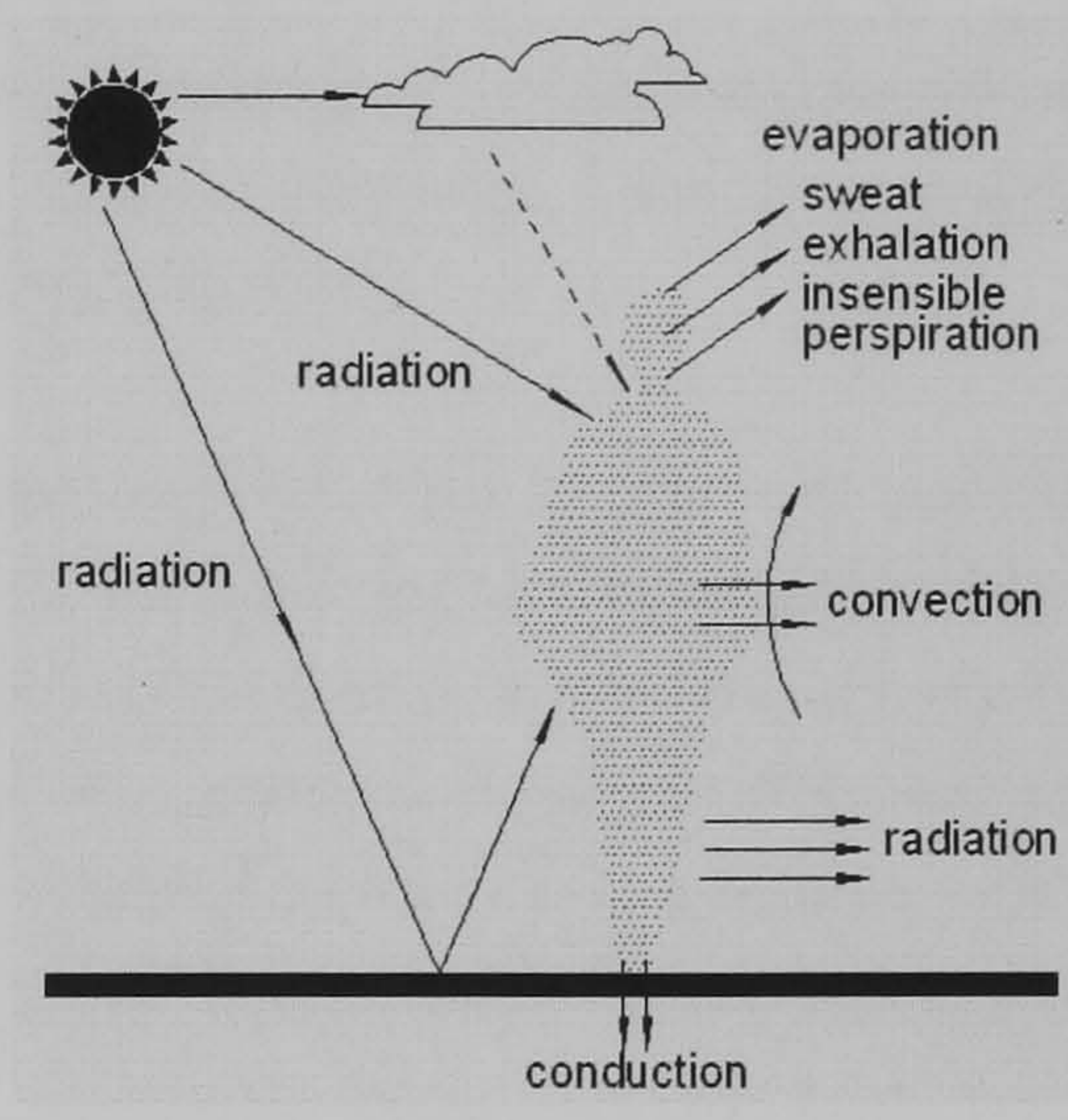

Figure 2.3 Heat exchange between body and environment

There is a continuous process of adjustment to ensure a balance between heat produced and heat lost. In a cold situation, physiological responses such as shivering can increase the metabolic rate so that more heat is specifically generated. Conversely the body can produce sweat, and great quantities of moisture may be released from the skin to provide cooling [9, P47]. Blood capillaries and sweat glands in the skin are spread over the entire body and allow for a highly sensitive temperature control system. Thermal equilibrium in the human body is achieved when heat is produced in the body at the rate at which it is dissipated by the body into the environment. The occupant is thermally comfortable when a proper balance is maintained between the various modes of heat loss and gain. Generally the variables that affect this rate can be organized into three categories:

- environmental factors: air temperature, air movement, humidity, radiant temperature;
- personal factors: activity, clothing, state of health, acclimation;
- other factors: food, drink, body shape, subcutaneous fat, age, gender etc.

2.2.2.2 Factors of Thermal Comfort

Among these variables discussed above, the environment, activity and clothing are six identifiable factors, while others cannot be specified clearly. Although they are also important to thermal comfort, they are beyond the scope of this study.

Air temperature This is the dominant environmental factor, as it determines the rate at which heat is lost to the air. Above 36°C, the heat flow reverses and the body will gain heat from the air. Generally in a well-designed office environment a comfortable internal temperature is in the region of 18°C in winter and 23°C in summer. This is especially true when the relative humidity is between 40 and 60% [10, P12].

Radiant temperature The radiant temperature is the temperature of the surrounding surface elements, each weighted by the solid angle it subtends at the measurement point. It includes the effect of incident solar radiation and has a great impact on the indoor environment [11, P61]. Under actual conditions, within a room space there is always some differences between air temperature and the surface temperature of the walls, ceiling, window and floor. It becomes significant when the room space is well insulated or has a large area of glazing.

Air movement Generally, air movement with a very low speed will result in stuffiness, or conversely, if the opposite conditions apply, draughtiness. It has a significant effect on removing heat from the body by affecting two rates. One is the rate of convection between skin and air. The other is the rate of cooling through the evaporation of skin moisture. This is important especially in a warm humid environment. Design specifications for air velocities over the body within the range 0.1 to about 1.5m/s are regarded as being acceptable for comfort [10, P31].

Air humidity With a high humidity over 90%, the evaporation and respiration from the skin will be reduced or even cease. On the other hand, very low humidity with less than 20% will lead to drying out of the mouth, throat and skin [4, P17]. However, it is not normal to find those two extreme situations in the vast majority of indoor environments. Humidity usually ranges from about the mid 30s to the upper 60s percentage range [10, P13]. People are quite able to tolerate this range. Therefore, although air humidity is considered to be a direct influence on thermal environment, it normally has only a minor effect on comfort.

Clothing Apart from its social and fashion value, this also provides the body with insulation against the gain and loss of heat. Therefore, clothing is classified according to its insulation value. It is measured with the Clo unit (1clo=0.155 m^2K/W). A naked person has a 0clo while a 3-piece business suit, with cotton underwear corresponds to 1clo [10, P31]. According to a rule of thumb cited by Goldman (1978), air temperature departures from the optimum for 0.6clo resistance can be offset by 1°C for each 0.1clo deviation from the standard for sedentary individuals.

Activity (metabolic rate) The metabolic rate is the amount of energy produced per unit of time. It is influenced by activity level. Naturally the higher the metabolic rate, the higher the heat transfer rate from the body. The unit adopted is the Met (W/m^2) (1met=58.15W/m^2). A normal adult has an average body surface around 1.8m^2 and the metabolic rates for various activities are given in Table 2.2 [11, P60]. The lowest metabolism occurs while people are sleeping (0.8met) and is at its highest during sporting activities, where 10met is frequently reached.

Activity	Met (W/m^2)
Sleeping	0.8
Sitting (normal office work)	1
Standing (relaxed)	1.4
Slow Walking	2
Fast Walking	3
Running	Over 8

Table 2.2 Met rates related to activity

2.2.3 Sun Path and Solar Heat

Energy from the sun, in the form of insolation from sunlight supports almost all life on earth and drives the climate and weather. It has the most significant effect on a building's thermal and luminous impact. Sunlight is about half to half visible and invisible energy (Table 2.3). The invisible portion is made up of shorter wavelengths called ultraviolet and longer wavelengths called infrared. When both visible and invisible solar radiation is absorbed by a material, it becomes heat [6, P17].The essential things to understand about this process are the apparent movements of the sun and the energy flows from the sun.

Radiation type	Wavelength (nm)	Percentage of energy
ultraviolet	200 - 380	7 %
visible	380 - 700	47 %
short infrared	700-3000	46 %

Table 2.3 Distribution of solar radiation

Sun Path The path of the sun across the sky varies with time at any point on the Earth's surface. There are three issues involved in this phenomenon: the rotation of the Earth, about its own axis and around the sun and the tilted angle between the polar axis of earth with the plane of the solar orbit (23.45°) (Figure 2.4). The sun's position according to the earth now can be predicted with great accuracy. Two angles are measured to determine the sun's position and path

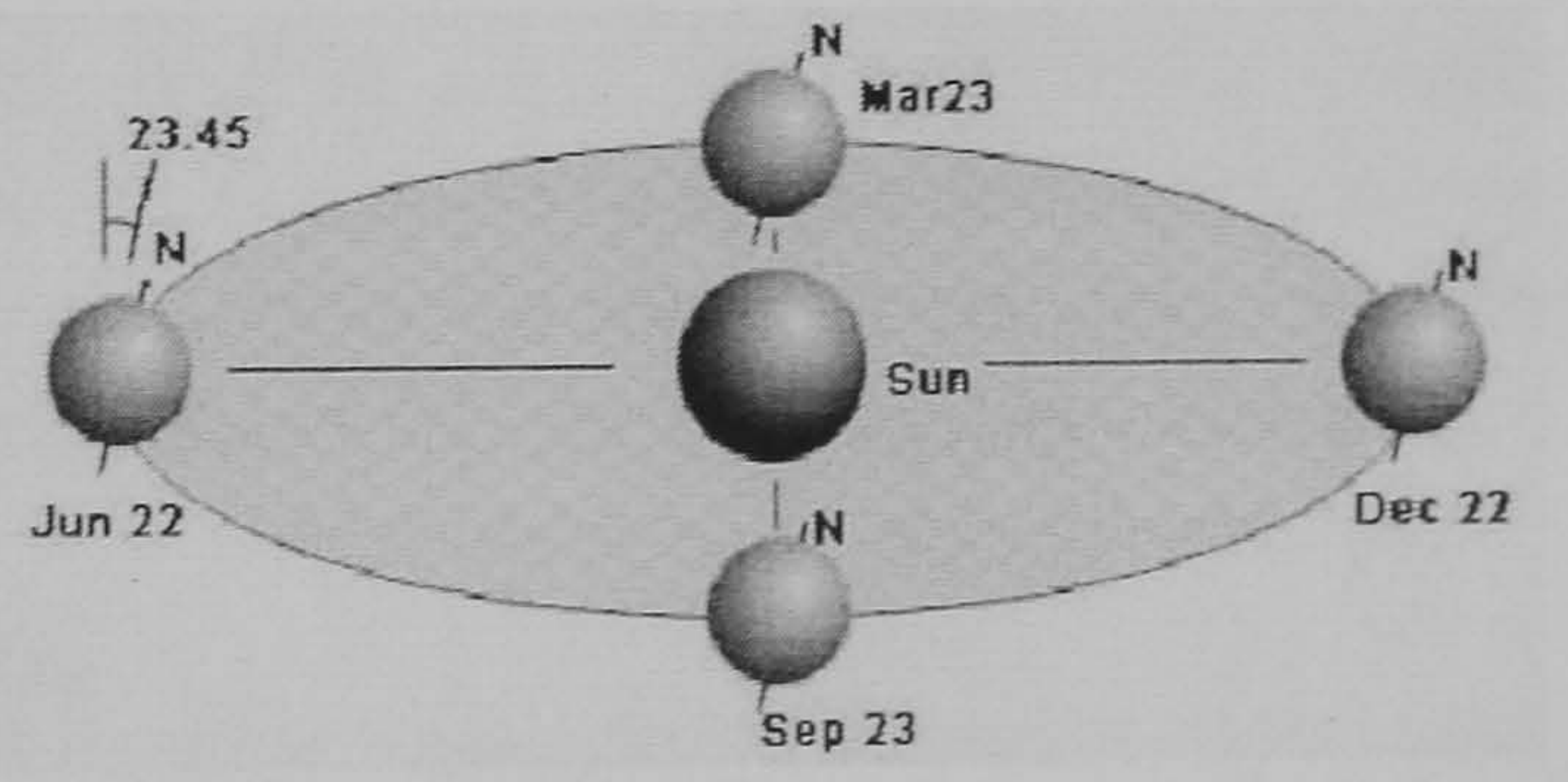

Figure 2.4 3D section of the earth's orbit

from a given place on the Earth.

- Solar Altitude (ALT) is the vertical angle between the horizon and the line of sight to the sun;
- Solar Azimuth (AZI) is the horizontal angle between the projection on the ground of the line of sight to the sun and the north-south axis (Figure 2.5) [12, P39].

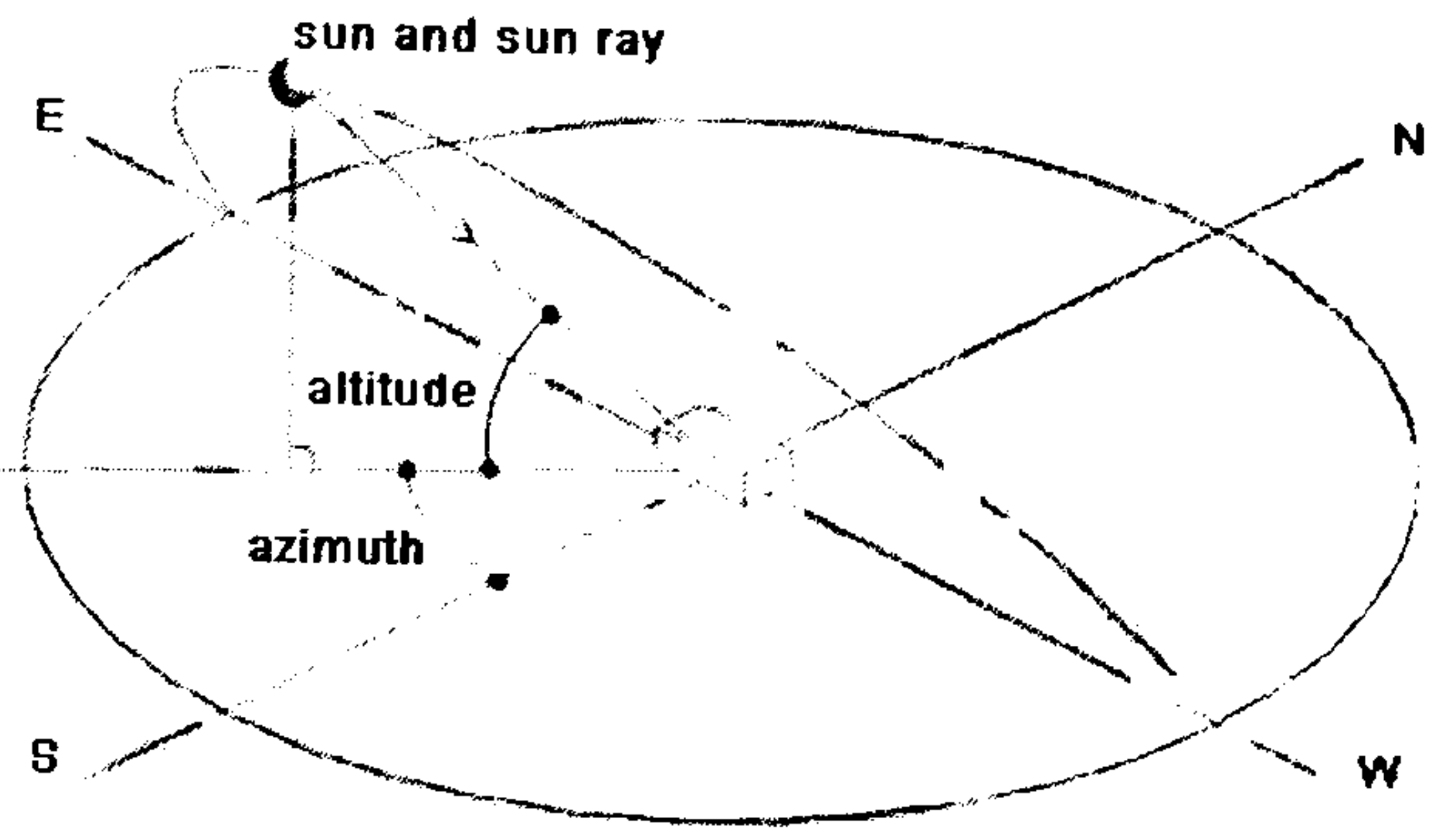

Figure 2.5 Altitude and azimuth angles

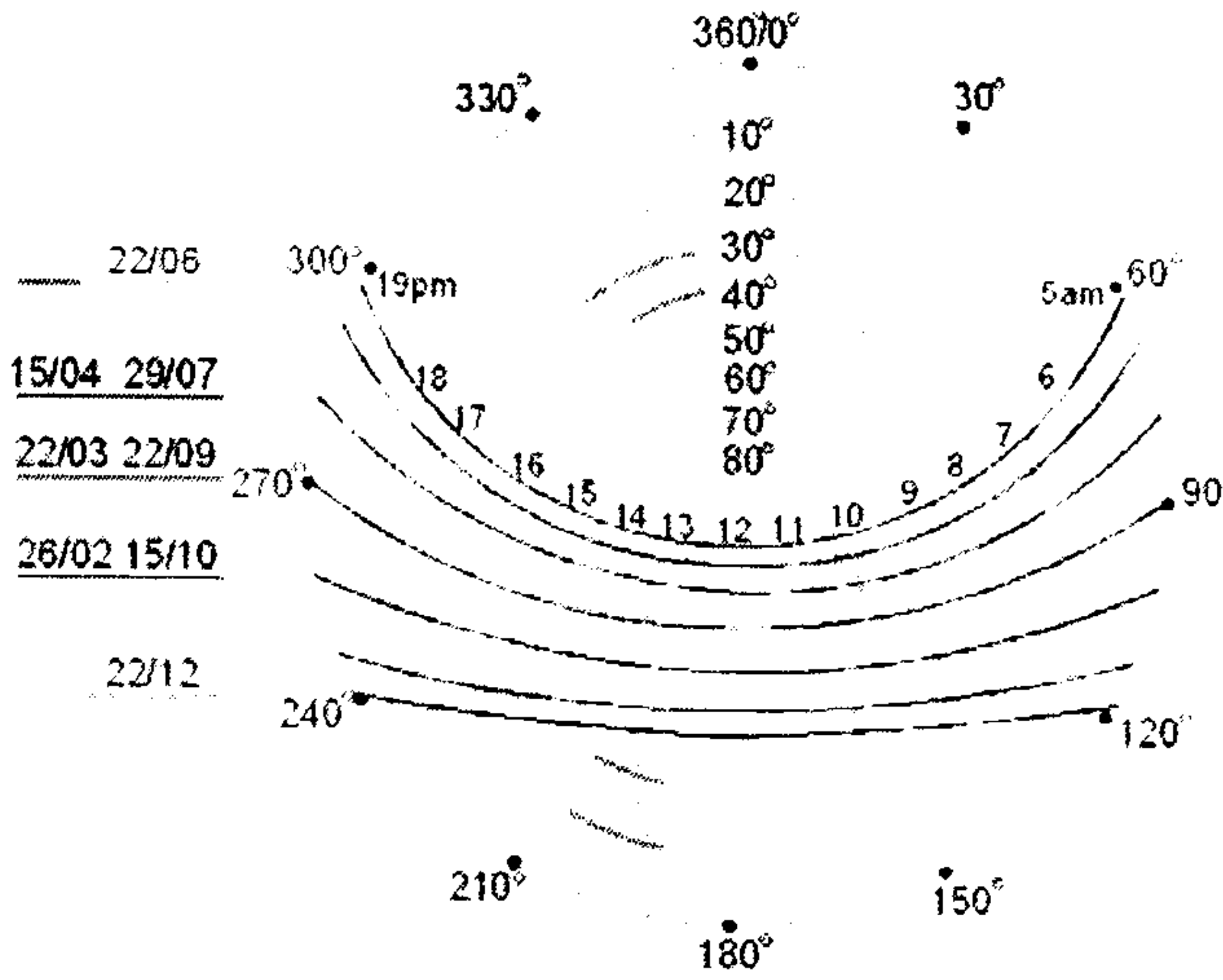

Figure 2.6 Sun path diagram for latitude 36°

A practical tool for depicting the sun's movement is well established – the sun path diagram, which is the stereographic projection viewed from the sky on the horizontal plan. Figure 2.6 shows a typical complete sun-path diagram, the latitude on the ground is given with 36° and the sun-path lines are plotted with selected typical days. The radial line shows the solar azimuth and the concentric circles, the solar altitude. The sun-path lines are intersected by hour lines. The middle one is 12:00. The diagram clearly shows that the 22ndJune has the longest sun path and highest solar altitude at noon, with these values being exactly reversed on the 22ndDec. On equinox dates 22nd Mar and Sep the sun rises at due east on 0600am ands sets at due west on1800pm [4, P25].

Solar Heat Solar radiation is an electromagnetic phenomenon. Its emission spectrum has different intensities and wavelengths so that the total energy distribution varies, but is essentially contained in three regions (Table 2.3). When the solar radiation is striking the earth's atmosphere, an average irradiance value fluctuates between 1322 and 1465 W/m^2 throughout the year at various high-altitude sites, 31% of which is reflected back into space by the atmosphere, the Earth's surface and clouds. The remaining is partly absorbed by the atmosphere but most (about 49% of total irradiance) warms the surface of earth [13]. The intensity of solar energy received upon earth varies with latitude, because the radiation has to pass a much longer distance through the atmosphere at lower altitudes. For example, total irradiation varies from 400kWh/m^2 per year near the poles to a value in excess of 2500kWh/m^2 per year in the Sahara desert [4, P26].

2.2.4 Thermal Performance of a Building

Basically, human comfort in a building is achieved by maintaining temperature, humidity, air movement and human activity conditions within a comfortable range. Space heating and/or cooling loads, which are required to maintain this comfort, to some extent, depend on the building's quality itself to modify the external conditions and how far the outdoor conditions are from the acceptable range. Broadly, there are four building design aspects which have the greatest influence on thermal performance: orientation and shape, material, fenestration and ventilation [4, P63].

2.2.4.1 Building Orientation and Shape

The orientation and shape of the building has a marked impact on the indoor environment. The amount of sunlight, daylight, shade, ventilation and other factors are, up to a point, all determined once the orientation and shape are chosen. A building facing east or west is more susceptible to receiving adverse low altitude sunlight in the morning and afternoon. In most instances the north and south walls are longer than the east and west ones. A rule of thumb is that the ratio around 1.3 to 2.0 will optimize wanted or unwanted heat gain or heat dissipation in terms of solar incidence [4, P64].

As the heat loss or gain has a direct relationship with the area of a building's envelope, for a given volume a compact and simple plan is always better than a spread-out and complicated arrangement. Figure 2.7 shows that the more complex the form, more surface area it will have. This may result in more heat loss with more exposed surface and less heat gain due to self-shadowing [9, P63].

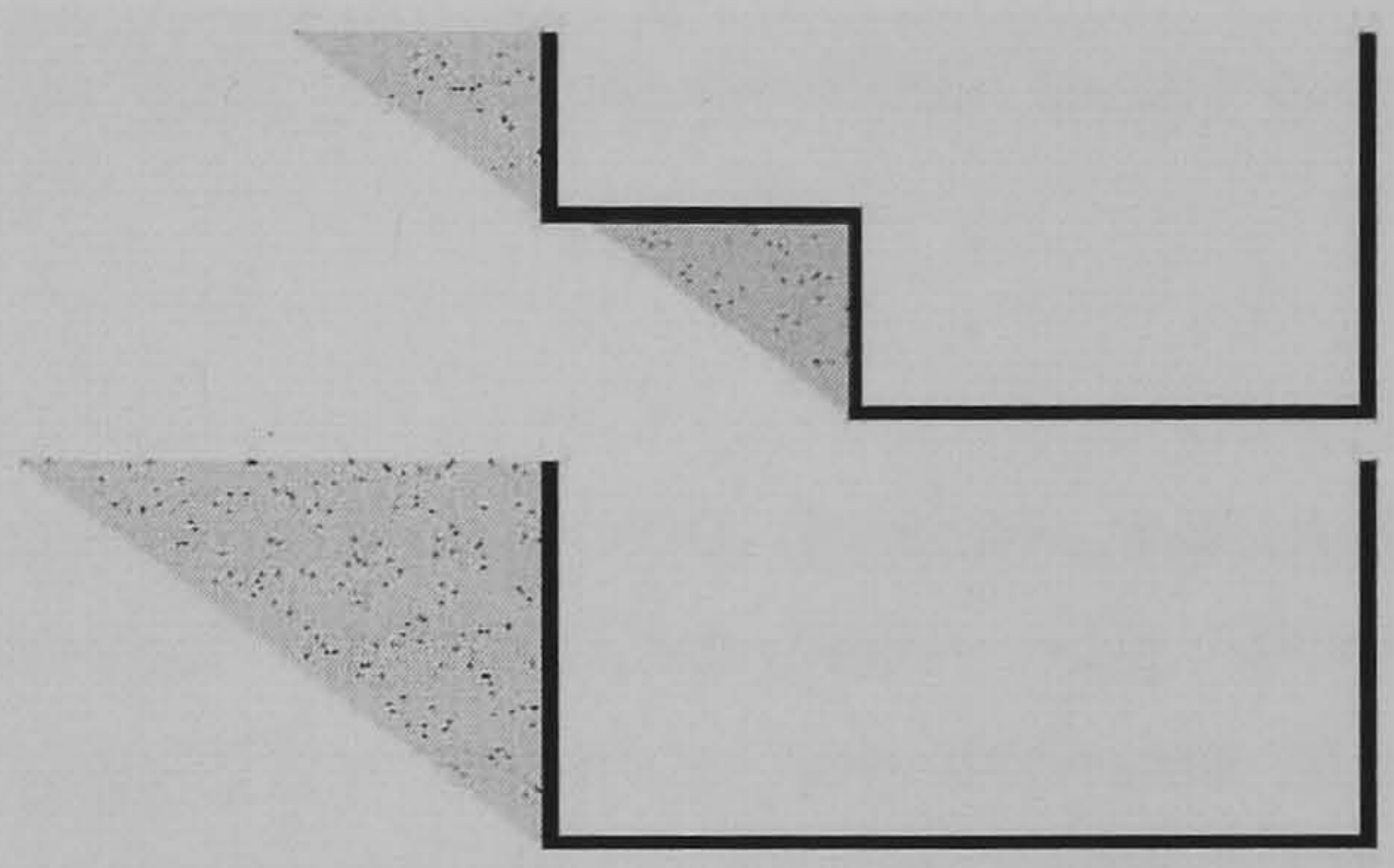

Figure 2.7 Effect of plan on self-shadowing

2.2.4.2 Building Material

When a building is constructed, two main physical resources are involved. These are materials necessary to form the various parts, and technical ability to assemble the parts into an enclosure. Aside from technical and aesthetic considerations, the material used for the building, especially the material used for envelopes functions simultaneously in relation to outside environmental change. However, its behaviour is different under different situations. The presence of the envelope provides a total and immediate barrier in relation to wind, rain and light. Heat, on the other hand, partly passes through over a period of time. This time lag in heat transfer to and from buildings is a smoothing out of the outside temperature.

Most building components have a certain capacity to act as a heat sink for heat storage from solar gain. This capacity to store heat energy is actually directly proportional to the specific heat capacity of the building component's material. Under stationary conditions, the amount of heat flow through a building component can be determined by reference to the material's thermal conductivity and the thickness of the individual layers of which the components are composed. The decisive factor is the heat transfer coefficient U-values (W/m^{2}K) [2, P61]. Table 2.4 shows U-values of several building materials. The performance is varied. The highest value shown is for single glazing which is 17 times as great as that of a pitch roof [14, P37].

Material	U-value (W/m^{2}K)
Concrete 75mm	4.28
Brick 220mm	2.26
Solid wall	2.3
Cavity wall	1.6
Timber frame wall	0.45
Pitch roof	0.25

Table 2.4 U-value of several architectural materials

When a construction material's heat conductivity is less than 0.1W/mK, it can be described as having the properties of thermal insulation. Thermal insulation is not normally capable of having structural strength due to characteristics such as low density and lightweight, although it can provide a restriction to heat flow which is used to reduce the magnitude in a 'resistive' manner. Since air provides good resistance to heat flow, many insulation products are based upon materials that have numerous layers or pockets of air trapped within them. To satisfy different requirements, the transfer of heat can be regulated by varying degrees of thermal insulation material either singly or in combination with others.

2.2.4.3 Building Fenestration

The arrangement of the windows and other openings in the walls provides the main architectural character of a building, generally called fenestration [15, P74]. Fenestration is a critical control element in regulating the whole environment of a building room by providing an opening for the flows – inward and outward – of heat, light sound, air and view. A window performs an important role in the thermal environment of the building. The larger the window the more the solar gain and the greater the heat loss [10, P16].

Table 2.5 shows some typical glazing options' U-values [16, P55]. Normally glazing has a very high U-value except in those cases where a special insulation treatment has been applied, which means in some extreme situations, this may result in a main weak thermal link due to its high heat transference, in and out, e.g. in summer, not just from the overheating resulting from heat gain, but also due to the rise in radiant temperature from the glass surface. In winter, 20% of the total heat loss is from windows with single glazing in typical semi-detached houses and in addition the cool radiant temperature can also lead to great discomfort [17, P40].

Glazing	U-value (W/m^{2}K)
Single glazing	5.6
Double glazing	3.0
Triple glazing	2.4
Double with low E	2.4
Double with low E and argon	2.2
Triple with 2 low E and argon	1.0
Double with aergel	0.5 – 1.0

Table 2.5 U-value comparison of glazing option

2.2.4.4 Ventilation

The need for fresh air is generally a pressing consideration in ventilation. However, modern natural ventilation serves four ends in the environmental control of buildings.

- it provides a continuous supply of a sufficient quality and quantity of air for the occupant's life process and activity;
- it promotes heat dissipation and increases the rate of evaporative and sensible heat loss by the passage of air across the body thus having a cooling effect;
- it exchanges warm indoor air for outside cool air thus aiding structural cooling;
- it removes humidity, artificial contaminants, odours and bacteria etc.

Of these, the first one is the most basic need for human beings, whilst the second and the third have a direct influence on the indoor thermal environment. The fourth one, although it doesn't have a direct effect on the thermal perception of occupants, it has become increasingly important due to several factors: constant internal conditions, limited fresh air, absence of daylight and universal use of carpets. They provide an ideal environment for house mites to damage the air quality of a room [18, P48]. This contaminant has been identified as a cause of discomfort and health problems. Therefore ventilation is an important factor for maintaining acceptable indoor air quality.

In essence, building ventilation can be generally divided into two parts: purpose-built openings and involuntary infiltration. The purpose-built openings include vents, fireplaces, chimneys and openable windows that can be used to control the volume, velocity and direction of airflow. These openings are usually designed to be capable of adjustment so that they can always be arranged to give a large amount of ventilation. Infiltration on the other hand is defined as the fortuitous leakage of air through a building. The pathway for infiltration is mainly through or around joints, cracks, leaky window sashes and faulty seals in construction. It is considered to be a tractable cause of heat loss through some practical air-tight strategies such as insulation measures. However, building materials are porous that they will in general always be subject to the involuntary infiltration of air from the outside to the inside in real-life buildings.

2.2.5 HVAC System

It is necessary to correct the climate with the help of building devices for heating and cooling buildings. The three HVAC functions, heating, ventilating, and air-conditioning, are closely interrelated. All seek to provide stable and high-level thermal comfort. In modern buildings these functions can sometimes be integrated into one or more systems in order to make any environment achievable even in the most adverse and variable of climates.

2.2.5.1 Heating System

Domestic fireplaces or electrical heaters are the simplest ways to provide heat by direct

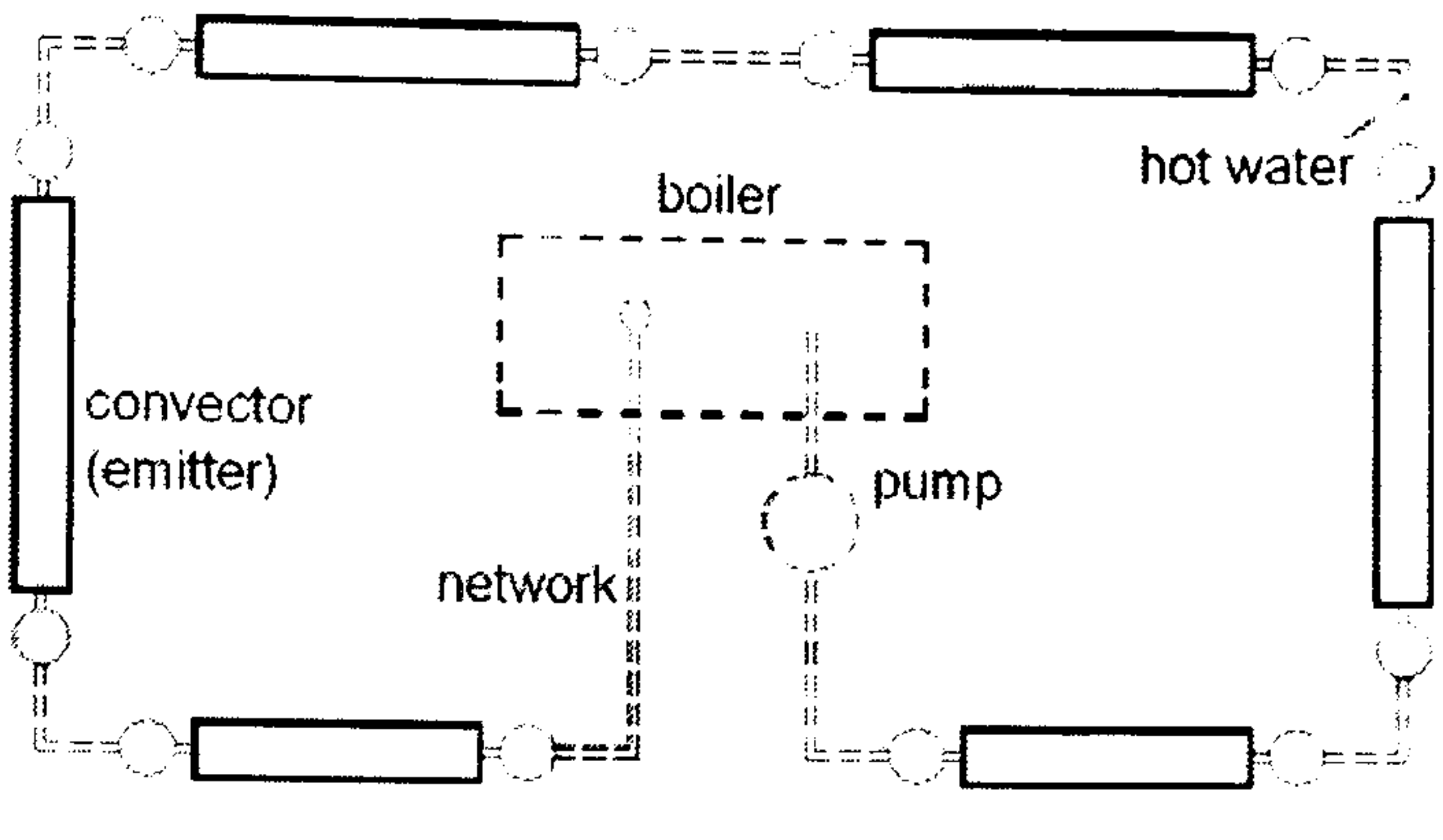

Figure 2.8 A hot water system with convector

radiation into the space or direct heating of the circulated air. Usually, the heat is generated centrally, and then transported by fluid to the occupied space, which may be either a single building or a group of buildings. Such a system contains a boiler to heat the water, steam, or air; a network to distribute the heated fluid, and an emitter to transfer the heat to the air space. Figure 2.8 shows a simple hot water system with convector [19, P383].

Coal, oil, gas, solar energy, and waste heat recovery are all possible energy sources. Coal is cheap but it needs dry storage, stoking and ash removal. Oil prices increasingly rise while gas, usually in the form of piped gas and supplied on the city grid is a convenient and popular fuel in many countries [1, P80]. Solar energy is a renewable source that has less impact on the environment and finite energy consumption. Wasted heat recovery is efficient but only available in certain areas and situations.

The distribution network can be classified as either water-based or air-based. Water-based systems can rely on gravity circulation, or can be pumped. They normally have compact pipes hidden within walls and beneath floors. Sometimes the hot water system can be combined with heating. However, it can only provide heat without humidity control and ordinarily it can't provide ventilation and cooling. The air-based system sends the hot air through ductwork. During warm weather the same duct can also perform other functions such as ventilation, cooling, humidity control and filtering. This is especially true in places where summer cooling is also required, and because it doesn't need an emitter, space is saved in the room. The disadvantage is the substantial amount of a building's volume for ducts and air handling equipment [19, P380].

The emitter for a heating system may be mounted on walls or buried in floors. The former needs a radiator in order to release heat, mainly, as the name suggests, by way of radiation but also convection. Nowadays, most emitters consist of fin-tubes to maximize the heat transfer by natural convection. These require a medium feed temperature and provide a quick control response. The latter is called under-floor heating. It normally involves large transfer surfaces in order to heat the whole space both by radiation and natural convection. The resultant time-lag will ensure constant heat but prevent quick response to changes in temperature and allows low feed temperatures [19, P382].

2.2.5.2 Ventilation System

A ventilation system includes both the exchange of air to the outside as well as

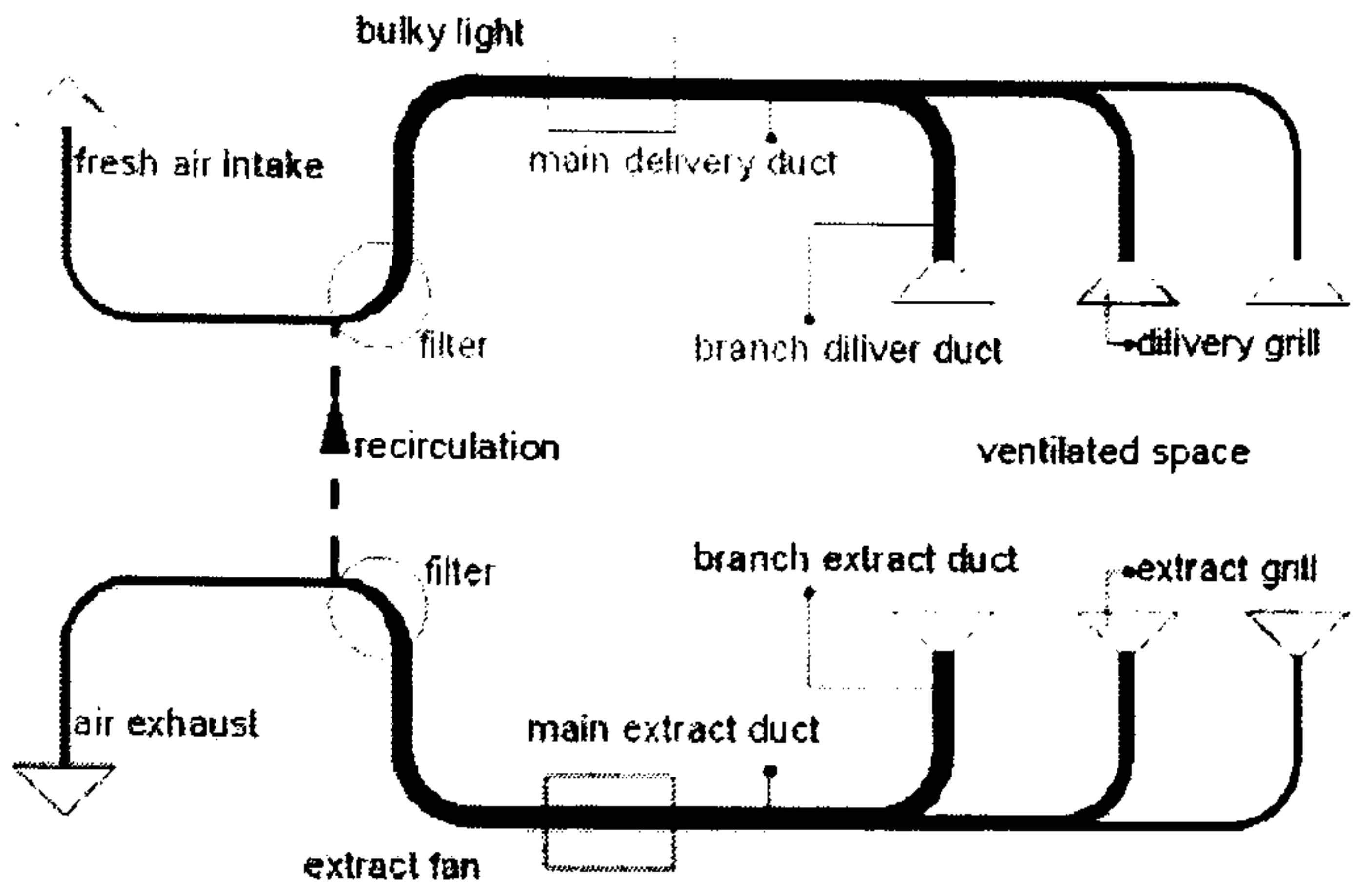

Figure 2.9 Operating principle of a typical mechanical ventilation system

circulation of air within the building. Mechanical ventilation can often be controlled via dilution or replacement with outside air and the rate of air movement. Typically, the system comprises air-handling filter units, ducts, terminal units, and a whole variety of intake, exhaust and air supply devices in the form of grilles and diffusers [20, P15]. Figure 2.9 shows a typical mechanical ventilation system [18, P160]. Often systems are coupled with heating and cooling plants in selected temperatures for thermal comfort [15, P81]. Where a source of contamination is found, fans can be installed near the source to directly extract stale air, which in turn creates negative pressure. It is immediately replaced by fresh air from the outside flowing through openings around grills [15, P81]. Direct extract is very common in the toilet, kitchen and laboratory.

Compared with direct extract air from inside, the supply system is more elaborate because the fan is required to connect the filter and duct. The air has to be filtered because of health problems caused by quantities of dust, pollen, and bacteria, as well as odors. The return air also has to pass through filters so that fans can be kept free of dirt. Among the many filter types, the dry filter is mainly for large dust and dirt particles. The electronic filter is very good at removing very small particles such as bacteria and pollen while the water spray is efficient at dealing with odor [19, P418].

The duct distributes air throughout the building, where a reliable and positive flow of air for ventilation is required. A separate duct system can be installed for exhaust stale air, from that used to distribute clean air. The supply flow is usually kept higher than the exhaust in order to keep up a slight positive pressure and thus prevent unwanted dust entry. Often the duct has sound-absorbing insulation treatment to prevent noise transmission.

The supply air enters a room either through a grille or diffuser. The grille permits direction control and the diffuser can rapidly mix with the room air and prevent discomfort. The inlet and outlet have to be located so that the air can gently circulate in the room without stagnation or draft. In a large space, the ideal air flow is often achieved by supply air coming across the ceiling and returning near the floor wall [19, P417].

2.2.5.3 Air Conditioning System

Air conditioning is a defined by the CIBSE as being *'the supply and maintenance of a desirable condition of the atmosphere within a building despite any changes in the* *external climate or causal, internal gains'* [21, P72]. This implies a year round process that controls air purity, temperature, and humidity, together with speed and direction.

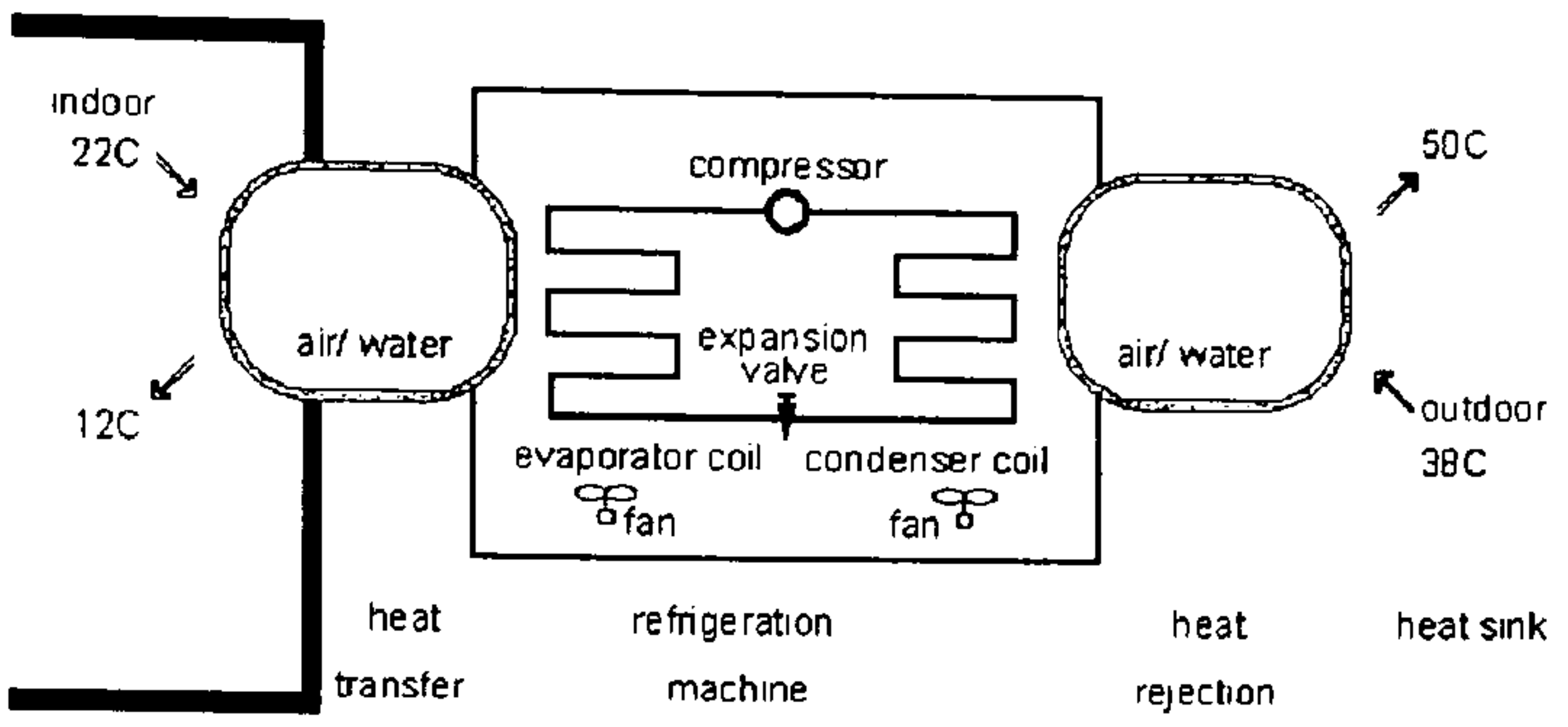

Figure 2.10 Operating principle of a cooling system

Air conditioning involves the cooling of the air using a refrigeration system, together with humidity control [16, P121]. Generally, the standard components of an air conditioning unit are the compressor, condenser coil, evaporator coil and the necessary fans. Its operating principle is shown in Figure 2.10. The cooling systems vary mainly in how heat is transferred to and from the refrigeration machine. The simplest system is the room conditioner, which packs all the components together and can be installed in a window or external wall. It is a self-contained unit offering low installation, operating and maintenance costs. Usually a 'packed' unit serves a small building. In a 'split' system, the compressor and condenser coil are outdoors while the air handling unit and evaporator coil are indoors. The split system is very flexible but these units cannot be much more than 15m apart. Thus, it is appropriate for small to medium sized buildings [19, P406].

The air conditioning design for large buildings is normally divided into separate parts. These have highly centralized air conditioning equipment and the air is treated in an air-handling unit with a very large number of variations and permutations, both in terms of the system arrangement and size. Usually, the building is subdivided into zones, groups of spaces or rooms likely to have similar demands placed on them at the same time. The central plant delivers air to suit average requirements in different zones, with re-heater batteries or secondary units making local adjustments [1, P109].

In general, the HVAC equipment may be of considerable size, requiring sufficient located spaces with proper floor areas and ceiling heights. The mechanical equipment room is centrally located to minimize duct sizes, and placed along an outside wall for easy servicing. In order to minimize the noise level, the duct needs a well-organized layout with sound-absorbing insulation. Although the HVAC system is necessary to ensure full thermal comfort, with proper design of the building and service specifications, the size and energy demands of the mechanical equipment can be minimized and optimized.

2.3 Visual Comfort in a Built Environment

Basically, the criterion for general illumination of a built environment has been the quantity and uniformity of light falling on the room surface and working plane to ensure satisfactory living and efficient working conditions. In most of cases, daylight and artificial lighting are the two main sources for providing sufficient brightness to the building room, either separately or combined with each other. This study, however, mainly focuses on the impact of natural light on the built environment. Therefore, electric lighting is treated as supplementary to daylighting and not addressed in detail, although it is also important.

2.3.1 Physics of Light

Light is a flow energy as well as radiant heat. In a purely technical or scientific context, electromagnetic radiation of any wavelength in the spectrum is light. However, only a very narrow wavelength band of electromagnetic radiation can be perceived by the human eye, and this is shown in Figure 2.11 [22].

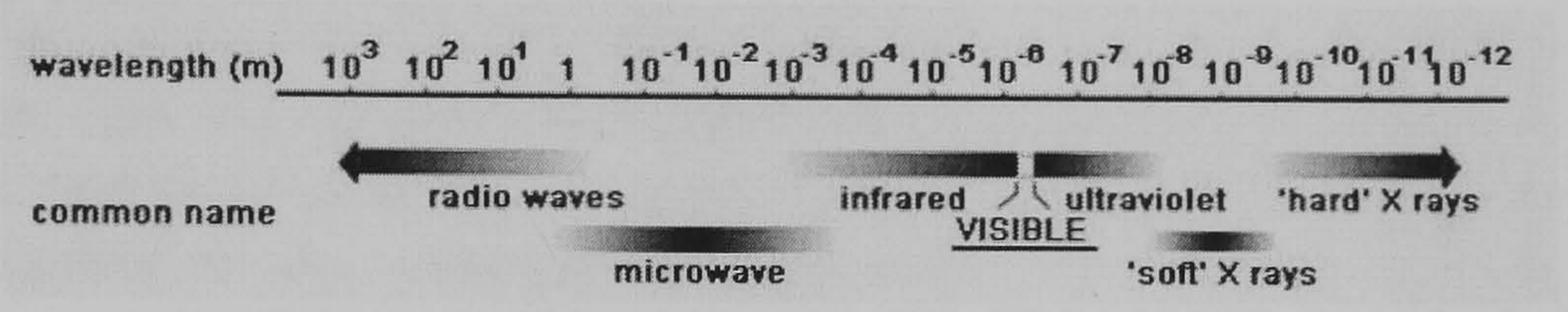

Figure 2.11 Electromagnetic radiation in the spectrum

Illuminance – concentration of lighting (E)

In photometry, illuminance is the amount luminous flux incident on a surface, per unit area. It is a measure of the intensity of the incident light defined as 1lm/m^2 or Lux. Illuminance of light levels varies enormously from 100000lux in bright sunlight to 0.2lux in bright moonlight and 0.02lux in starlight. The human eye can register information across a range starting with the brightest sunlight down to about 0.005lux [23, P17]. Table 2.6 shows some typical values for illuminance [24, P4].

Typical illuminance	lux
Bright moonlight, outdoor	0.2
Candle 1m away	1
General room lighting	100
On desk with moderate light	500
Overcast sky on the ground	5000
Sunny day with bright sky	100 000

Table 2.6 Illuminace of typical light sources

Typical luminance	cd/m^2
Normal black paper	5
Normal white paper	100
Full moon	2500
Fluorescent lamp	8000
Filament in clear lamp	7 000 000
Sun	1 650 000 000

Table 2.7 Some typical luminance value

Luminance – brightness (I)

Luminance is a photometric measure of the density of luminous intensity in a given direction. It describes the amount of light that passes through or is emitted from a particular area, and falls within a given solid angle. The magnitude depends on two elements; one is the intensity of light from the surface and the other is on the projected area of surface's reflectance or emittance [24, P4]. The actual impression of brightness is influenced by the state of adaptation of the eye, the surrounding contrast and the amount of information on the viewed surface [8, P21]. The unit of luminance is candela per square metre (cd/m^2) Table 2.7 shows some typical values of luminance [24, P4].

The term 'illumimation' is the general process of lighting while 'luminance' is the resulting illumination level. Their relationship is expressed by the inverse square law: The illuminance produced by a point source of light decreases in inverse proportion to the square of the distance from the source: $E = I / d^2$ [14, P119].

Light Transmission

Light is directional and travels in a straight line in a vacuum or in a transparent homogeneous medium (air). When it strikes a material body, the light behaves in various ways. Basically, it can be distributed as: reflectance (r), transmittance (t) and absorptance (a), in general expressed as a percentage and in all cases is equal to1 (Figure 2.12). According to the material's property and quality these three ways always occur singly or in combination with one another. In optics, the reflectance is the ratio of light that is reflected back to the fraction of the incident light. Transmittance is the fraction of incident light at a specified wavelength that passes through a surface. It happens on all real transparent and translucent materials. The size of the transmission fraction depends on the angle of incidence for a given material. Absorptance is the fraction of incident light that absorbed by a surface. Normally, the dark colour is better in terms of absorption compared with light one. An opaque material can absolutely absorb the entire incident light with perfect black colour [24, P6].

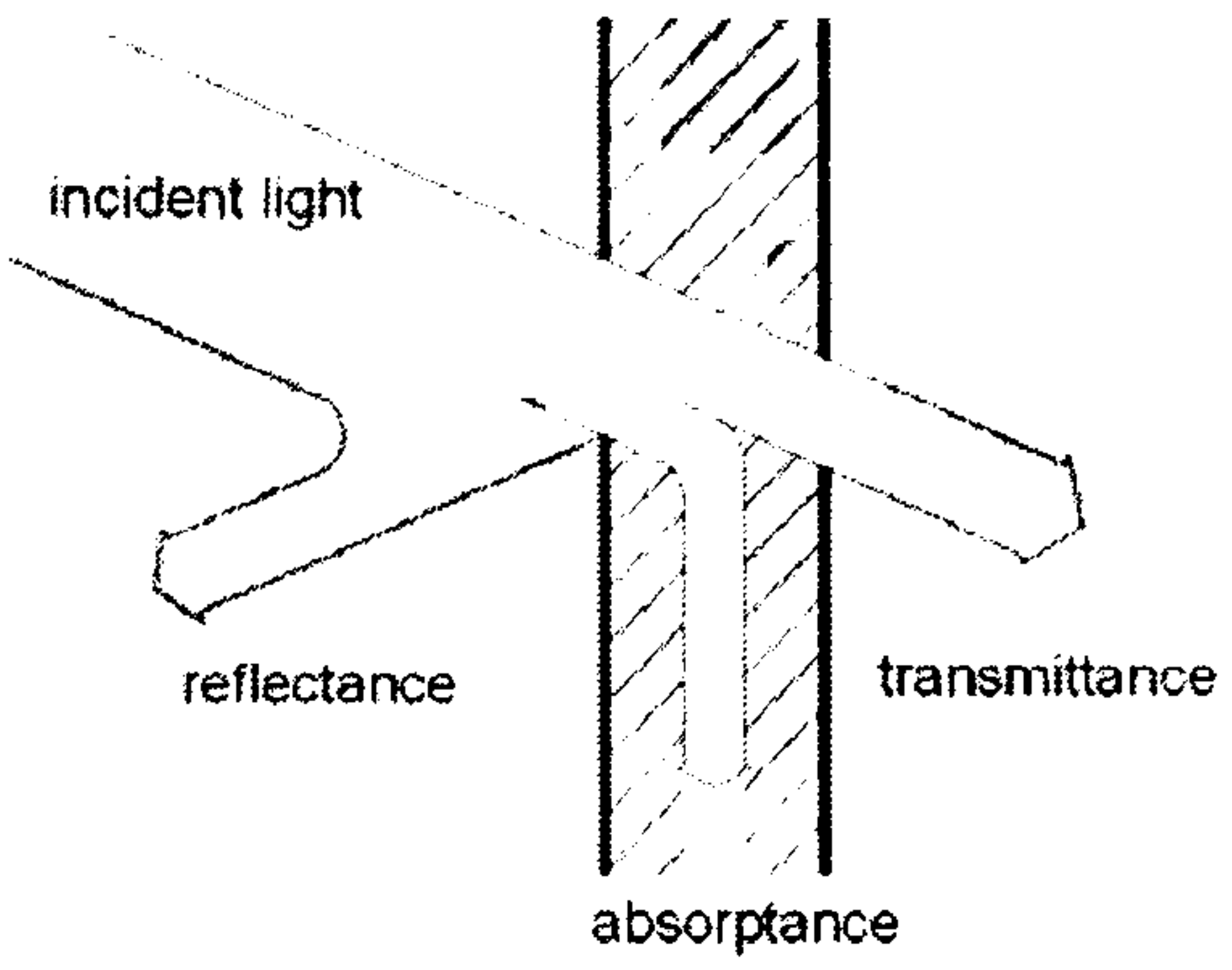

Figure 2.12 Light incident on the surface

2.3.2 Visual Comfort

The Earth's transparent atmosphere gives people a clear and reliable means of perceiving their surroundings. High visual comfort has a greatly positive influence on the occupants' ability to perform visual tasks and contributes to their feeling of wellbeing, leading to an increase in productivity in working, living and leisure environments.

2.3.2.1 Eye and Visual Comfort

The eye is an organ of vision that detects light. The simplest of eyes, for example those of a snail, do nothing but detect whether the surroundings are light or dark while more complex eyes, such as those possessed by human beings, can distinguish distances, shapes, colours and textures etc.

The structure of the human eye is completely subordinated to the task of focusing light onto the retina. The retina contains two forms of photosensitive cells important to vision — cones and rods. Cone cells need high light intensities from 3 cd/m^2 luminance to respond to and have high visual acuity. Different cone cells respond to different wavelengths of light, which allows an organism to see colour. Rod cells, conversely, are highly sensitive in order to respond to dim light and dark conditions. These are the cells that allow humans to see with very little available light and are also the reason why the darker conditions become, the less colour objects seem to have [25].

The pupil is the black circular opening, the size of which may be adjusted, in the centre of the iris that regulates the amount of light that enters the eye. Sometimes the brightness of the surroundings in direct sunlight can be 10000 times more than in the softly-lit domestic interior, and yet the pupil can practically instantaneously respond by adapting to the decrease by way of dilation and contraction. When it comes to around 1000 cd/m^2, the pupil closes to its minimum size. In this way, the eye can deal with a quite broad range of lighting levels. Therefore, the level of visual comfort can be measured by the efficiency of the visual process: visual acuity, adaptation and contrast sensitivity. These three visual performances together generally provide a good criteria for the measurement of comfort.

Visual acuity is acuteness or clearness of vision, which is the ratio between the size of a discernible detail and its distance. Although only up to a certain level, acuity can be improved greatly with even a low level increase of illuminance. Adaptation is the ability of the eye to adjust to various levels of darkness and light. However the time that is needed in order to adapt is quite different. The eye will take approximately 30 minutes to fully adapt from bright sunlight to darkness. On the other hand it takes approximately just 5 minutes to adapt to bright sunlight from darkness. Contrast is the difference in visual properties that makes an object (or its representation in an image) distinguishable from other objects and the background. Contrast is determined by the difference in the luminance of the object and other objects within the same field of view. Therefore, the human visual system is more sensitive to contrast than absolute luminance [24].

Visual task	**Illuminance (lux)**
Casual viewing (cloak room, corridor)	100
Rough task (store, lift, dining room)	200
Ordinary task (reception, food shop)	400
Fairly severe task (dress making, art room)	750
Severe prolonged task (supermarket display)	900
Very severe task (engraving, precision assembly)	More than 2000

Table 2.8 Illuminance level with visual task

2.3.2.2 Lighting Requirement

Lighting is required for functional purpose in the building to enable the completion of visual tasks and for human safety. In the built environment, it is determined by how long the user is going to spend on a certain kind of visual task. Usually the range is huge so that the highest is 20 times that of the lowest. (Table 2.8) [4, P291]. Most agreed standards and codes of practice for lighting are concerned primarily with the task of illumination. The adequacy of lighting requirements is normally defined in terms of the amount of light falling on a horizontal plane at working level - the so-called 'working plane'. Quantities are given according to the illuminance in Table 2.9 [18, P180].

Environment	Illuminance (lux)
office	500
Drawing offices	
General	500
boards	750
Auditoria and foyers	100
shops	500
Living rooms	
general	50
reading	150
sewing	300

Table 2.9 Illuminance level required in some spaces

In a dark environment, it is impossible to undertake productive visual task work. With the increase of illuminance the type of work performed can get more and more elaborate and detailed. From the table, the need to detect and recognize very small parts of the total visual field requires a high level of illuminance and the scale moves in large steps. However, the illuminance control for improvement cannot continue indefinitely. Figure 2.13 presents the relationship between task illuminance against visual performance [4, P106]. The effect of the influence is dramatically positive only in a period of phase. Over a certain point, the curve starts to flatten out which means the increase of illuminance doesn't have much effect. Therefore, the level of task illuminance - in other words the level of lighting required to perform a given task - although a pervasive aspect of the lighting requirement is lower than the point at which the graph becomes almost horizontal. There are other important criteria that need to be satisfied before the final level of performance is reached:

- distribution of task illuminance;
- contrast between the task and its surroundings;
- absence of discomfort glare [24, P65]

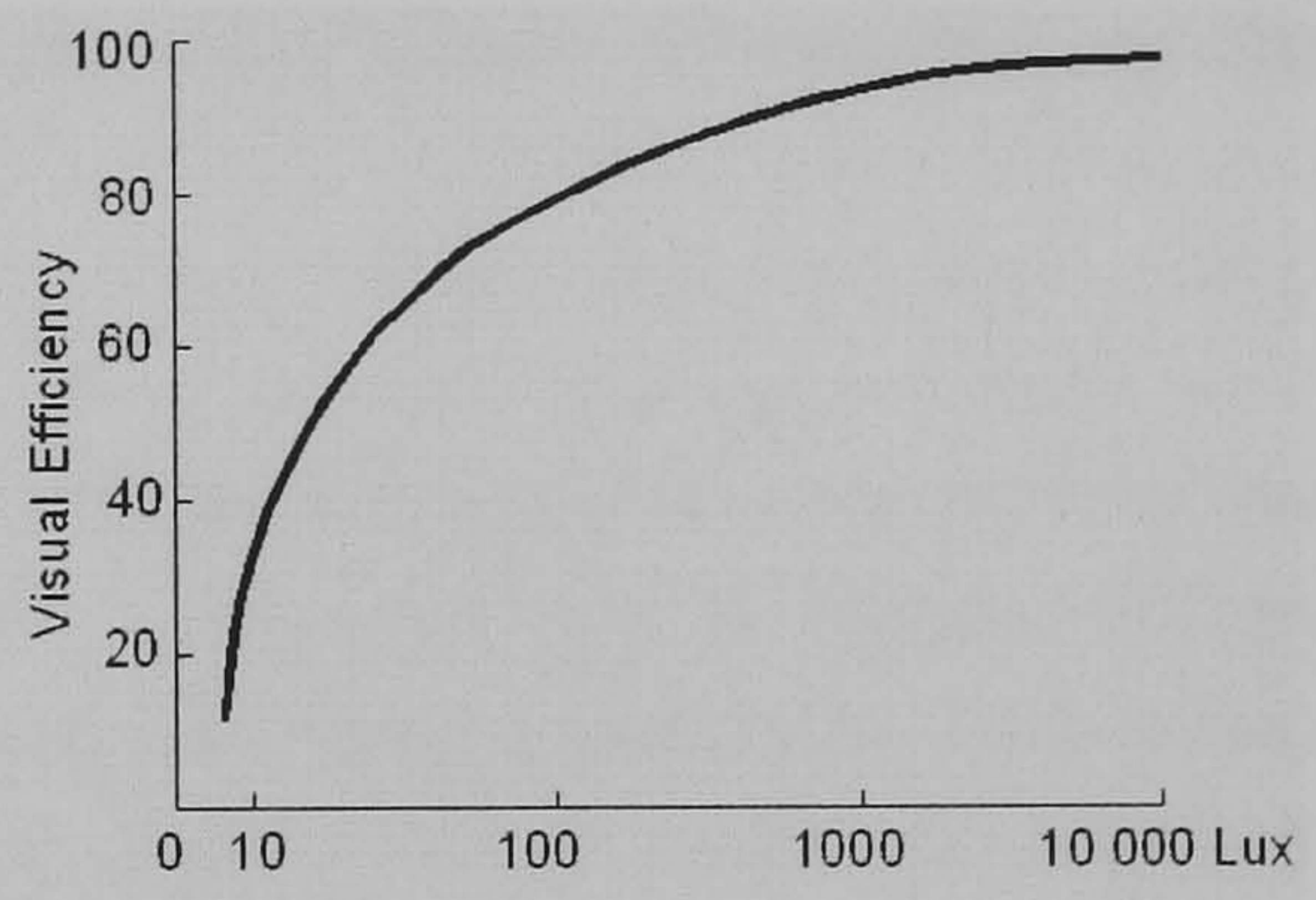

Figure 2.13 Visual efficiency with illuminance increasing

2.3.2.3 Glare

Glare is the result of excessive contrast between bright and dark areas in the field of view. It is a complex visual phenomenon and governed by the brightness, size, number, distance away and direction of the light source in relation to the general background. Figure 2.14 shows a typical glare phenomenon by specular reflection. In the room of a building, it principally occurs where windows or artificial lights appear too bright compared with the average brightness of the interior. If the luminance ratio (L_{max}/L_{min}) within a visual field is greater than about 15, visual efficiency will be reduced and discomfort may be experienced [1, P141]. Glare can

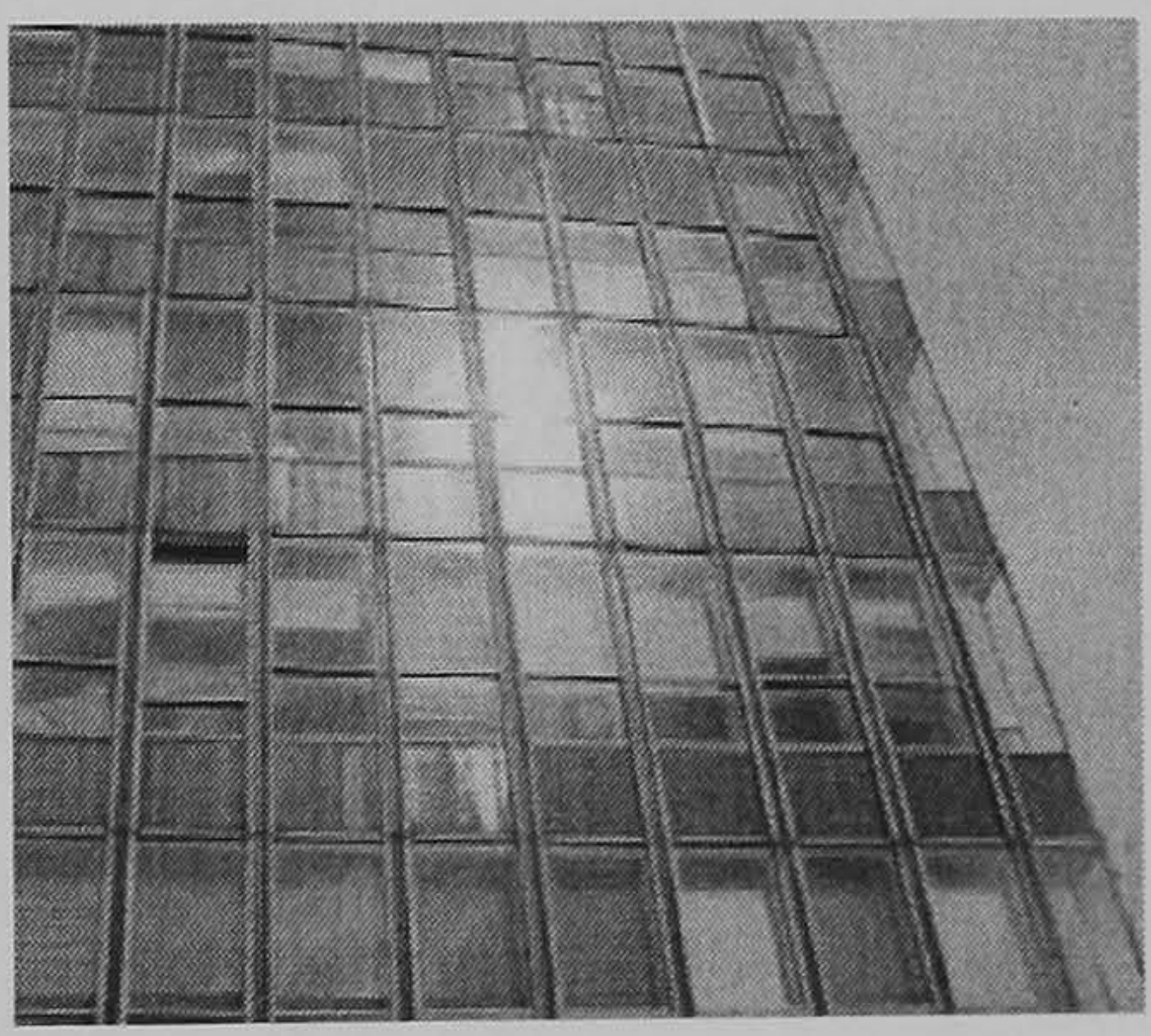

Figure 2.14 Glare by a specular reflection

be categorized into types. One such classification is described according to people's different manifestations of adaptation conditions. There are three aspects that may be described[26]:

Blinding Glare This is caused by a saturation effect with a very high luminance in the viewing field. When the illuminance is greater than 10000cd/m^2, the adaptive ability of the human eye is exceeded. The effect is completely blinding resulting in either temporary or permanent deficiencies in vision. It occurs, for example, when people stare into the sun or at very bright artificial lighting.

Disability Glare This is the loss of performance due to very bright areas in the field of view, and it occurs frequently in practice. When sunlight is reflected from a computer screen resulting in significant reduction in sight capabilities, a bright luminous area is in the immediate field of view. The amount of light falling on the eye in such cases makes screen reading impossible.

Discomfort Glare This does not typically cause a dangerous situation in itself but is annoying and irritating. It can potentially cause fatigue if experienced over extended periods. When concentrating on a task the existence of a bright source elsewhere in the field of view, may not be noticed over a short period of time or by a person who is avoiding looking at it; but, in the long term, task performance is affected by this discomfort glare.

2.3.3 Daylight

When sunlight reaches the Earth, the visible part of the spectrum makes up 47% of the total energy (Table 2.3) and is the primary source of natural light for people. Of the visual light from the sun, some of the light directly reaches the ground as sunlight, which is very directional and extremely bright. Some is scattered by the earth's atmosphere, taking the form of 'skylight', which is both diffused and of low brightness. The term 'daylight', in a loose sense is often used for both sunlight and skylight.

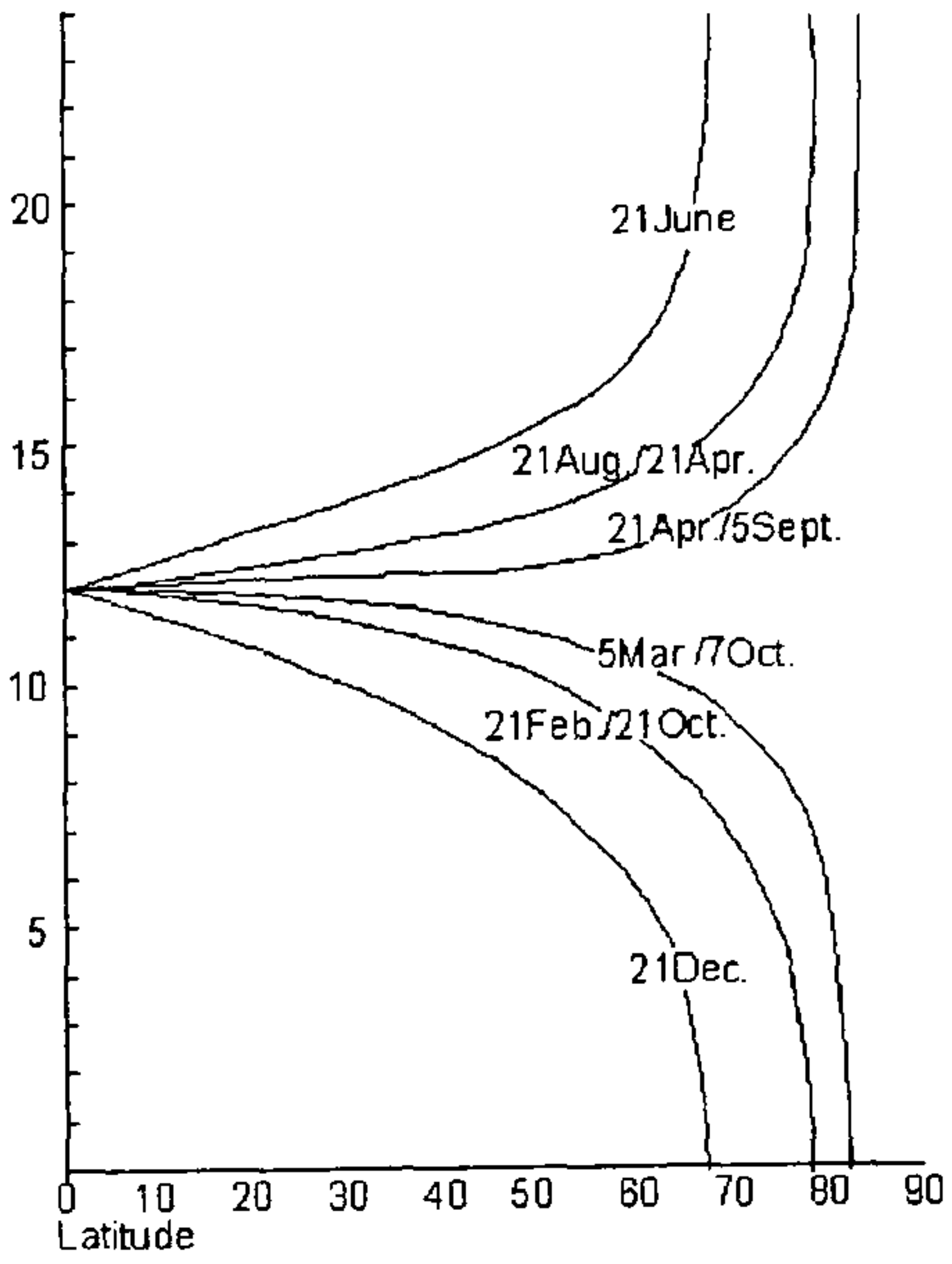

Figure 2.15 Duration of daytime as a function of latitude

2.3.3.1 Daylight Illuminance

The duration of daylight received at a certain position varies throughout the year and is related to the position's latitude and season. In the area around equator, the duration of daytime is the same throughout the year. However, it differs considerably when the distance from the equator is increased (Figure 2.15) [11, P119]. The strength of illumination received from daylight is greatly influenced by the movement of clouds and sun. At the edge of the earth's atmosphere, the level of solar illumination is approximately 150,000lux. After passing through the atmosphere of a clear sky to sea level, the level can still exceed 100,000lux [27, P43]. The overall skylight can give 40,000 – 50,000lux diffuse illuminance in a clear sky. Compared with direct sunlight distribution, diffused skylight is less intense and more uniform. Even on an overcast day, the illuminance is 10 to 50 times more than is needed in a certain kind of space for the performance of visual tasks [19, P313].

Normally, an assumption is made as a basis for daylight illuminance at a certain point on the ground: under an unobstructed heavily overcast sky, a constant 5,000lux is taken as one standard for daylight calculations. This is a conservative design assumption – it is exceeded for 87% of normal working hours from 8am to 5pm throughout the year [11, P187]. The quantity of skylight that reaches the ground is far more variable than the sunlight: in bright sunshine the solar illuminane is steady, but light from the diffuse sky can vary from minute to minute, and apparently similar skies on successive overcast days can differ greatly in brightness. Even on cloudless days the presence of water vapour and pollution affects the relative intensities of daylight. Where the sky is cloudy for much of the time, as in a tropical humid climate, it is effectively the subject of random variation [24, P65].

2.3.3.2 Daylight Factor

The amount of light received inside a building is usually only a small fraction of that received outside. Different sizes and positions of openings, other building's reflection and changeable sky conditions etc. make it impracticable to express the interior illuminance actually obtainable inside a building at any one time, because within a few minutes that figure is liable to change. However, the illuminance of a naturally lit room changes proportionally to the changes in skylight. Therefore to characterize the way in which natural light penetrates a building, the percentage of interior to exterior illuminance can be specified as the 'daylight factor'. This 'daylight factor' is defined as *'the ratio of the daylight illuminance at a point on a given plane due to the light received directly or indirectly from a sky of known or assumed luminance distributions, or a horizontal plane due to an unobstructed hemisphere of this sky [27]'*.

$$DF = E_i / E_o \times 100\%$$

When it is used to estimate the lighting in a room:

DF= daylight factor at a chosen reference point in the room, and is normally carried out with reference to an overcast sky (%),

E_i = illumination indoors, at the point of observation, usually the working plane plus the wall surfaces below the mid-height of the window (lux);

E_o = illumination outdoors from an unobstructed sky hemisphere [2, P189].

The daylight factor is valuable as a predictor of the likely daylit appearance of a space. Its use not only ascertains the illuminance available for a certain last, but also indicates the relative brightness between the interior and the exterior, and the higher the factor, the less extreme the brightness, thus minimizing any difficulty in visual adaptation. In general it is accepted that whenever the proper daylight factor is satisfied, there will be sufficient illuminance to perform the specific tasks [24, P37].

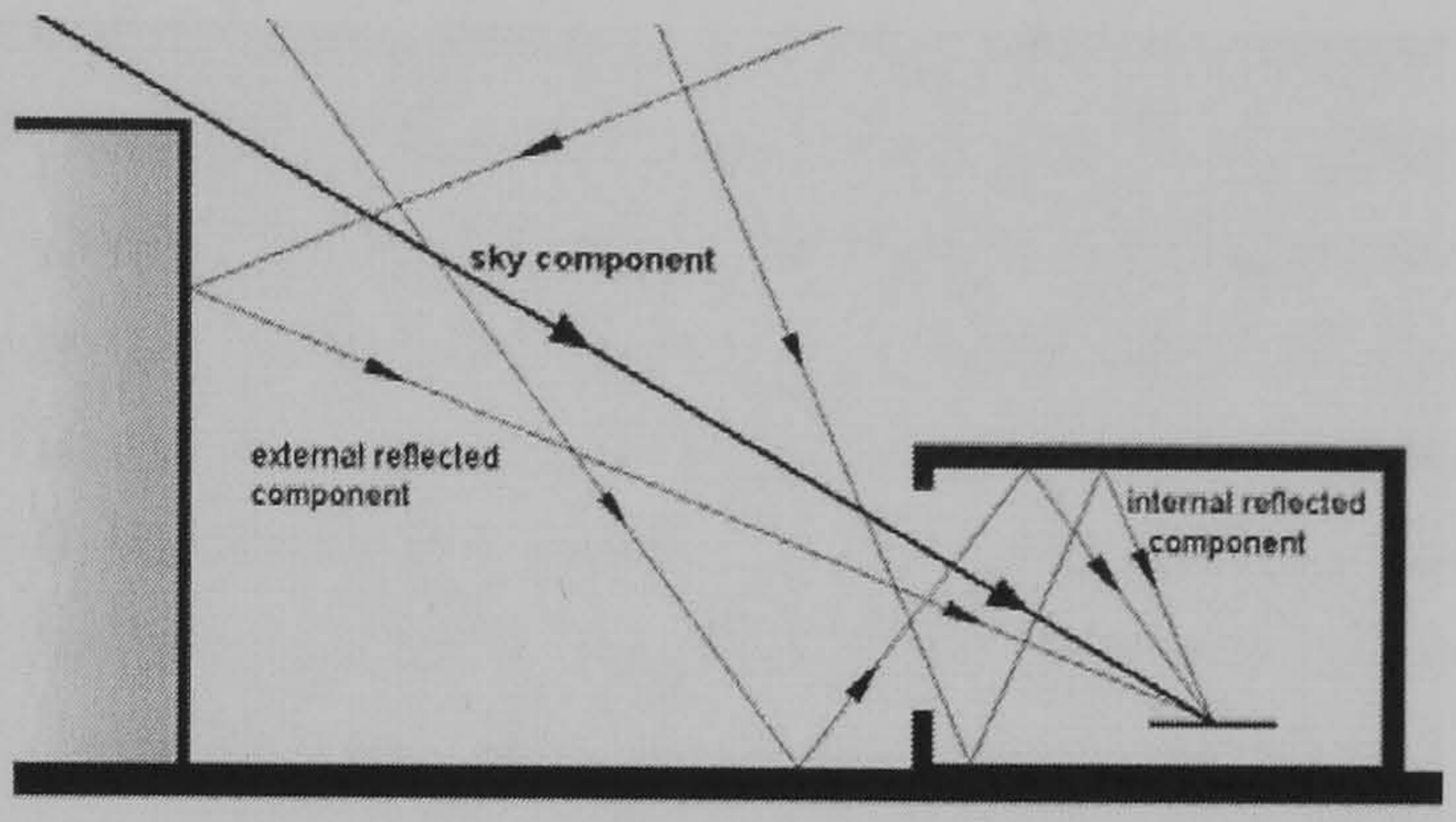

Figure 2.16 Component of daylight factor

Figure 2.16 shows three components that make up the daylight routes: the sky component, the externally reflected component, and the internally reflected component. The sky component is the part of the daylight illuminance at a point of the working plane (a horizontal plane at desk level) that received directly from the skylight. Direct sunlight is excluded here. Thus the sky component denotes natural lighting from the sky. The externally reflected component is that light which is reflected from obstructions outside, such as buildings. The amount of reflected light depends on the reflectance of the surfaces of the obstructions and the exposed area. And the internally reflected component is the light entering the room, not reaching the work plane directly, but only after multiple reflections [27].

2.3.4 Lighting and Room Character

For a building, good lighting design, natural or artificial is not only good from a quantitative point of view for the performance of certain visual tasks, but also from qualitative point of view in that it provides a desirable and pleasant luminous environment. These two main sources of room lighting are regarded as complementary to each other, the advantages of which can be properly taken at all times. In the case of daylight, when the varying quality and intensity of natural light enters the room of a building, it brings a diverting and welcome sense of the world outside - a very valuable amenity to psychological well-being [1, P142] - while artificial light is used for night-time illumination and also as a daytime supplement when daylight alone is not sufficient. Naturally speaking, there are several principal factors that affect the overall luminous environment of the building when its site is chosen:

- building orientation and shape;
- window feature;
- obstruction and reflection to light admission;
- internal surface reflection;
- electric lighting arrangement.

2.3.4.1 Building Orientation and Plan Shape

The sky component is the main contributor to the amount of light received within a space thus the building orientation is the fundamental element in the control of daylight. The east and west side receive sunlight for half of the day when the sun is in a low position. The south façade can provide lighting by way of a combination of direct and diffuse light. The resulting soft shadows and shading allow for a vivid view of the three-dimensional qualities of the environment. The north façade, although having relatively low illuminance, has the most constant and uniform daylight throughout the day and year, and therefore seldom experiences problems with glare discomfort for occupants. In addition, the horizontal window from the ceiling is not always applicable. Nevertheless once in place, this allows for fairly uniform illumination over very large interior areas. However, the strength of light is strong in summer, which is just about the reverse of what the indoor environment requires. In general, after establishing the lighting requirements by determining what the visual task is, the lighting features of different directions can be used and controlled so that a pleasing indoor environment is already put in place in the initial stage of design.

A building's room normally is an opaque or enclosed space with openings that allow access to daylight. Although the total illuminance of external sunlit surfaces can be dozens of times greater than the illuminance required inside, it is the shape of the plan that inevitably influences the desired daylight to be introduced into the room. A side window is the most common way of letting sunlight penetrate, thus the daylight illuminance on the working plane reduces very rapidly with increasing plan depth from the side window (Figure 2.17) [8, P46]. Only when the depth of the plan is in a range of meters can much of the space benefit from the daylight. In multi-storey buildings a 6m perimeter zone can be daylit to an acceptable depth.

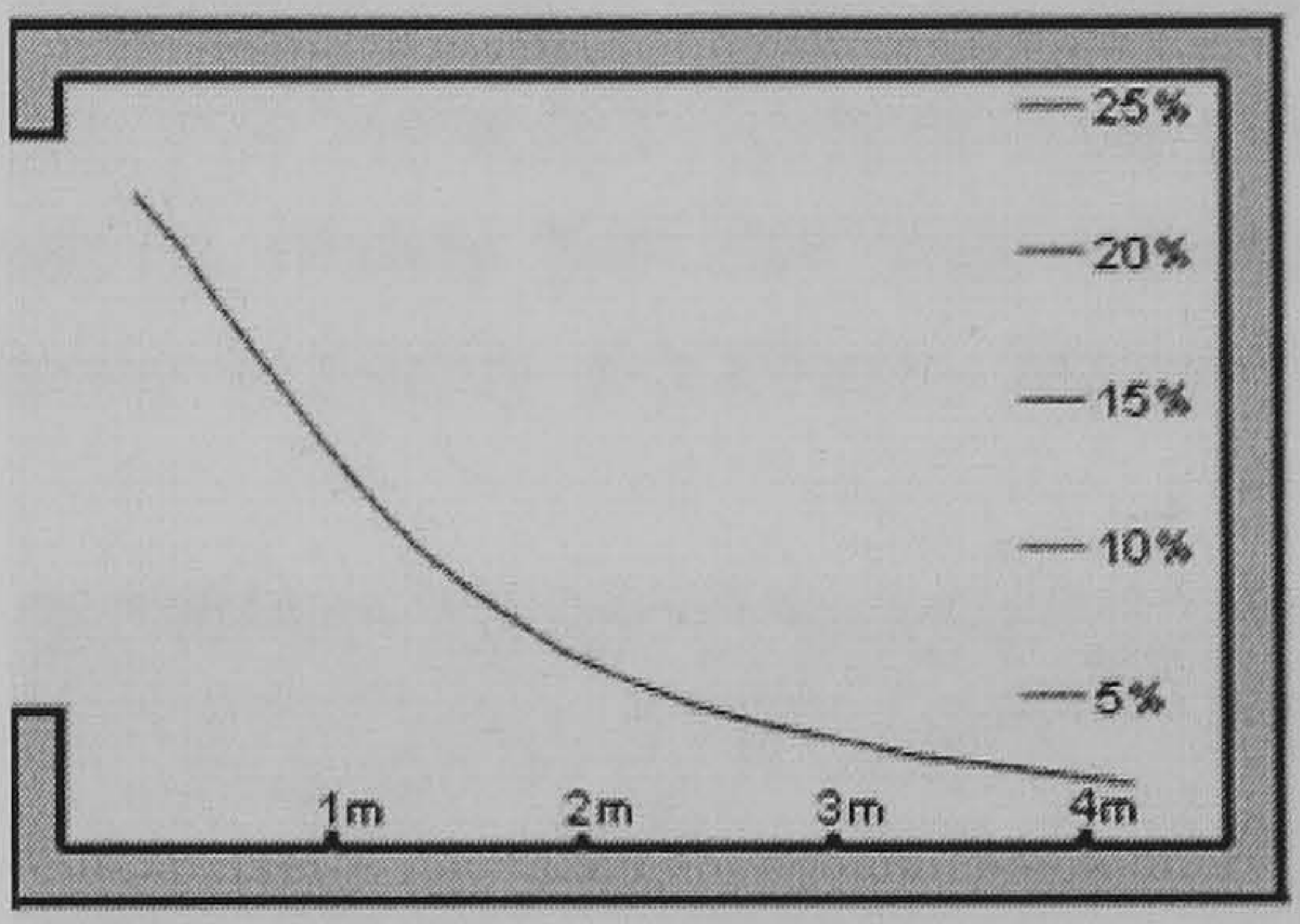

Figure 2.17 Daylight factor in relation to the distance from window

2.3.4.2 Window Glazing

Daylight is introduced into a building mainly using a variety of window openings, side-lighting or top-lighting strategies. Once building is erected, the amount of light that enters a space and the distribution within the space is mainly determined by the overall glazing design factors, such as numbers of windows, the size of glazed areas, disposition and shape. The daylight penetration into a space can be increased by increasing the height of windows, mainly because it offers the chance for the back of the room to be exposed to more sky, and consequently improve the lighting levels.

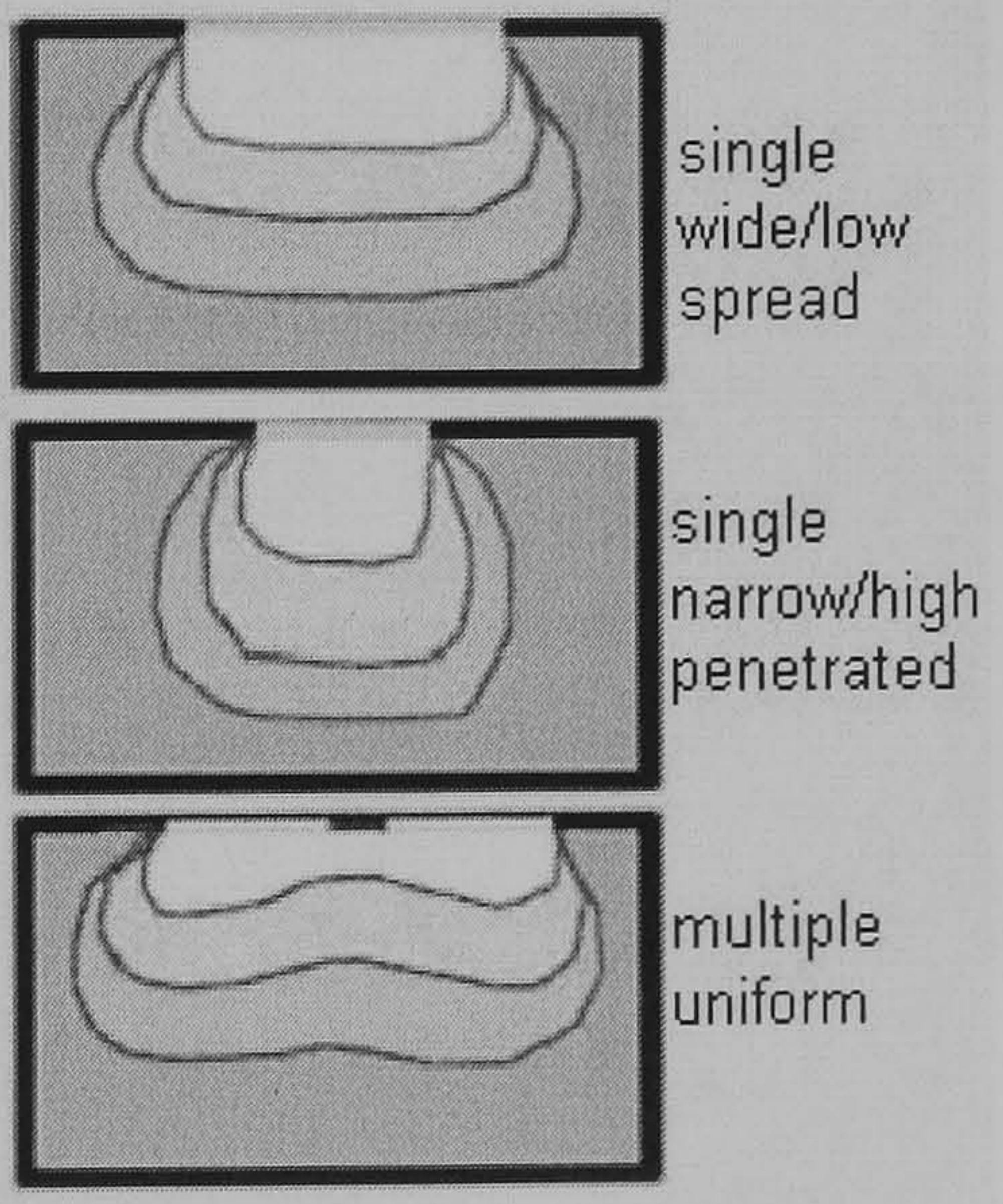

Figure 2.18 Effect of glazing on the illumination of indoors

Therefore, high windows tend to admit more useful daylight than low ones, if those windows are identically sized in terms of total surface area as the high ones. And with more windows in the room, the daylight will be more uniformly distributed in space compared with the room that has just one single window, as can be seen from Figure 2.18 [2, P191].

The necessary requirement of the illuminance level can be obtained in general when the desired daylight factor is known. Table 2.10 shows the suggested daylight factor in order to quantify the illuminance and predict daylight performance for plans with various interiors and specified tasks [19, P316].

Location	Minimum daylight factor
Corridor, bedroom	0.5
Living room, lounge	1
General office	2
Class room	2
Entrance hall	0.6
Library	1.5
Drawing office	2.5
Sports hall	3.5
Art studio, galleries	4 – 6

Table 2.10 Typical daylight factor levels

2.3.4.3 Surface Reflection from the Inside/Outside

The sky component and window glazing are, generally, the two most significant issues that affect the luminous environment. But this is not always the case. When the window glazing is turned closely toward a building or courtyard, this ‘reflected daylight’ may play a profound role and, in some cases, can contribute to nearly half the total internal illumination, making the reflectance of room surfaces a highly significant factor [1, P144].

The balance of brightness of the internal surfaces affects the amount and direction of reflection and multi-reflection daylight, thus making a bright and cheerful surface the preferred choice. Usually the room proportions determine which internal surfaces are to be the main daylight reflectors. In high-ceilinged rooms with low volumes, the walls have very much greater areas than the ceilings and thus they are more significant in terms of their reflectance effect on lighting quantity and appearance. Conversely, in a very large open-plan office, the ceiling is visually much more significant than the walls in affecting the overall space illuminance level except in places close to the wall [1, P156]. Figure 2.19 shows how finish influences the ability of surfaces to absorb and reflect light. The performance varies greatly. This ability of materials to behave in a differential

Figure 2.19 Effect of different finish on building room

manner in relation to building performance can be highly controllable thus opening up excellent design possibilities.

Reflected light from outside comes mainly from ground and neighbouring surfaces. It is often the case for this part of reflected light to be the major source of daylight, especially in high density urban areas. A white painted building will frequent reflect 80% of the incident light. Ground reflection varies according to the different properties of objects such as trees, lakes, grassed areas and pavements. For example, grass can only reflect only about 10% of the light, most of it green [18, P123].

2.3.4.4 Electric Lighting Arrangement

The chief drawback of daylighting for visual task illumination is its inconsistency, especially its total unavailability after dusk and before sunrise. Nowadays, electric lighting has been continuously developed in terms of efficiency and type with instant and constant quality [15, P76]. It provides not only a supplement to daylight but also allows for special visual effects. Primarily there are two types of lamp used in buildings: incandescent and discharge. Each is available across a wide range, with variations in size, power, colour appearance, colour rendering, efficacy and operating characteristics [24, P21].

Lamp The incandescent lamp has a thin wire (usually tungsten) filament with a high resistance, which is heated by the electric current passing through it. The high melting point allows the lamp a reasonable length of time to glow without breaking. To prevent oxidation of the filament, it is enclosed in a glass container, in vacuum or partial vacuum with some small quantity of inert gas (krypton, argon or xenon) (Figure 2.20). Although their luminous efficiency is quite poor at converting electric power into light with an average 10-18 lm/W, it remains cheap and effective with no special control system required, and is therefore in widespread use [18,P178].

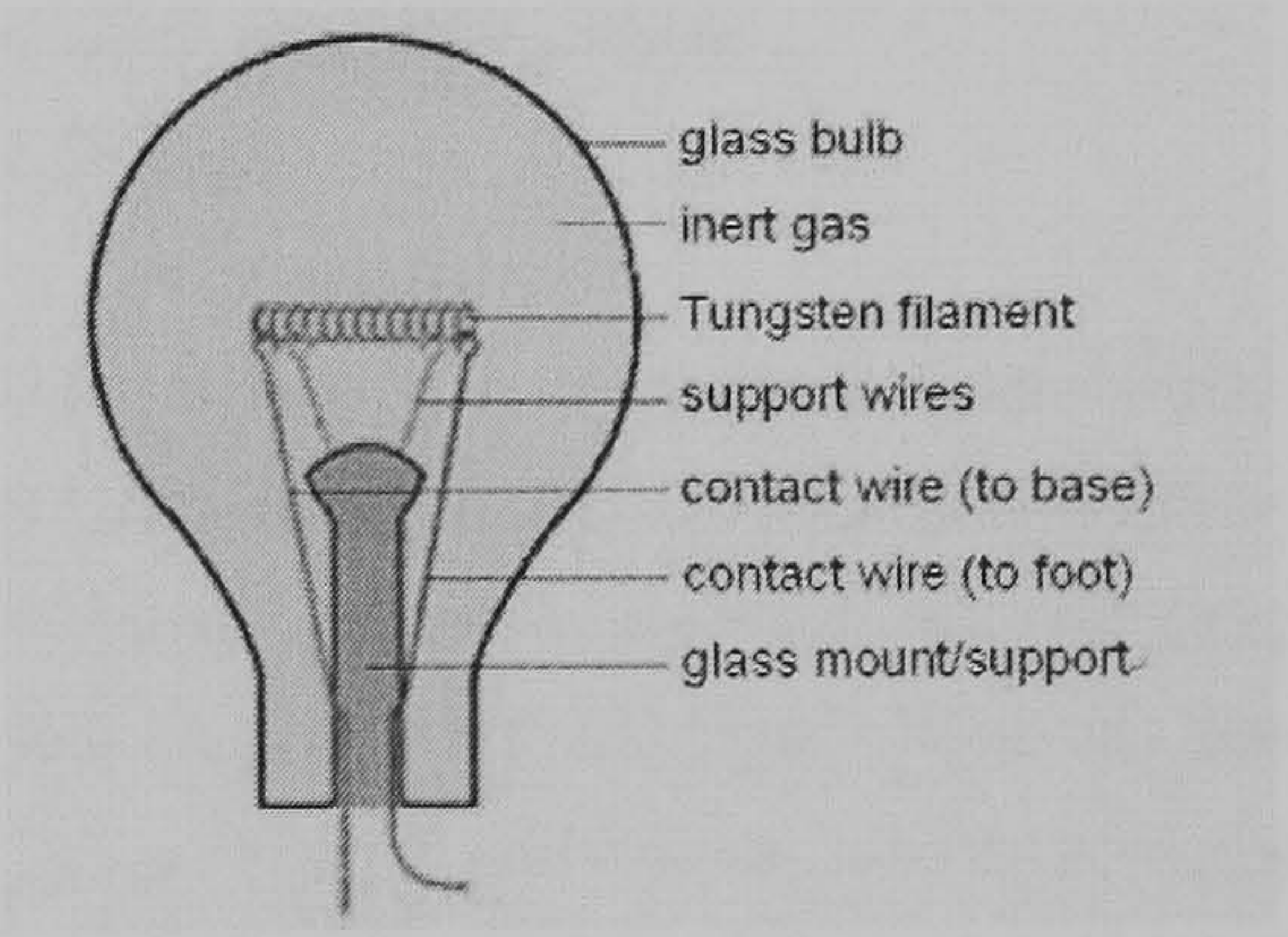

Figure 2.20 Component of an incandescent lamp

Light can also be produced by an eclectic discharge in a gas-filled transparent tube. The discharge is started by the application of a high voltage across electrodes at each end. This ionizes the gas, enabling an increasing current to flow, and resulting in further ionization. The radiation produced depends on the materials in the tube and on the gas pressure. Its spectrum is discontinuous, and comprises bands of radiation at specific wavelengths (Figure 2.21). The most

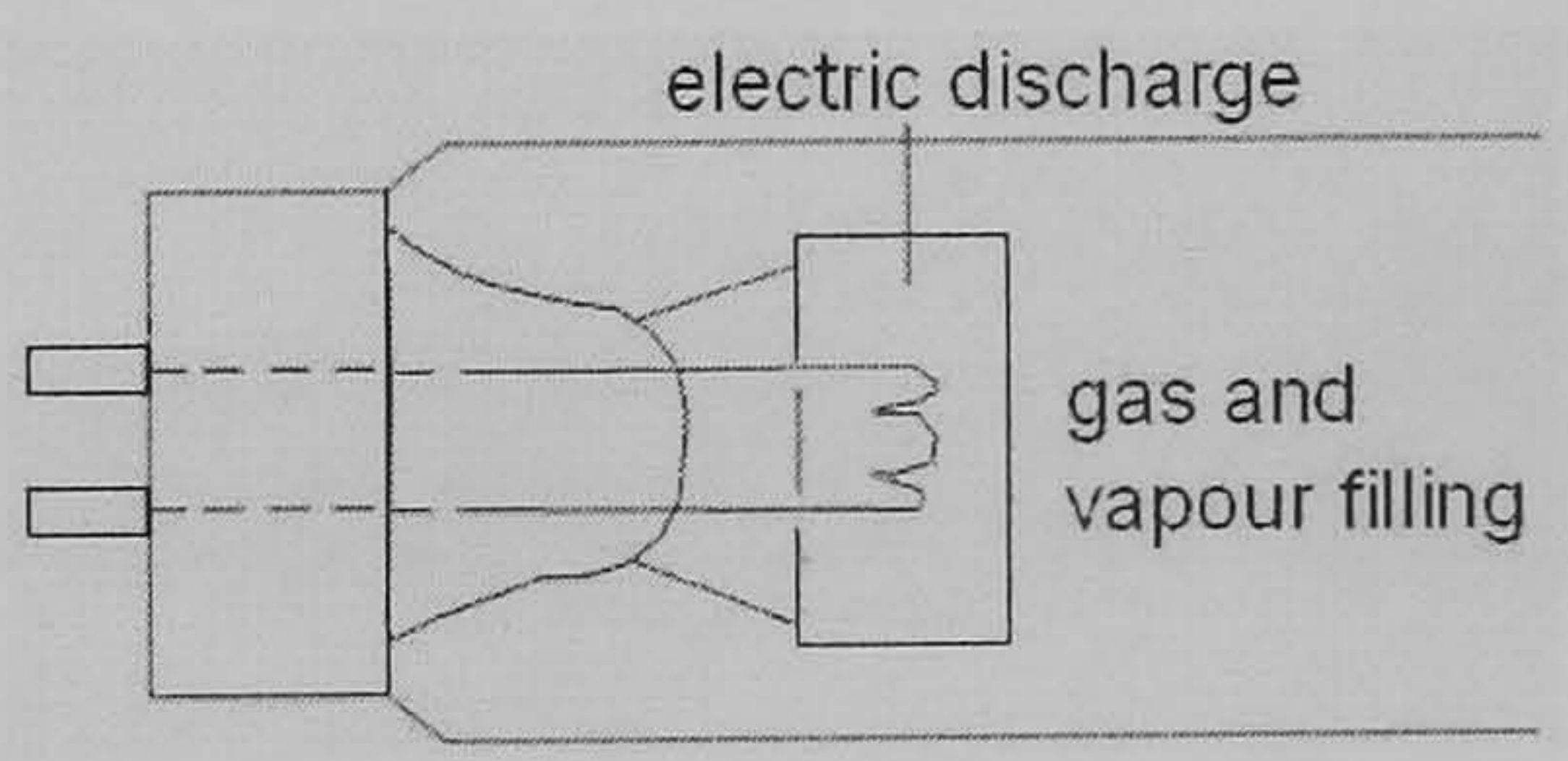

Figure 2.21 Component of a discharge lamp

commonly used discharge lamp is the low-pressure fluorescent tube. The inside wall of the lamp tube is lined with a phosphor powder, which absorbs the ultraviolet and re-radiates the energy in the visible spectrum [24,P23]. Discharge lighting can produce more light per watt and less unwanted heat: high-pressure sodium can reach 100lumens/watt - much higher than incandescent lamps. But it has poor colour-rendering qualities [1, P199].

Electric Lighting Design The lighting installation not only has to provide sufficient light but also take into account quality, attempting as far as possible to eliminate glare and other defects. To calculate the lighting illuminance from a single electrical lighting source, one can simply use the application of the inverse square law, corrected by the cosine for the angle of incidence [4, P133]. However, this only considers the direct source impact on the indoor environment. In fact, overall illuminance is determined also by luminaries appearance of all walls, ceilings, floors and furniture surfaces. This results in a very complicated process and the calculation requires experienced and professional knowledge. In daytime, it is always possible to integrate electric lighting with daylight so that sufficient light is provided, especially to the place that is beyond a depth of about 2.5 times the window head height [4, P140]. There is a commonly used technique to estimate the output of lighting installations, intended to be used in conjunction with daylight, which has to play the prevailing role in providing the lighting:

Level of supplementary lighting =
10 X average daylight factor over the area supplemented
X 1/3 sky illuminance [18, P186].

Figure 2.22 shows a practical arrangement. The electric lighting sources are in five rows parallel to the window wall. The solid line is the effect of daylight on the indoor environment with a general daylight factor value. It is clear to see the level of daylighting rapidly drops with the increase of distance from the window. The dash line is the night-time electric lighting with one lamp on in each row. The illuminance stays almost same no matter how far from window, while the dotted line is the combination of daylight and electric light during the daytime. Two rows that are near the window are switched off and the other three are on. This represents a high quality and quantity effect of luminous environment. The middle row just has two lamps instead of one or three, so the daylight factor in this area provides a smooth transition [4, P141].

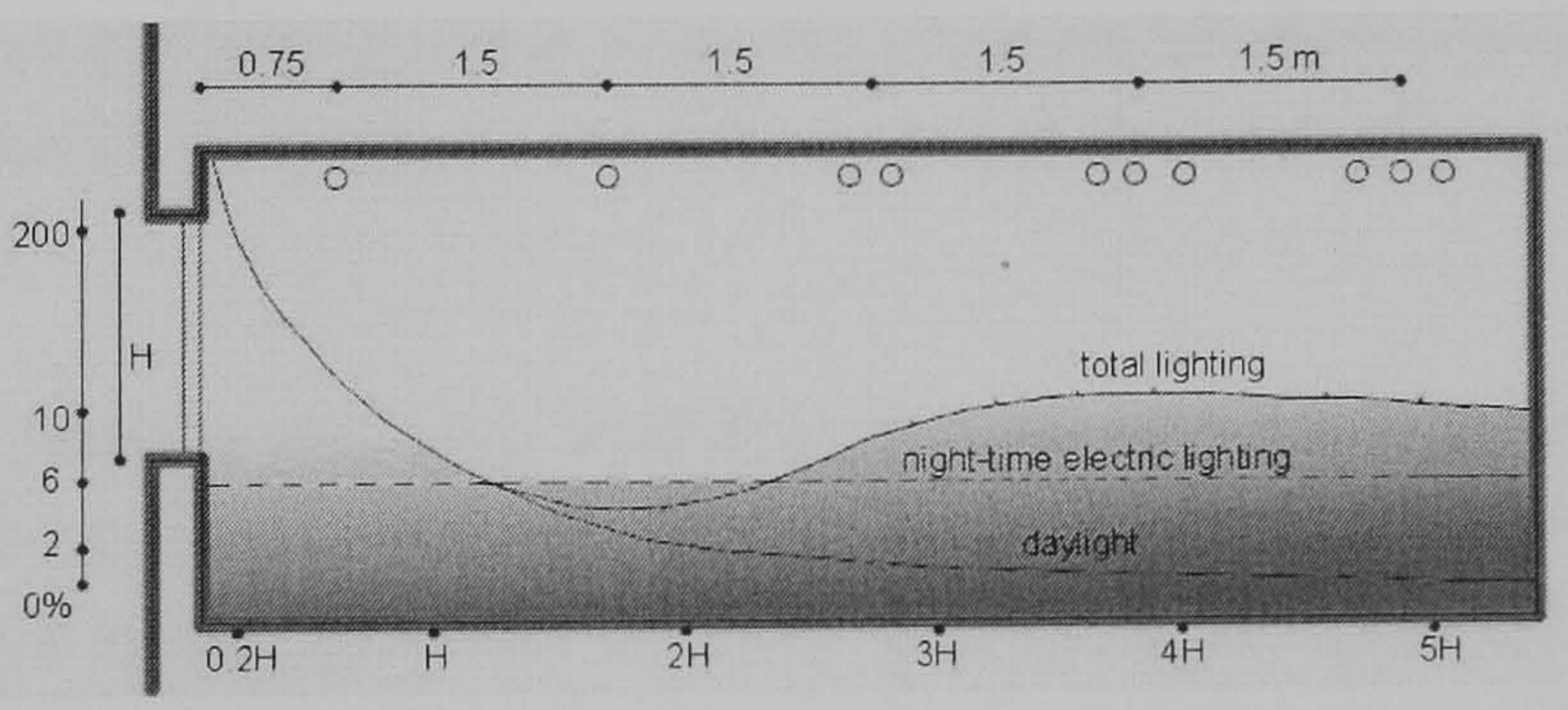

Figure 2.22 A practical arrangement of electric lighting

2.4 Acoustical Comfort in a Built Environment

The acoustic environment is an important fraction in shaping the built environment. The quality of auditory perception and the control of noise are two principal aspects of determining the acoustic environment of a building. However, this study is only concerned with the noise issue, as it is the main problem that is related to the degree of environmental control that can be exercised by the occupant.

2.4.1 Sound Physics

Sound is a vibration produced by pressure pulses in an elastic medium such as air, water, etc. Most building materials can become a sound path. Therefore, although sound is a waveform like light, sharing some of same physical principles, it can not travel without a proper medium due to pressure waves that can only be caused by something vibrating (Figure 2.23 [28, P220]). Sound is a disturbance of mechanical energy. It travels and transfers energy from one point to another, producing oscillations around almost fixed positions with extremely small changes in pressure. It is characterized by the properties of sound waves: frequency, wavelength and speed. The relationship between frequency, wavelength and sound speed is fixed. Thus, the relevant equation can calculate the wavelength of a sound in a specific medium at a specific frequency: $c=f*\lambda$.

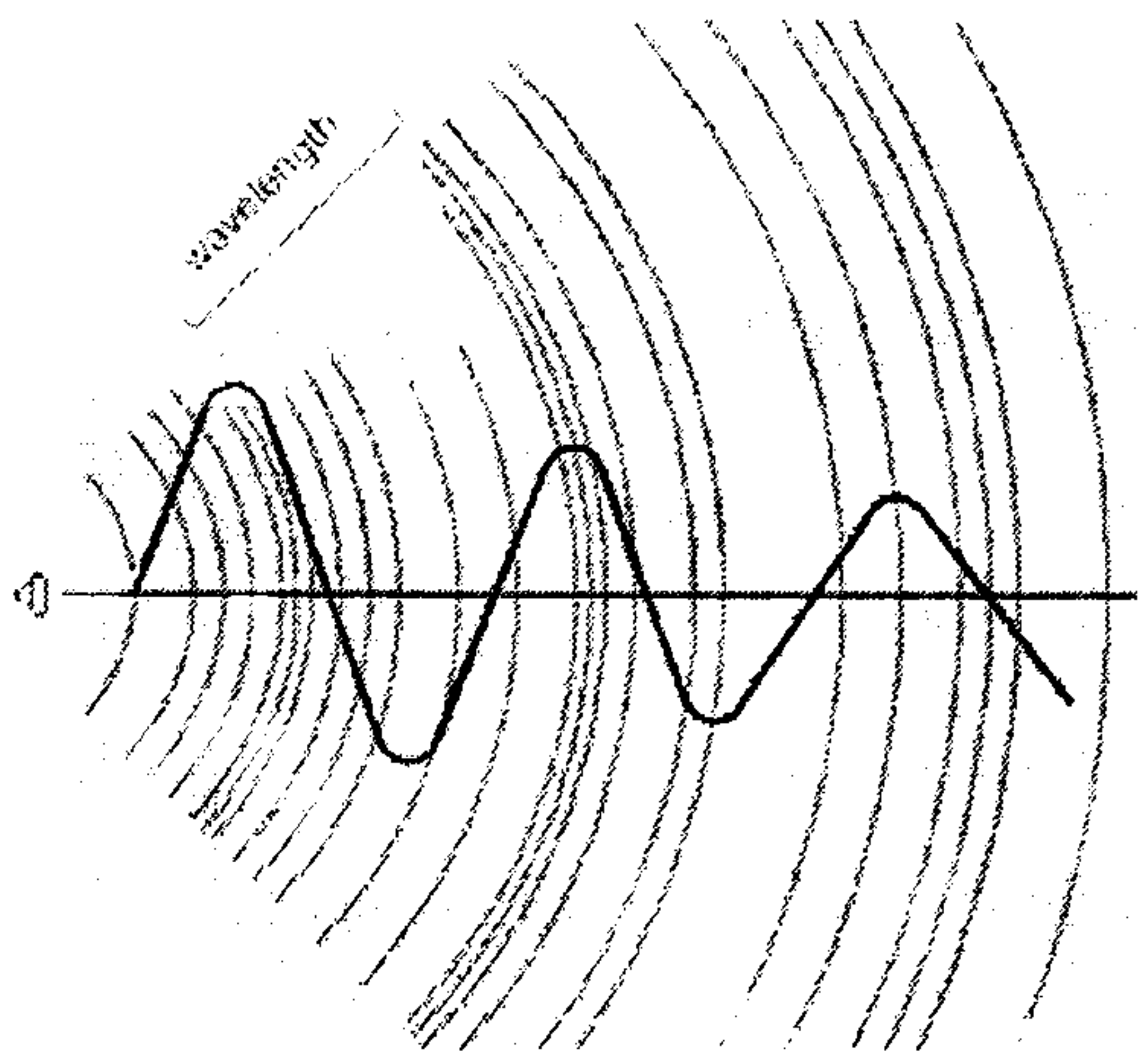

Figure 2.23 Vibration of a sound wave

Frequency (f) is the rate of repetition of a periodic event. The frequency of a sound wave is determined by the number of times per second a given molecule of air vibrates about its neutral potion. The greater the number of complete vibrations is, the higher the frequency will be. The unit of frequency is hertz (Hz). 1 Hz is 1/s which means that an event repeats once per second.

The wavelength (λ) is the distance between repeating units of a wave pattern. As sound passes through air, the air is alternately compressed and rarefied by adjacent air particles. This cyclical motion causes a chain reaction between adjacent air particles so that the wave is produced. Wavelength of sound is the distance that this sound wave travels during one cycle of vibration.

The speed of sound (c) is a term used to describe sound waves passing through an elastic medium. The speed varies according to the medium's elasticity and density. And it is also affected by the properties of the medium as well, especially temperature. Normally, it is faster in warmer and less dense air. At sea level, at a temperature of 21°C and under normal atmospheric conditions, the speed of sound is 344 m/s.

In architectural design, the frequency of sound from 100 to 1000 Hz is particularly important due to its wavelength from 0.0034 to 3.4m, which is the same and/or similar with some architectural components such as internal surface undulation, overhangs, beams, columns, decorations and finishes etc. Only if the scales of these components are closed or longer than the wavelength of a sound can the effect of reflection be efficiently realized. Much consideration has to be paid to this aspect, especially to diffuse soundscape design and the choice of sound-absorbing material [28]. Additionally, sound may travel along all kinds of pipes and ducts at over 600m/s, which is much quicker than the speed of sound in air. Unavoidably, these pipes and ducts are connected throughout the whole building, and, therefore, sound energy can travel through these building materials to places great distances away where it may be regenerated as airborne sound [29, P7].

Sound from a point source with no obstructions is in all radial directions, distributed over a sphere of increasing radius. Sound intensity (I) is proportional to the amplitude of the pressure difference with undisturbed atmospheric pressure. The unit of sound intensity is W/m^2. And sound pressure is the pressure deviation from the local ambient pressure with the unit N/m^2. In reality, these two represent a tremendous range of sound change with intensity 10^{-12} W/m^2 (pressure $2*10^{-5}$ N/m^2) as the lowest audible threshold intensity and 1 W/m^2 (20 N/m^2) as the pain threshold. Therefore, in order to simplify the expression of values and give a better correspondence with the subjective appreciation of sound, a modified version is used to relate sound intensity – bel unit. It is a logarithmic measure of the sound intensity called sound intensity level (SIL). In air under normal atmospheric conditions, the sound intensity level and the sound pressure level (SPL) are nearly identical. Figure 2.24 presents sound pressure levels from some common sound sources measured in decibels (dB) [4, P155].

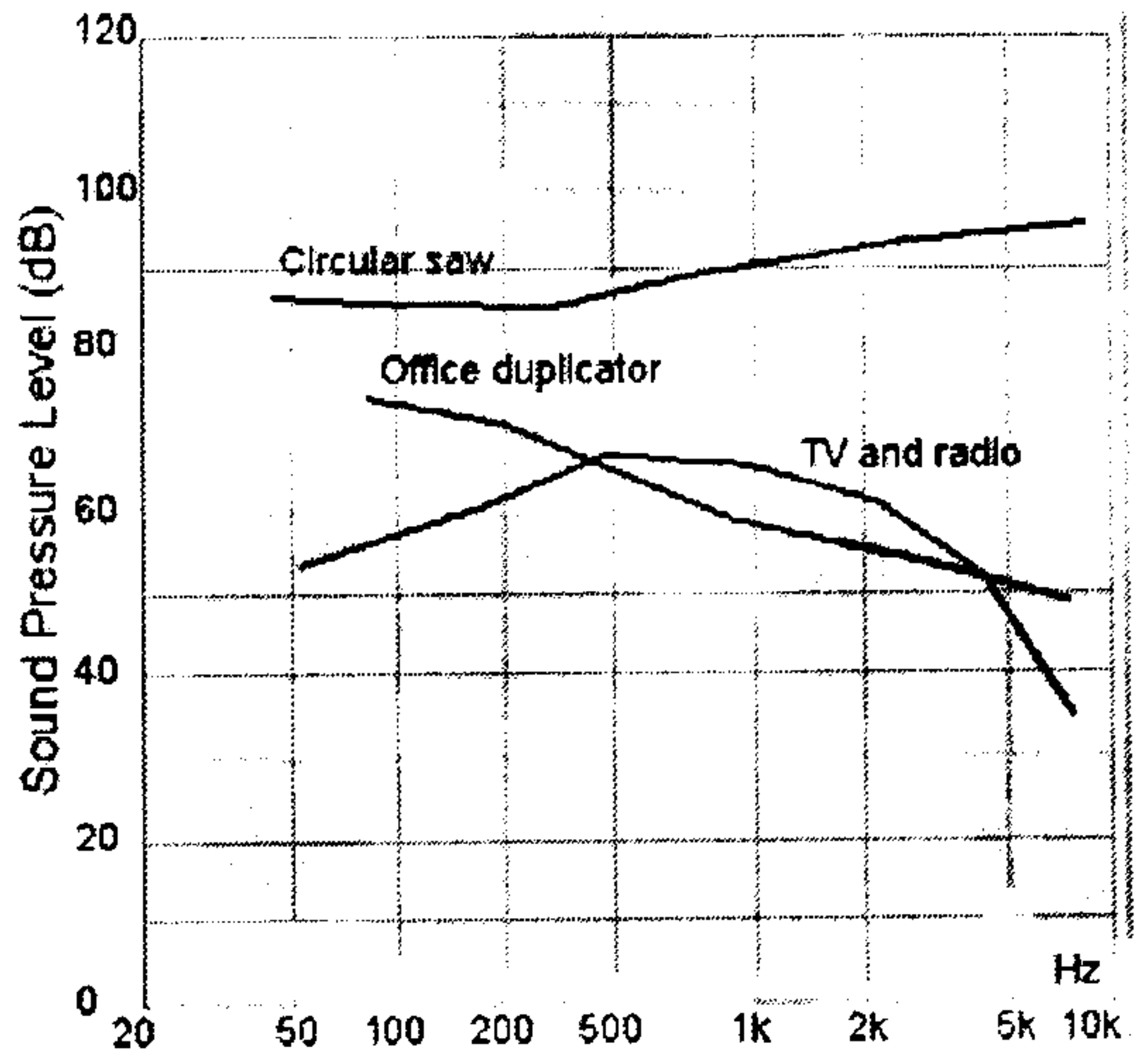

Figure 2.24 Sound pressure level from some typical sources

Because decibels are logarithmic values, they can not be combined by normal algebraic addition. Basically, when two sounds are together, the final effect will be the highest sound level plus 0-3dB. Generally, outdoors, in an open place without obstructions, sound energy from point sources drops off by 6dB for each doubling of the distance from the source of the sound, such as, say, a horn. If the sound is from sources lined up, it drops off by 3dB for each doubling of distance, for instance in the case of sound emanating from traffic on a busy road [29, P14].

2.4.2 Aural Comfort

For human beings, sound is an important means of communication. Comfortable and clear auditory perception, along with freedom from noise not only improves communication but also promotes working efficiency. Nowadays, the latter has become a major design consideration in conventional buildings.

2.4.2.1 Ear and Sound Perception

The ear has three areas: the outer, middle and inner. Sound travels through the outer ear and along the canal by movement of air molecules caused by the vibration of objects to the eardrum, then transmitted across the middle ear by three small bones in the middle ear (hammer, anvil and stirrup). After that the sound transfers the vibrations to the fluid-filled, snail-shaped cochlea of the inner ear to hair cells where they are converted into electrical impulses which are carried by the auditory nerve, finally are perceived and processed into a sensation by the brain [8, P23]. This, roughly, is the process of hearing.

The ear of a healthy and young person is usually able to react to vibration frequencies of 20 to 20,000Hz. The usual sensitivity of hearing is able to discriminate between tiny differences in intensity and pitch (frequency) over a large range of audible sound. With increasing age, the sensitivity especially the upper frequency limit is diminished. The most sensitive region is between 125 to 8000Hz, the range in which most human speech communication takes place [30, P32]. Below or above this range, people normally can not hear very well for the same loudness frequency [8, P25]. The sound intensity level is an objective measurement of sound. It cannot represent the human perception and evaluation criteria, which vary according to frequency, content, duration and psychological factors.

A-weighted sound level (in decibels, abbreviated dBA) is a scale that takes account of the intensity of all the audible frequencies and weights them in accordance with the ear's sensitivity and largely ignores low-frequency sound and corresponds closely to what human ears actually do. However, when frequency of sound is higher than 2000 Hz, people will feel the environment is much noisier than in the low and middle frequency situation even though the A-weighted sound levels are same, because human hearing is generally very sensitive to high frequency sounds. In spite of those limitations, the A-weighted sound level can be used to predict community response to many kinds of environmental sound. Table 2.11 shows some common, easily recognized sounds in

Type of sound	dBA
Near threshold of pain	120
Under airport exit path	110
Noisy traffic	100
Pneumatic drill	90
Loud passage from orchestra	80
Noisy office	70
Medium traffic	60
Busy restaurant	50
Ordinary conversation	40
Quiet domestic interior	30
Rustle of leaves	20
Human breathing	10
Threshold of hearing	0

Table 2.11 Typical sound level

order of decreasing sound levels in decibels [1, P57].

2.4.2.2 Aural Comfort

A sensitive human ear can detect sound down to about 10dBA, for example human breathing, the rustle of leaves in a breeze etc. Normal office activities such as talking and speech are between 50 to 70dBA. Sounds over 80dBA can be hazardous to health in cases of long-term continuous exposure. The threshold of pain is approximately 130dBA. It is possible to suffer permanent hearing damage if the sound level reaches 150dBA, as in huge explosions. Generally, a sound of more than 65dBA may result in negative physiological discomfort or bodily fatigue. Below this level, the discomfort may mainly be down to psychological factors[4, P153].

People cannot live without sound in normal situations. In reality, there are always several sounds from different sources within reaching of the ear. The sound around people that cannot normally be avoided is called background noise. Usually background noise is meaningless, and the human ear and brain can voluntarily discriminate and de-emphasize it. Not until the background noise is loud enough to disturb work, life or any specific activity up to a certain level do people feel discomfort in terms of the aural environment.

A specific sound level can measure the loudness and predict people's perception of sound, but, as with thermal and visual comfort, aural comfort is a highly subjective, psychological matter. It is mainly determined by the environment and the kind of activity people are engaged in. For example, the aural comfort criteria are quite different with regards to sleeping and listening. An adult can sleep comfortably in an environment with a built-up sound level of less than 45dBA, while an audience would perhaps ask for the sound level to be increased up to 65dBA in order to hear clearly what a speaker has to say. On the other hand, where sleep takes place in a non-customary place, the results are going to be quite different. For example, in a sleeper train a monotonous noise level of 65-70dBA does not seem to cause much disturbance, whereas in a quiet bedroom at home for a person, the tick of an alarm clock at 25dBA can cause sleeplessness and irritation [4, P154].

However, when the activity and environment are specified, there are technical properties which do affect human aural perception and these make the best starting point for designing or improving the environment. In the room of a building, aural comfort can be satisfied by several requirements in the acoustic environment generally:

- the sound field is well diffused and distributed throughout the listening space;
- there is no echo, loud focusing effect or other acoustic distortions;
- desired and wanted sound is sufficiently loud and clear with proper reverberation time balance according to different situational requirements.

- any background noise such as from mechanic services or intruding outside sources is sufficiently low enough to avoid interfering with the intended activity;

2.4.3 Noise Control and Room Acoustics

Of all these requirements discussed above, the last one, which is about noise effects on occupant comfort, is considered to be one of the potential influences on the issue of occupant environmental control, and as such is the concern of the discussion presented here. The others, although also important, are beyond the scope of this study.

2.4.3.1 Noise Control Strategy

Sound occurring inside an enclosed space can be affected by the mechanisms of reflection, absorption, transmission and diffraction, as shown in Figure 2.25 [14, P216] Diffraction is an effect which occurs at the edges of an obstacle thus ensuring that the obstacle then behaves as the virtual source of the sound. Of these, refection and absorption are the two main aspects that modify room acoustics. The noise, whether from the outside or the inside, will reach the interior spaces of the building, and these often have many sources of diffuse reflections, which give more body to the sound, and at same time raise the ambient sound level of a room. Strategies have to be put in place in order to keep within the specified noise limits so as not to affect the quality of communication or concentration of people at work.

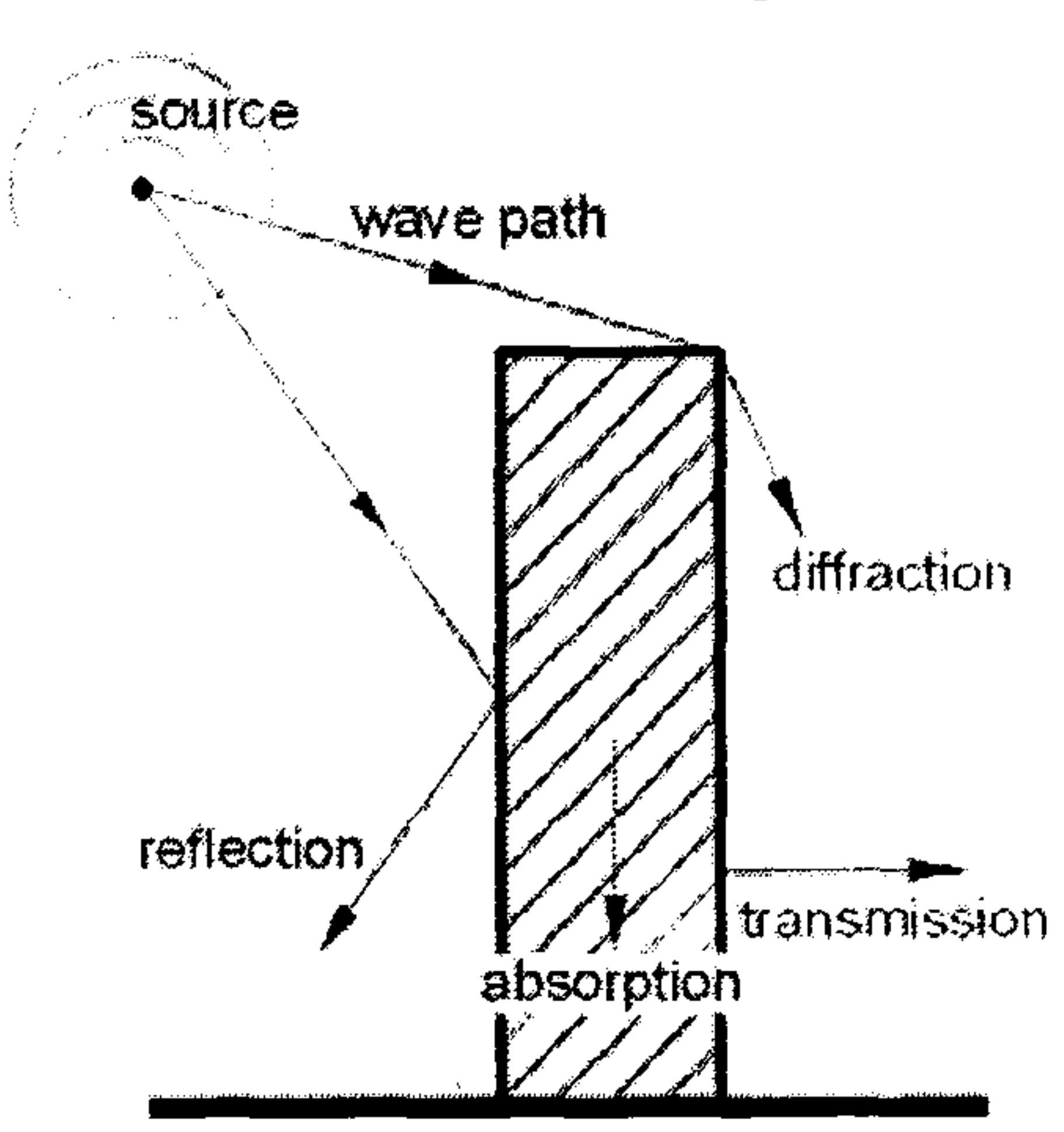

Figure 2.25 Sound path inside an enclosed space

Noise Definition The term 'noise' was once defined in an objective way as 'random vibrations, showing no regular pattern [4, P153]'. However, noise is a subjective phenomenon: a conversation between two people perhaps is very enjoyable but a third party may regard it as noise. The meaningful definition of noise is, therefore, 'unwanted sound'. The noise within a room consists of two components. One is direct noise that travels in a straight line through the air or the enclosure into the room of a building from the source. The other is reverberant noise, which is the reflection or inter-reflection of sound from room surfaces. Nowadays the lightweight nature of many modern constructions, deep reliance on mechanical service systems, the increasing density of urban development and the popularity of motor vehicles, either separately or in conjunction, make the source of noise increasingly a problem in architecture.

The road, rail and air transport and industry are some of the main producers of noise, especially motor traffic. Internal noise is mainly generated by mechanical service systems, such as HVAC, office equipment etc. However, when the noise generated is an avoidable by-product, careful design and planning can eliminate, or at least reduce, the impact of noise on the built environment [15, P49]. Generally, it is far more convenient and effective to control noise at, or near, the source. Apart from that, there are several basic design strategies for the design of room acoustics.

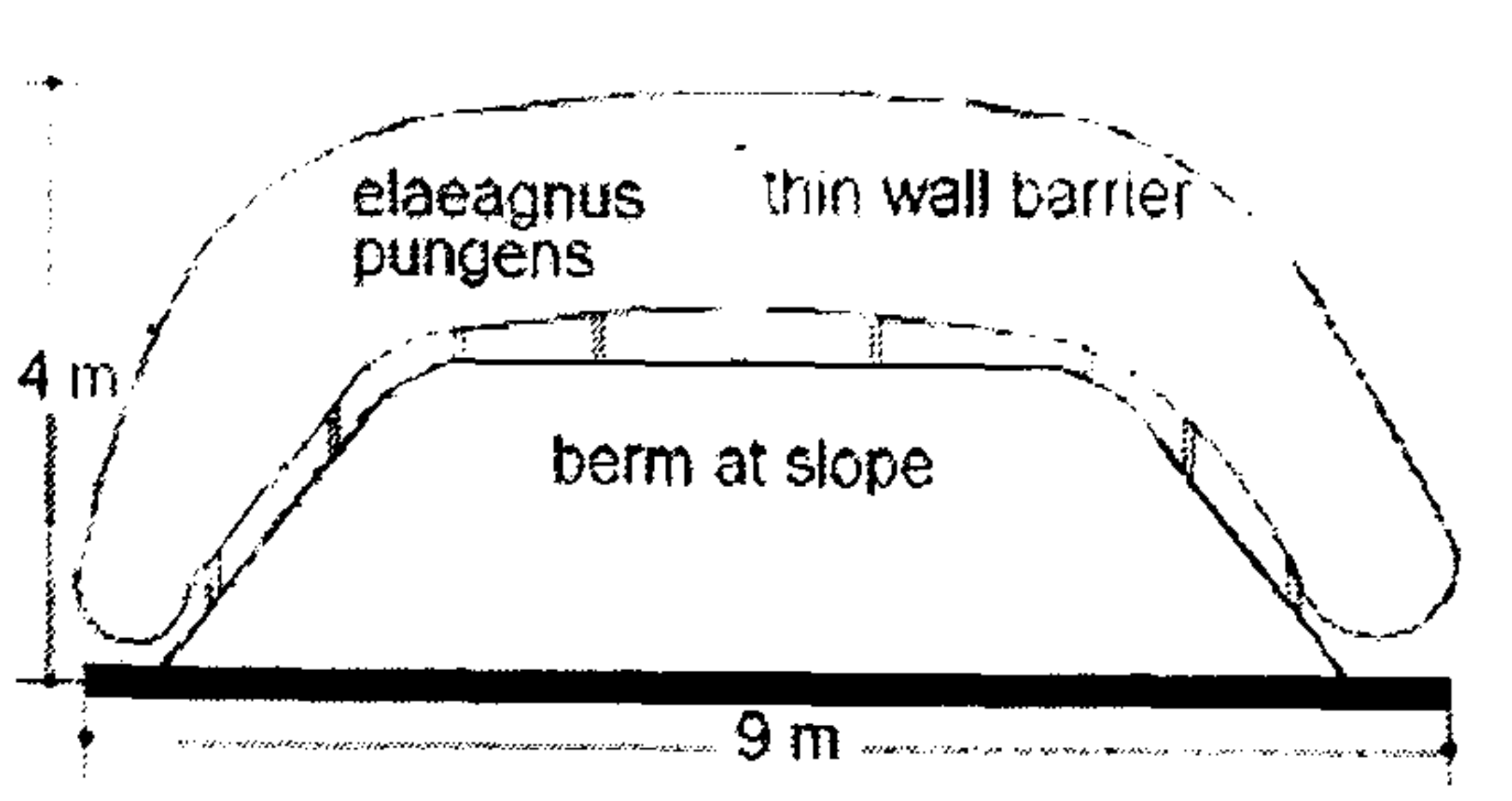

Figure 2.26 A berm barrier to reduce traffic noise

Site planning Planning measures can integrate site features, such as hill slopes or earth berms as barriers for considerably diminishing the intrusion of the noise. If these are covered with plants, then the noise can be further reduced. Alternatively, a reflective wall can be replaced in order to have the same effect. On the other hand, the fundamental defence against the intrusion of noise, such as motorway or industrial application lies in placing as much distance as possible between the source and the space where quiet is needed. Figure 2.26 shows a case of the combination of an earth berm and a thin-wall barrier to reduce highway traffic noise in South Carolina, U.S. [31].

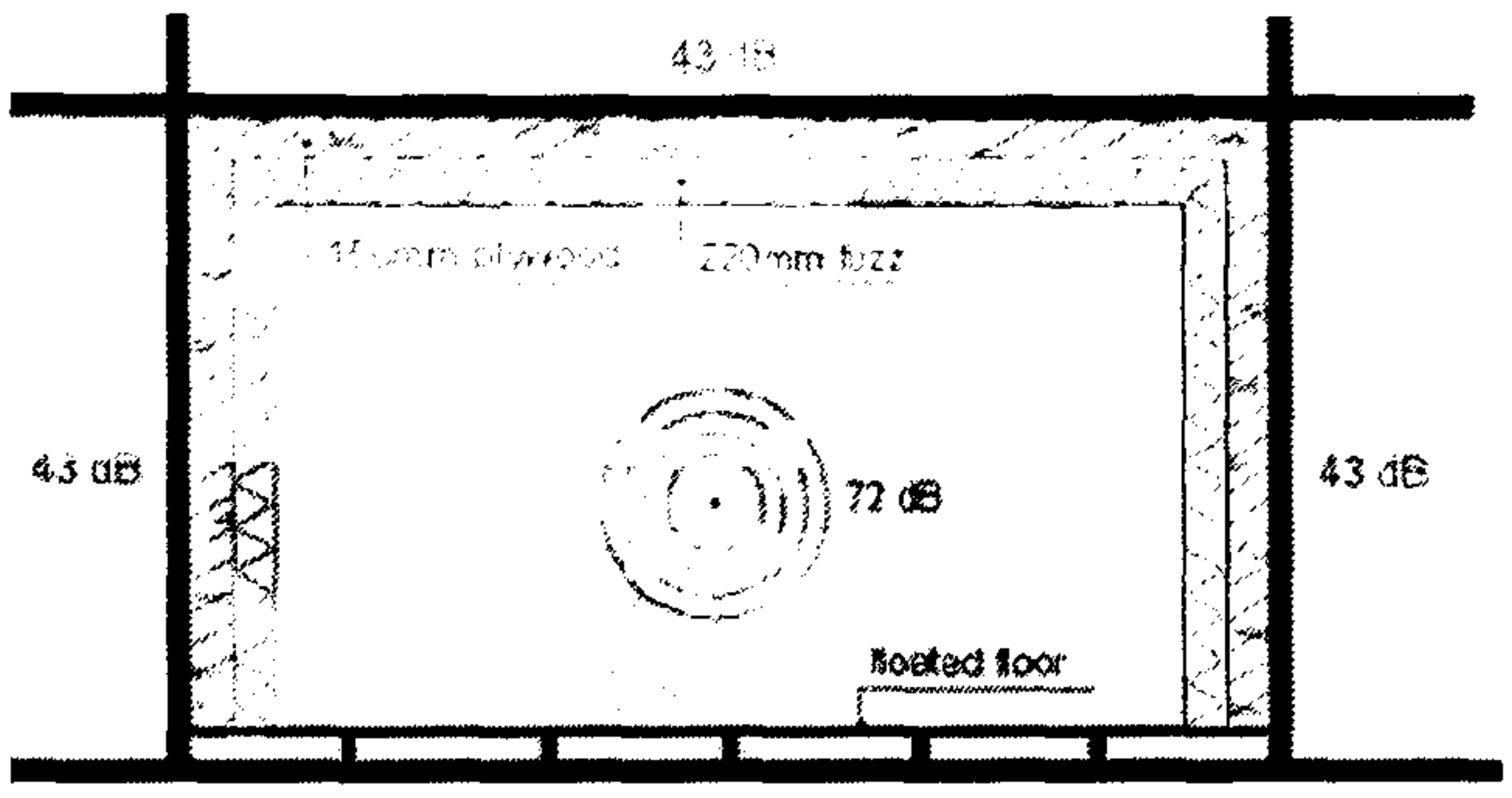

Figure 2.27 Special treatments for noise isolation

Isolation of mechanical room Layout of rooms in a proper way is an important aspect of the reduction of noise. The sensitive space or room can be carefully located and separated from intruding noise both from the outdoors and from within the building. Especially in the case of mechanical service rooms within the building, as from being placed far away from the main spaces when the building is designed, special measures can be taken in order to enclose the noise it produces, such as the use of a heavyweight wall or floated floor. In addition, with sufficient floor space design, the air duct and piping can be designed to take smooth turns so that turbulence will be less likely to occur. The effect of a special treatment for noise isolation is shown in Figure 2.27 [29, P173].

High mass noise isolation This can be provided always by the heavy and solid partitions and by ensuring that there is little or no direct air path. The heavier the partition, the more difficult it is for the air pressure waves to vibrate it and the greater the separation is. For example, a noise level drops by more than 12dBA when it comes through a dense concrete wall of 600mm as compared with that of a 150mm thickness [29, P179]. The use of heavy construction to achieve effective isolation is the fundamental principle architectural acoustics in order to control noise.

Crack sealing Openings or cracks in the building construction may provide a connection that allows for noise to travel through the rooms and spaces regardless of how small these weak points are. [29, P182]. Sometimes, the noise leak from these cracks may greatly weaken the quality and quantity of any noise control strategy. The proper sealing of openings or cracks in building construction is vital to the isolation of noise.

Sound-absorbing surface When noise energy strikes a room surface, the ratio of reflectance to absorbance is greatly affected by the properties of the surface. Normally, the effect of adding sound-absorbing treatment to rooms is very significant. Porous material is a good acoustic absorber, for example heavy curtains. These allow the pressure noise wave to be absorbed into the surface, thus converting sound energy into heat, while membrane absorbers convert noise energy into vibrations in the panel facing. A sound absorbing surface can reduce noise by 6dB in a room with an area of less than 45m^2 if the noise is far away [29, P41].

2.4.3.2 Noise Rating with Space Usage

In order to protect occupants from adverse noise level exposure both from outside and inside the building, much work and research has been done on the built environment relating to noise control. Initially, the exterior acoustic environment is usually measured in order to evaluate the general situation and then based on the building function, the performance standard required for building construction and structure are designed to arrive at the most cost effective means of creating the satisfactory interior. The important elements such as glazing, material, caulking standards etc. are normally considered in a very detailed process of analysis.

Room usage	**dB**
Auditorium	20
Conference room	25
Bedroom, hospital ward, cinema	30
Living room, lounge	35
Library, private office	40
General office space, restaurant	45
Cafeteria	50
Noisy computer room, games hall	55
Typing office	60
Workshop Factory (depending on process)	65

Table 2.12 Suggested noise level value at 1000Hz

A single-figure description called 'noise rating' is used to evaluate existing situations by measuring sound levels to describe the level of noisiness. This can also be used to specify the acceptable noise level in a space, as a given brief to achieve the satisfactory acoustic environment design [4, P154]. Provided levels are varied depending on the listening requirement of the target usage. For several cases, Table 2.12 gives the recommended and suggested criteria values all at 1000 Hz [1, P173].

2.5 Summary

In this chapter, the analytical treatment of the indoor environment has mainly concentrated on the thermal, luminous and acoustic aspects of architecture. In order for the information to be relevant and accessible, it helps to study the effect of overall environmental issues on occupant perception and preference with regards to the building. The interactions between building environment and occupant sensation from the review of this section are summarised as follows:

- The presence of hills, valleys, slopes, streams, paving, plants and other features create a unique microclimate based on the local climate. The built environment is generally influenced by the microclimate systems around the site area; at same time, the building itself creates further microclimates in the local area.

- Solar radiation, wind and noise pollution sources can be directional at a specific point on the earth. Site planning can affect the solar heat, daylight penetration and overheating, glare and noise control in the initial and fundamental stages. Once the building orientation and room arrangement are chosen, these factors are all determined up to a certain level.

- The window glazing is a breach in the enclosing skin of the building. It performs a quite complicated multi-purpose function with conflicting requirements. The demand for daylighting may require a large sized window while thermal performance prefers a small one. The issue of the view from the window may argue for high and wide windows while the structure prefers narrow ones. Noise control and privacy may require a high sill levels with sealed windows while the need for ventilation demands an adjustable opening.

- The materials used in architecture are made from a wide variety of raw materials combined by the use of advanced techniques. They further modify the indoor environment by way of thermal insulation, light transmission and reflection, noise absorption and sound reflection etc. These properties are relevant to many situations, thus different balances of these properties are required in order to be acceptable for different purposes.

- The development of mechanical and electrical plant for heating, cooling, ventilation and lighting has made it possible to provide closer control of internal temperature and comfort than can be achieved by natural means. In most buildings, it allows for the simultaneous adjustment of the immediate environment in accordance with the conditions required by the occupants of the space. When the building form, fenestration and materials are balanced well with HVAC and lighting, they can interact with each other resulting in optimal environmental performance.

These five building elements play a substantial role in the overall architectural environment. Based on the analysis from this chapter, the next chapter will focus on the building in a detailed and integrated way to indicate how building design can affect the indoor climate with special attention paid to environmental control strategy.

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Chapter Three

Building Environmental Control

House design has reflected, throughout its history, the different solutions advanced by each period to the continuing problem of securing a small controlled environment within a large-scale natural setting – too often beset by adverse natural forces of cold, hot, wind, water and sun.

\- V.Olgyay, 1963

Chapter Three
Building Environmental Control

3.1 Introduction

The preceding chapter provides an overall view of environmental issues, which are primarily in the domain of architecture and related to occupant sensation and comfort. This chapter will be more specifically focused on how building design strategies affect the indoor environment. From Olgyay [1], a simple but elegant model serves to illustrate the essence of environmental control potential (Figure 3.1). The biggest varying quantity occurs in the macroclimate situation, which displays the highest amplitude. This is influenced primarily by the site's latitude, longitude, altitude, topography, the relation to water or land mass and the pattern of vegetation. Furthermore, the building utilizes its landscape, envelope and fabric in order to control heat, air, wind and daylight so that the variations of temperature, moisture, light and noise can be smoothed over. Since the building envelope and fabric elements can not ensure comfort all year round and all the time, it is necessary to correct the environment, backed up by the installation of artificial lighting, heating and air-conditioning systems to produce a stable comfort level whenever necessary.

In this study, how landscape, envelope and fabric affect the built environment in a natural way will be explored in detail. The mechanical control that has been briefly discussed in the previous chapter although is also important will not be further pursed due to its being primarily an engineering undertaking. In this part of the analysis, the control strategies are grouped into three aspects: building landscape, form and envelope. In each part a number of them will be examined along with a discussion of their basic principles, performance, and practical examples. For the sake of brevity and simplification, some methods requiring sophisticated mathematical skills have been abbreviated or eliminated [2, P1].

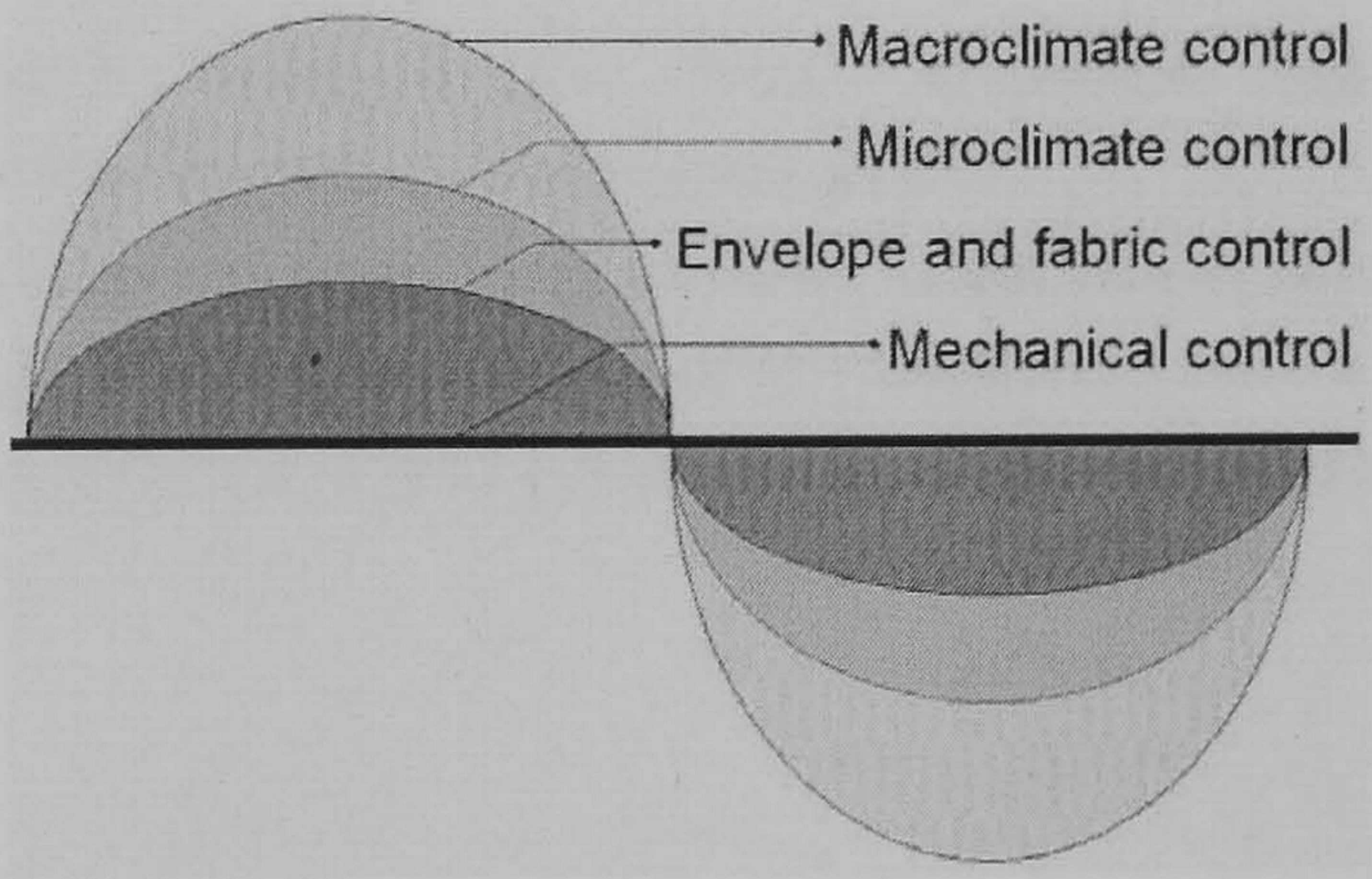

Figure 3.1 Potential of environmental control

3.1.1 Environmental Control

A tight and sealed space capsule creates a totally separate and highly controlled interior environment for people to stay in by means of all kinds of advanced life-support systems which make for stable and ideal conditions, completely independent of the outdoor environment. Most of the buildings, however, are not normally in such extreme or hostile environments. Their envelopes and fabrics can either by themselves or combined with mechanical systems provide a comfortable indoor environment. Hawkes (1970) makes clear the difference between buildings that rely predominantly upon mechanical plant to create controlled, artificial environments and those that use ambient energy sources in creating natural environments. The former he dubs 'exclusive' and the latter 'selective' [3, P11]. In terms of the effective control of comfort distribution, the system can be categorised according to two aspects: active and passive control.

The biggest advantage of the former is its 'exclusion'. It satisfies the environmental demand without being subject to seasonal variation, while the latter is characterised by the natural phenomena commonly taking place, and not by the mechanical technology used to mitigate these phenomena [4, P63]. It sometimes uses a very small amount of conventional energy to enhance the efficiency of distribution. Because the passive control system largely makes use of the ambient energy, the requirements of the buildings are much harder to control due to the diurnal and seasonal variations of climate, as well as other temporal and changeable weather variables. Flexible adjustment has to be made between air, humidity, and heat flux in order to achieve balanced conditions. All these require the correlation of heat and air flux with local weather conditions and other factors inherent in the site, design, and building materials [5, P62]. Generally, any cursory exploration of this concept can be split into three different levels:

- Microclimate environmental control includes the local landscape and topography, such as outside surface characteristics and vegetation etc.
- Building control relates to the location in relation to the sun, wind, noise and neighbouring buildings such as building form, shape and orientation etc.
- The third relates to specific details of the building envelope such as materials, fabric and structure [6, P31].

3.2 Landscape

The physical processes that dictate macroclimates such as solar radiation, wind direction, or light transmission can be modified on a local scale by variations in landscape. The presence of dense woodland, a group of buildings or a small hill can all interact with the general climate of the region and cause local variations. In this part, three aspects of the local landscape that affect the built environment are discussed: the reflectivity of surfaces, the vegetation and the unique environmental style that is integrated into its site landscape – the earth berm.

3.2.1 Reflectivity of Surface

Solar radiation is the main source of light and heating when it is above the horizon. Although the seasonal and latitudinal distribution and intensity of solar radiation received at the earth's surface varies greatly, changes in winter and summer tend to be offset. This leads to the annual average received at any given location being nearly constant [7]. However, even if the same amount of solar radiation reaches the ground, the temperature of its surface can be quite different due to its ability to reflect the incident solar energy. For example, a black surface can experience a temperature rise of 50°C in full sun, while a white one rises by just 8°C in the same conditions [8].

Colour code	Solar reflectivity
Very light	0.75
Light	0.65
Medium	0.45
Dark	0.25
Very dark	0.10

Very light: smooth building material surfaces covered with a fresh or clean stark white paint or coating

Light: Masonry, textured, rough wood, or gravel surfaces covered with a white paint or coating

Medium: Off-white, cream, buff or other concrete block, or painted surfaces and white-chip marble covered roof

Dark: Brown, red or other dark coloured brick, concrete block, painted and roofs with gravel, red tile, or brown shingles

Very dark: Dark brown, dark green or other very dark coloured painted ,coated, or shingled surfaces

Table 3.1 Suggested colour-reflectivity classification for building materials

Therefore, the fraction of incident solar energy reflected by the surroundings and the exterior elements of a building significantly affects the overall thermal and luminous environment of the building's room. The material's ability to reflect solar energy is measured by solar reflectance, also called 'albedo'. It includes the visible, infrared and ultraviolet wavelengths on a scale of 0 to 1. A solar reflectance value of 0 indicates that the surface absorbs all solar radiation, and a value 1 represents total reflectivity. Generally, the different materials and coatings are conveniently classified in the different colour-reflectivity groups and given in Table 3.1 with 'light', 'medium', and 'dark' categories [9, P83].

Depending on the design purpose, the selection of the solar reflectance properties of the surroundings and its own envelope surface can be used to modify the thermal and luminous requirements. A material with low reflectance and high absorbance not only weakens illuminance strength, thus eliminating the risk of glare, but also reduces the building heat transfer to the interior and thus minimizes the heat load. Conversely, for the surface of the building, it requires a light painted coating to reflect as much solar radiation, especially in hot climates. For example, Givoni and Hoffman once performed experiments in Israel on buildings with exterior surface of different reflectivity ratios. These proved that unventilated buildings with white walls were approximately 3°C cooler in summer than the same buildings that were painted grey [10].

There is also a risk associated with achieving reflected radiation at a minimum through locating low reflectivity material. The heat absorbed by the surface material can make air temperatures outside much higher than most other light surfaces. In this case, lawns, shrubs or water pond, fountain can be adopted because they not only have highly absorptive features but also provide an evaporative air-cooling effect. Generally, in the daytime, a hard pavement is much warmer than grass or other soft ground surfaces, while at night pavements become much cooler. Therefore, hard surfaces normally display a larger diurnal swing than soft surfaces [9, P90].

3.2.2 Vegetation

At a microclimate scale, vegetation represents a first line and quantifiable measure of the improvement of solar heat, wind, skylight and noise filtering. This vegetation, for example trees, plants, shrubs and lawns etc. has a pronounced effect on the site's climate, not only on the existing open space but also on the building environment [11].

Vegetation forms an intermediate layer between the surface of the earth and the atmosphere. The most obvious benefit of vegetation is its shading ability. A dense cover of plants can intercept the sun's radiation before it reaches the ground and building skin, thereby reducing the surface temperature and the amount of heat transferred into the interior [9, P165]. It is estimated that the air temperature below trees in the shade is 3 to 4°C lower than the ambient air temperature which is also in the shade [8, P158]. Furthermore, its evapotranspiration can also convert solar heat into latent heat thus reducing the dry-bulb temperature. For example, in summertime non-evaporating surfaces can easily exceed 70°C, but in the shadows cast by trees they may not rise above 35°C, which shows that they can great alleviate the situation [12, P76].

Normally, deciduous trees are a highly recommended choice for the control of solar gain because they can perform the dual function of offering an opaque screen in summer to avoid excessive temperature, while, in winter, when the sun is welcome, permitting solar energy to reach the building and surrounding area because of their leaflessness (Figure 3.2). However, in many practical instances trees do not follow the calendar, especially in temperate climates, and may cast too much shadow in winter and not enough in summer. Thus the right trees must be suited ecologically to the site, especially the deciduous trees, which must satisfy certain criteria: how long they are in leaf and how transparent they are to solar radiation both in and out of leaf are are key questions that

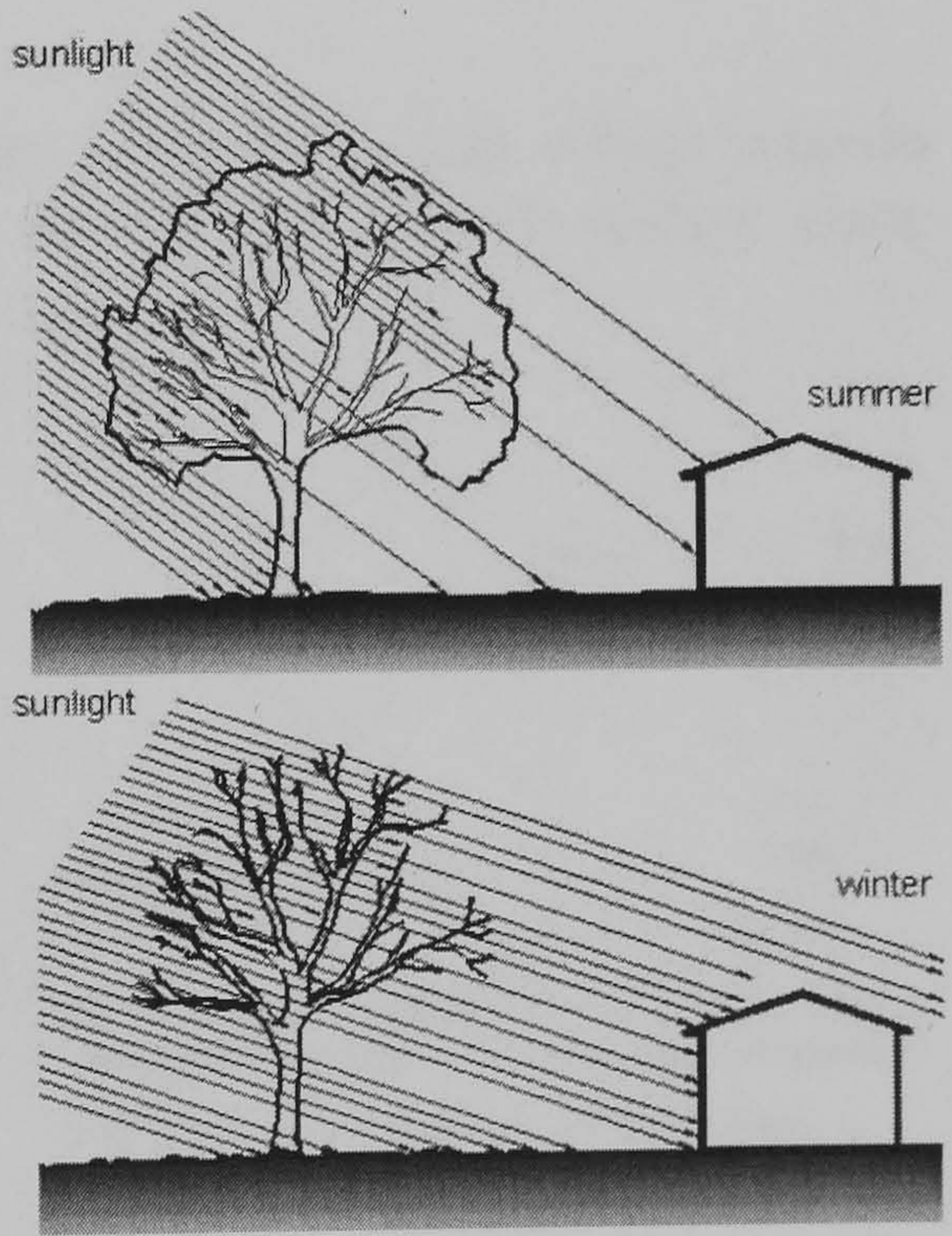

Figure 3.2 Building surrounded by deciduous tree in winter and summer

that need to be asked when selecting tree-types. For example, the majority of UK trees are beginning to come into leaf by mid April. By mid May they are in full leaf, with single trees typically allowing through only 18% of the solar radiation incident upon them. By mid September the majority of trees are beginning to lose their leaves, a process which is complete by mid October. When out of leaf, the trees typically allow through 65% of the solar radiation incident upon them [13, P33].

When a tree is located besides a building, the strength of winter-time passive solar gain and year-round skylight is unavoidably reduced up to a certain point no matter whether it is deciduous or evergreen, which makes the total loss even worse. The elm for example, can block out 85% of the sun's radiation when in leaf in summer and block out 35% in winter [14, P59]. This can be a strong argument especially with short day lengths in winter. Depending on the design, there tends to be a quite reasonable compromise between the amenity value of the trees and their functional role as windbreaks and solar screens.

Wind movement around buildings can be both a benefit and a nuisance. Wind with an acceptably low speed can provide the necessary ventilation for the exchange of air, and increase the convection currents needed to 'wash' away the boundary layer of heated air, while strong winds, on the other hand, always cause heat loss and noise. While wind picks up speed when its travel is unhindered, contact with any surface will create drag and slow the wind down and, thus, the coarser the surface the greater the drag and slowing effect is. Vegetation including rows of trees, lawn, shrub and plant contributes to its roughness thereby slowing down the wind as it passes over and through these cultivated areas (Figure 3.3) [12, P74].

When protection from the wind is the main consideration, trees do little to help because the tall trunks allow for a free passage of wind near ground level. Therefore, lower evergreen shrubs around the building may be considered in order to act as shelters, screens or fences. Compared with the lower solid walls, which are often used as windbreaks, the natural features of plants are better because they allow some air to pass through, which enhances their performance as they are able to prevent a rapid change in wind gradient from the ground upwards. In general terms the windbreak belt can be expected to work as a shelter when the distance from it is up to about 10 to 15 times its height [15, P151].

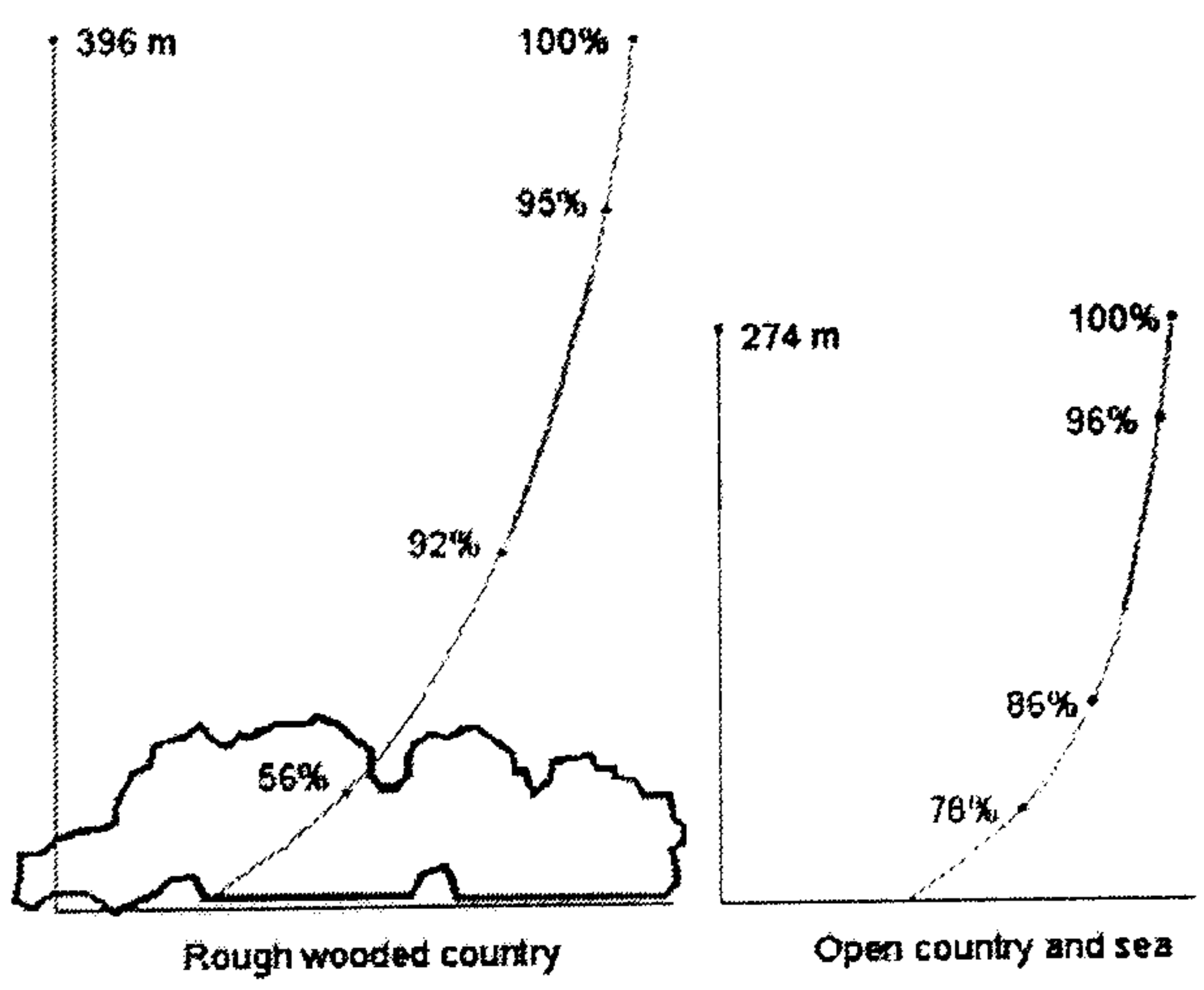

Figure 3.3 Wind velocity and surface roughness

Another feature of soft ground cover is that it is permeable, thus reducing water run-off and allowing ground water to be replenished. This advantage, along with additional plant transpiration can often produce a considerable amount of humidity. This is true especially in hot and arid climates with relative humidities over a long period below 40% where additional means for the humidification of the environment are normally desirable for comfort and health [8, P185].

Moreover, it is well-known that vegetation absorbs carbon dioxide and releases oxygen as part of the photosynthetic process. At present it is also been proved that many plants such as the peace lily, the bamboo palm, English ivy, mums, and gerbera daisies etc. have a filtration system which has the ability to absorb benzene, formaldehyde and trichloroethylene, all of which are hazardous to health in some degree [16]. In these cases, the plant can also be regarded as way to cleanse the atmosphere and thereby improve the air quality of the built environment.

3.2.3 Earth Berm

Earth-bermed construction or built up earth in contact with perimeter wall fulfils the requirements of many climatic design strategies, including thermal control, wind protection, the stabilization of moisture effects on materials, and protection from other extraordinary stresses such as brush fires, tornadoes, and excessive noise [9, P104].

Soil is a very good moderator of temperature due to its density and specific heat capacity, which gives it thermal insulation properties and a high capacity for retaining heat. The deeper the soil, the less sensitive it is to potential thermal perturbations. The high thermal mass of the structure and the surrounding earth is another distinguishing feature. This delays and dampens the effect of rapid fluctuations in temperature and typical day-night temperature swings. Even at night, when a net heat loss occurs, this heat is radiated back into the space. The process can be slow enough in a structure that has a large mass to supply adequate heat to the house for several hours (Figure 3.4).In other words, by reducing thermal fluctuation of the outside envelope surface and by increasing its thermal capacity, the high thermal mass contributes to the cooling of the spaces during the summer and to the increase of the heat during the winter.

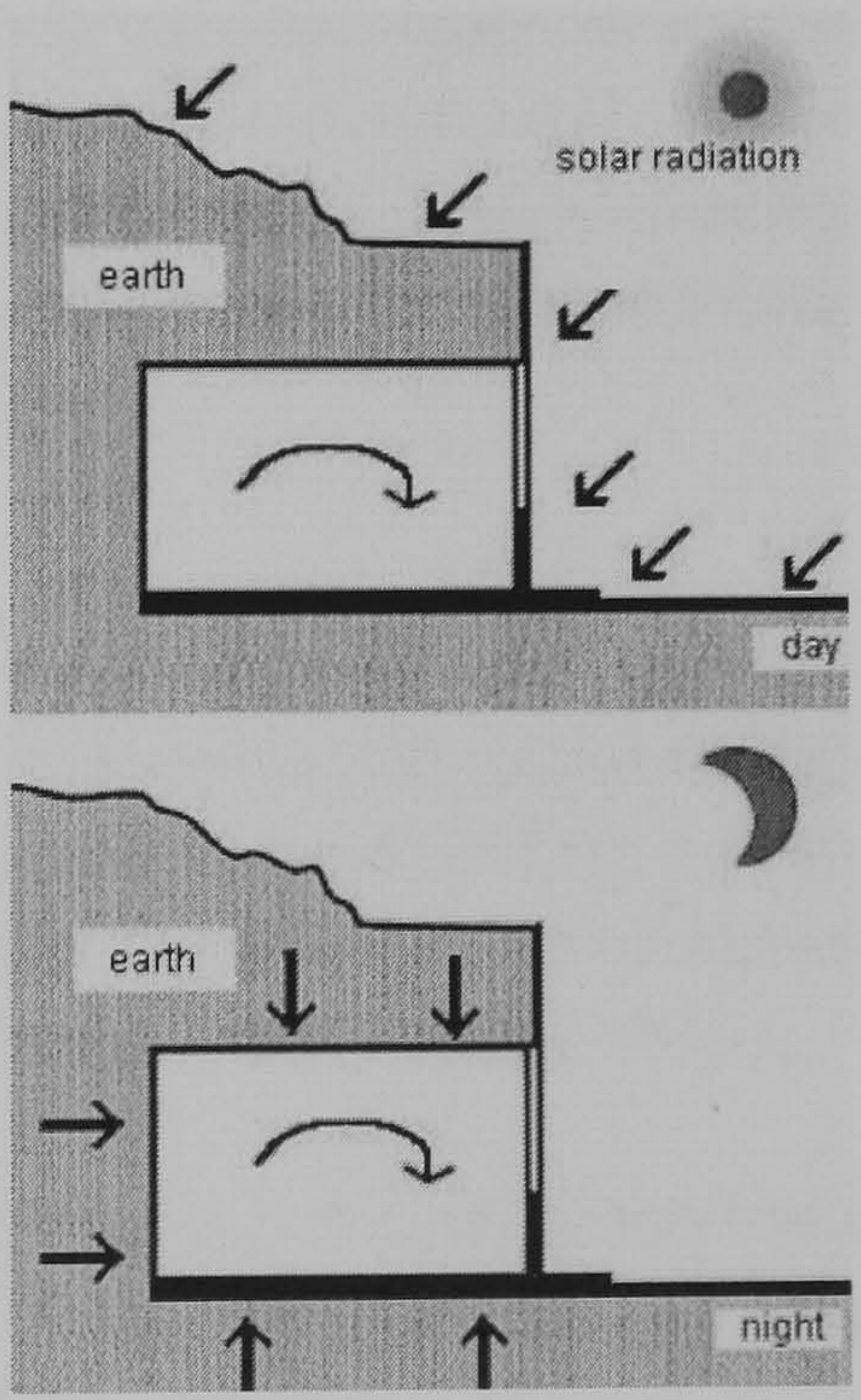

Figure 3.4 Thermal mass of earth-bermed building

Another earth-bermed feature, which is unique in terms of aboveground structures, is the lower level of heat loss due to infiltration. A conventional aboveground house, no matter how good the insulation, loses about 25-40% of its heat through air movement, structure and openings, windows and doors – a process that is accelerated when the wind blows. The earth, which is placed against walls and on top of the roof can protect an earth-bermed house from strong wind and infiltration, which results in both heating and cooling load reduction [17].

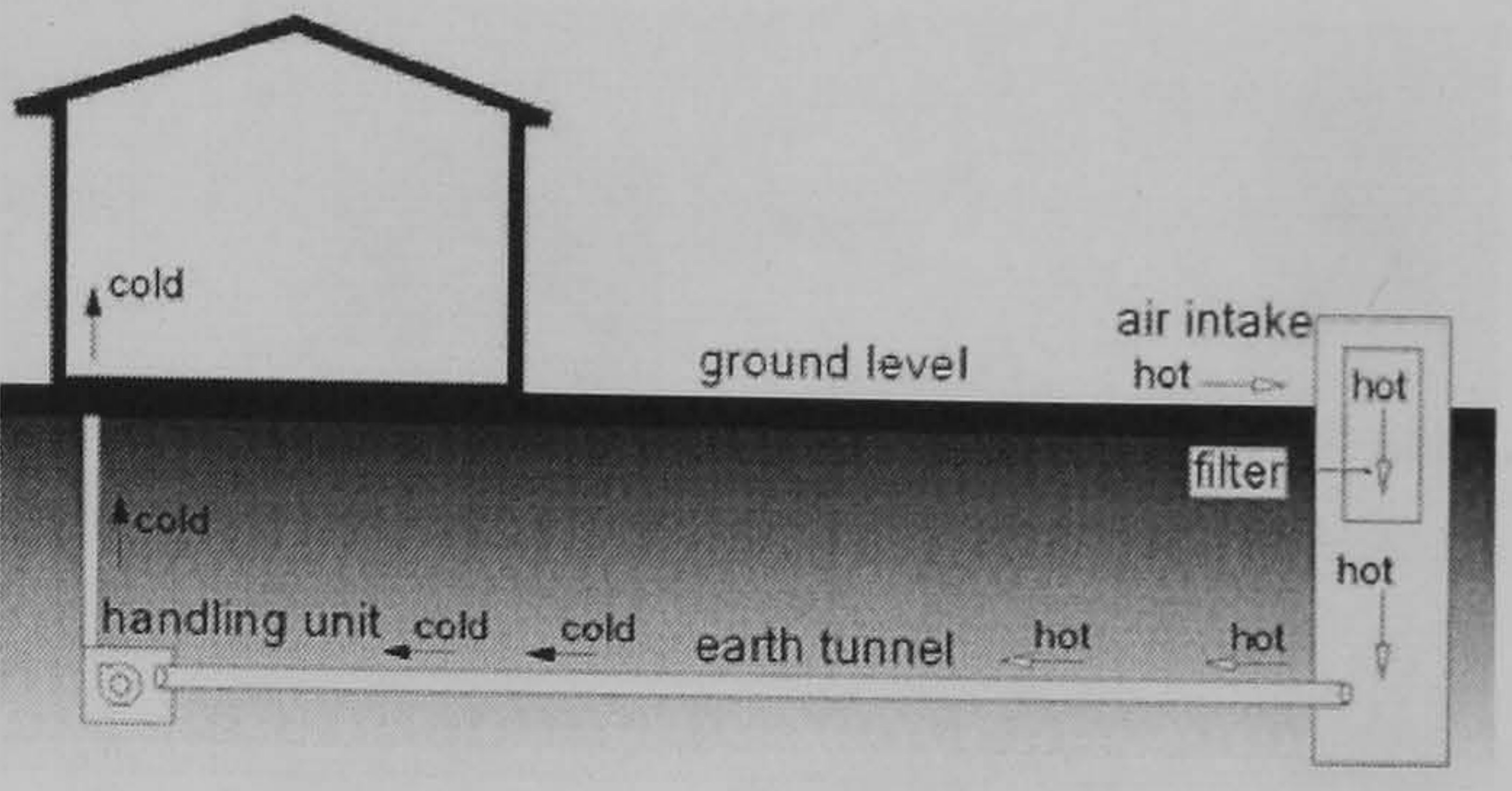

Figure 3.5 Schematic of earth-air-tunnel system

In addition, the deep underground soil can also be a cooling sink, thus developing another typical design strategy: earth-air-tunnel. The method here is to install air pipes in the soil, and then circulate air through them. The air is blown by a fan-driven machine into the imbedded tubes and pumped in amounts that allow sufficient contact time for the heat transfer from the air to attain a much lower temperature than ambient air thereby producing a cooling system (Figure 3.5). During a heat wave with abnormally high outdoor temperatures, the cooling effect can be even greater. For example, an 80m earth tunnel is potentially adequate to the task (19 kW) of maintaining an average room temperature 27.65°C [18].

3.3 Building Form

The term ‘building form’ encompasses the building elements, materials and associated landscaping of the site [6, P31]. There are many factors that have an influence on the form of a building, and, of these, function is a major consideration. In terms of environmental control, the building form normally refers to its interaction with the outside environment: exposure to incident solar radiation, availability of natural daylight, and air flow within and around the building. Broadly this involves enhancing and/or avoiding heat, cold, air movement and sound control. Three aspects are discussed specifically: shape, orientation and a special building form – the atrium.

3.3.1 Shape

Indoor air and surface temperatures change with the rate of heat flow through the building envelope consisting of opaque and transparent components [19]. Given the fact that natural light is to be the main daytime source, the effect of plan depth on light penetration is of profound influence. This also concerns the effective natural ventilation from one side. All of these factors inevitably have an influence on the building shape.

The fabric heat exchange between the outside and the envelope is directly proportional to the surface area. Therefore, any changes to the form that increase the surface area exposed to the air outside will result in an increased heat exchange rate [33]. If the shape of a building of a given volume is optimized, taking the minimum heat exchange as the key criterion, the hemisphere is the most efficient shape. However, with an additional restraint introduced, a cubic building form is included among those regarded as efficient shapes. In order to specify this concept, the surface to volume rate is defined as the ratio of the area of external walls with respect to the volume of the building. Figure 3.6 compares the ratio of four buildings with the same volume but different floor plans thus leading to different surface areas. It can be seen that the three shapes have 16.7, 25.0 and 41.7% more surface area respectively than the one with a square plan [13, P30]. It is advisable to present the lowest possible surface area for a given volume because it can offer advantages for the control of both heat losses and heat gains through the building skin without conflict between design priorities for winter and summer conditions [20, P97]. Other strategies may accompany this such as additional insulation and attached buffer spaces to offset the heat loss due to increased surface area.

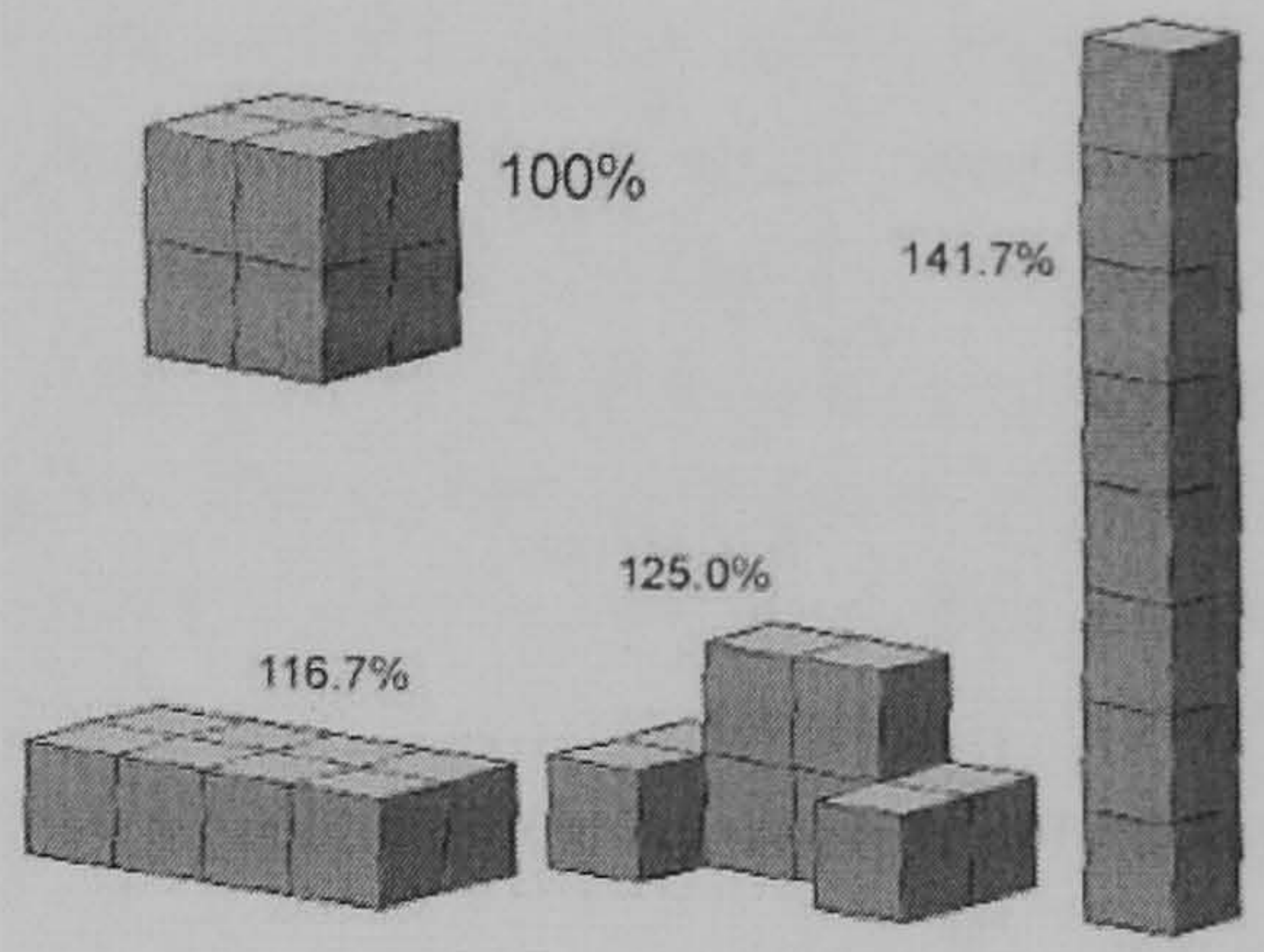

Figure 3.6 Surface-to-volume ratio of buildings with same volume

On a domestic scale, heating dominates total energy use. But in a large building, the lighting and ventilation take on an increased level of importance. Making allowance for the difference of function and activity patterns, this can be partly explained by the great decrease of surface-to-volume ratio (Figure 3.7). Here the volume is increased several times, while the ratio has fallen from 100 to 25%. In practice, this means less space is in contact with the outside environment via the external surface, and as a result is poorly supplied with daylight, ventilation and solar gain [13, P40].

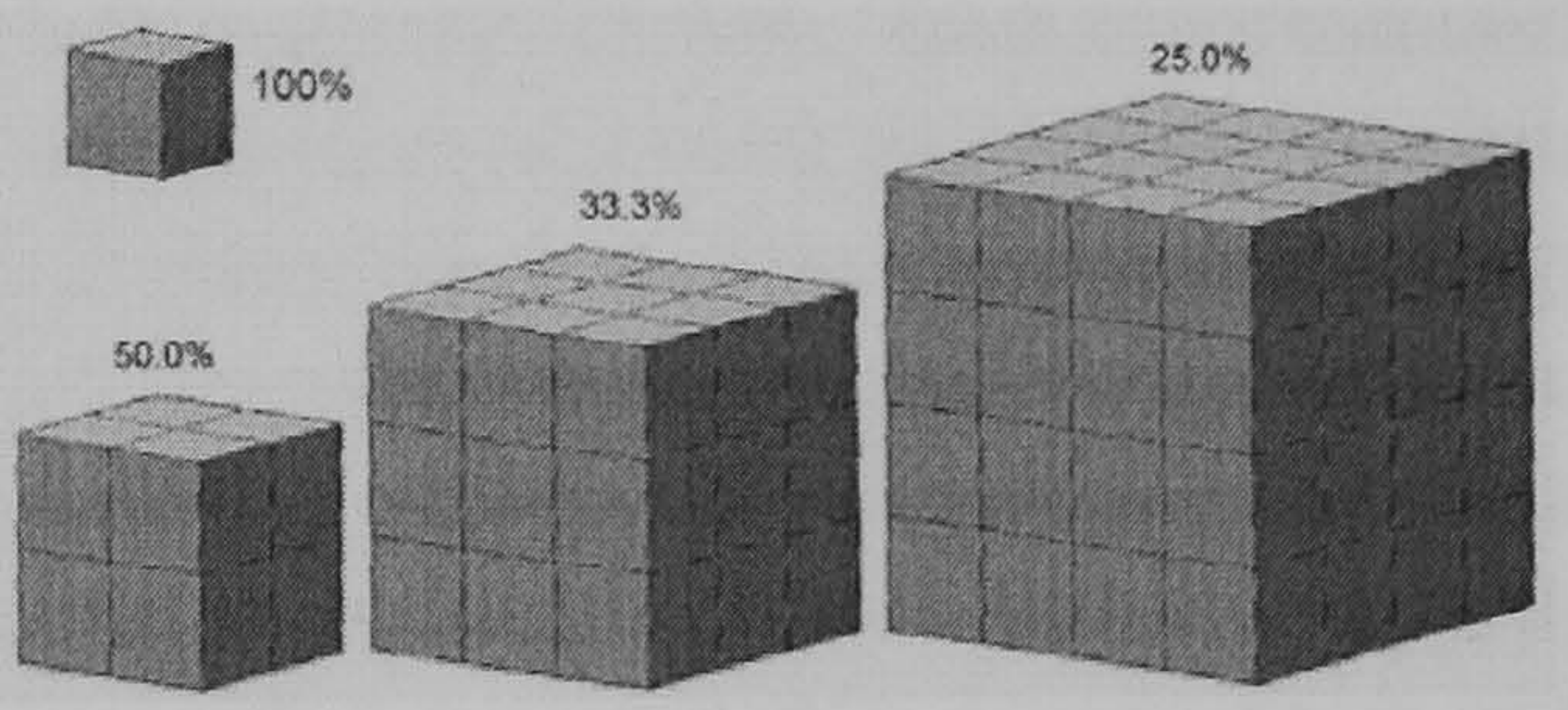

Figure 3.7 Surface-to-volume ratio of buildings with increasing volume and same shape

In order to promote natural ventilation, the internal plan form of the building has to be kept as simple as possible. Open-plan spaces are the best as they offer little resistance to air flows, whereas highly partitioned spaces reduce the ability of the air to flow across or up the building [15, P107]. It is generally accepted that a place up to maximum 14m deep from opposite side openings is able to take advantage of natural cross ventilation, while it is still possible to extend the depth by making the ceiling higher. An 8m high space can in theory be 40m deep [15, P55]. But this is not recommended due to the ascent of warm air towards the ceiling. As a result a tall space may experience temperature gradients between floor and ceiling and increase the ventilation heat loss as well [13, P43]. Depending on the design, compromise has to be made, but building depth is not more than about 5 times the floor-to-ceiling height [21, P112].

If day lighting is prerequisite of the design then the depth, shape and space of the building are largely governed by penetration considerations. The more opening areas there are the greater the number of places can be provided with daylight. However, in terms of energy exchange, the influence of this effect may be positive only in a period or phase, because although large openings improve the luminous environment of the building room, its heating loss and gain may start to have a negative effect on the thermal environment as well. It is suggested that a depth of about 6 or 7m deep ought to be regarded as the upper limit for the floor slab to have effective daylight penetration and natural ventilation from one side [22, P43].

3.3.2 Orientation

The orientation of a building is important, mainly with regard to solar radiation and wind. Either the solar radiation is required in predominantly cold regions, or, conversely, where other conditions apply, regarded as undesirable. However, both situations can arise periodically when and where seasonal changes are very pronounced. Similarly, winds can be either desirable or unwanted. Quite often, a compromise is required between sun and wind orientations. But with careful design, shading or deflecting devices can be incorporated to exclude the sun or redirect it into the building, in the same way that as much wind as possible can either be received or diverted [8, P8].

3.3.2.1 Sun

On a daily basis, as the sun rises, the air temperature increases. Heat is transferred directly via the building envelope. As the sun sets the building starts to cool. The following day the cycle repeats itself. Environmental control strategy is ultimately an approach that integrates a building's features, elements, materials and components to best take advantage of the sun's energy in the design of the built environment. Given a proper building site, virtually any type of building can integrate solar energy when the apparent movement of the sun with respect to the site is recognizable at each significant times of the year. This is because the path of the sun varies with the seasons and the latitude. The intensity of solar radiation incident upon any surface of a building is directly related to that path, and dependent upon the same variables. Access for it into the building can be provided simply by a window, an atrium or a solar collection device. On the other hand necessary strategies can be applied as well to mitigate the effects of overheating and sunlight glare [23, P29].

Orientation		Spring / Mar.	Summer / Jun.	Autumn / Sep.	Winter / Dec.
South	G_r	2.53	2.81	3.11	1.03
	D_r	1.09	1.96	1.38	0.28
East / West	G_r	1.75	3.21	2.29	0.45
	D_r	1.03	1.94	1.28	0.29
North	G_r	0.93	2.18	1.14	0.27
	D_r	0.93	1.87	1.14	0.27

G_r: average global solar radiation; D_r: diffused radiation (kWh/m^{2}d)

Table 3.2 Average global solar radiation

Correct orientation is critical

if the maximum thermal advantage is to be taken from solar heat gains. For example, Table 3.2 shows the values that refer to the global solar and diffused radiation in Germany under a clear sky in four seasons [24, P181]. The amount of solar heat which reaches the south of the building envelope during the heating season is substantially greater than for any other orientation. Therefore, it is desirable that the long axis of the building lies east and west thus enabling the envelope surfaces and openings to receive more intense radiation and sunlight on the south side [8, P81]. On the other hand, if the levels of solar heat and sunshine are not desirable, the spaces can be located towards the north side in order to avoid direct contact with sun.

The term ‘aspect ratio’ is often used to denote the ratio of the longer dimension of an oblong plan to the shorter. In most instances the north and south walls are longer than the east and west ones, with a ratio around 1.3 to 2.0, depending on temperature and radiation conditions. This can be optimised in terms of solar incidence and wanted or unwanted solar heat gain or heat dissipation [12, P64]. Wherever possible, non-heated spaces should shelter heated ones, and, if possible, the structure should be arranged to avoid self-shadowing where passive or active solar gain may be used [25, P67].

3.3.2.2 Wind

Buildings with stubby and unstreamlined bodies are normally nearly non-permeable structures through which no wind can pass. When wind hits a building, it moves around and over the building, and then develops a zone of positive pressure on the windward side, whilst a zone of negative pressure on the leeward side is generated. On the sides parallel to the wind the flow separates at the edge facing the wind, which leads to the formation of a negative pressure peak (Figure 3.8) [22, P36]. In this way the wind speed can be translated into wind pressure, which, in turn, acts on the building. Very approximately the pressure on the windward face of a building is about 0.5 – 0.8 times the velocity pressure of the wind, and on the leeward side the negative pressure is about 0.3 – 0.4 times the same pressure [14, P123].

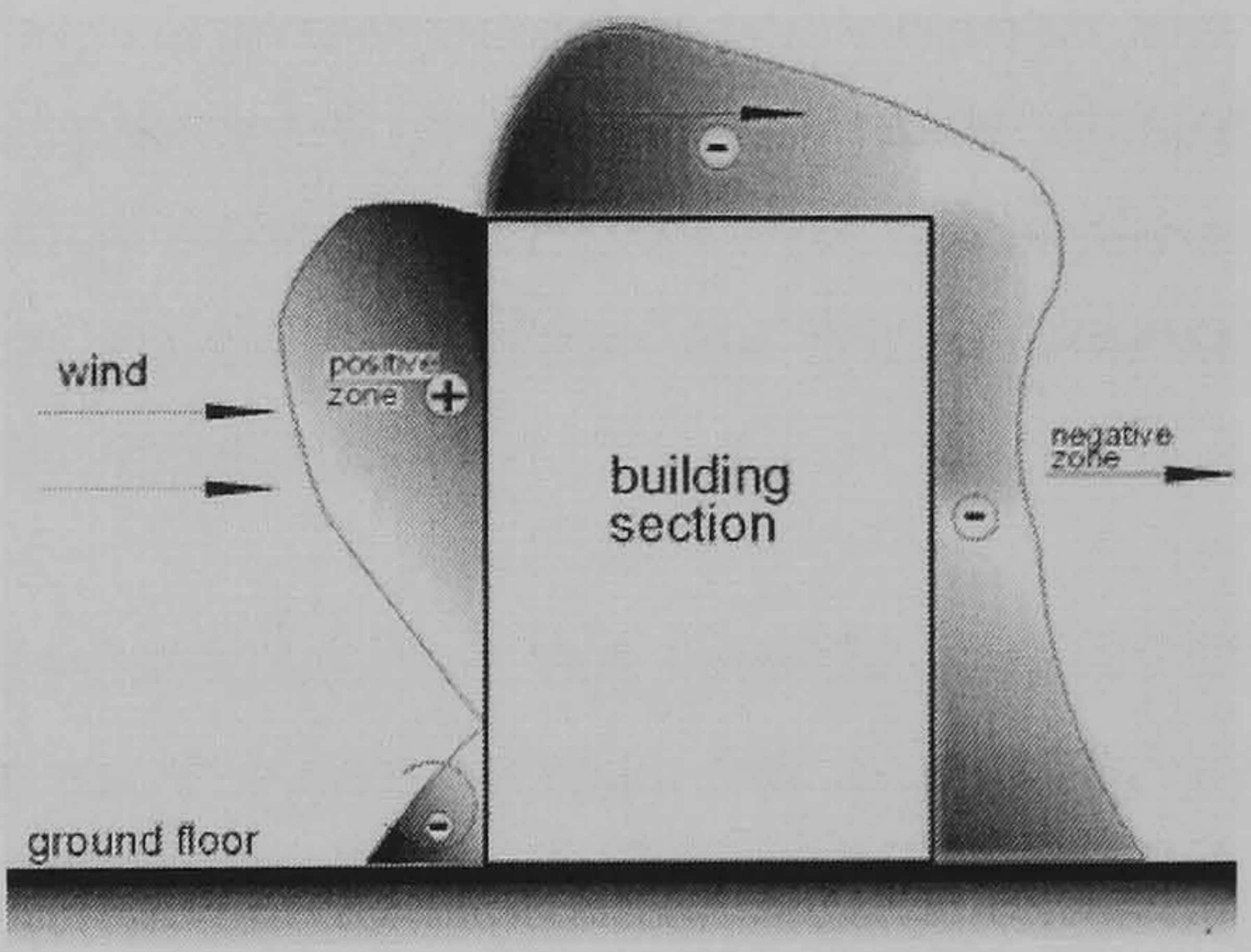

Figure 3.8 A typical pattern of pressure distribution of wind on building envelope

This pressure difference between the windward and leeward sides can produce benefits but also cause problems. It can be utilized to produce necessary ventilation inside the building through openings. This is especially true in hot summers because the encouragement of air movement in the built environment is a very important and efficient means of keeping buildings acceptably cool.

However, the pressure difference also leads to ventilation problems that the warm air is removed from inside and replaced by outside cold air, representing a loss of heat from the building. As wind speed increases so does the pressure difference across the building. This in turn increases the ventilation rate and heat loss. It occurs more or less on all real-life buildings because building materials are porous and the envelope unavoidably has joints, cracks or leaky window sashes so there is always a fortuitous leakage of air through a building known as involuntary infiltration [13, P29]. If the intention is to minimize the wind impact, the building has to be built in a direction that reduces its interaction with the wind. There are several general principles:

- The fundamental way is to avoid long walls facing the prevailing wind direction, which means the long axis has to be in parallel with the prevailing wind flow. Because of more direct exposure to the wind and/or longer path lengths for the wind to travel along, the likelihood of infiltration increases [26, P77].

- In the case of multiple and high-rise buildings it is advantageous to make the building step back successive storeys, so that large pressure differences across the building are avoided and smooth wind flow around the building is promoted. It is for this same reason that the hipped roof with pitches of 30-45° is better than a flat roof.

- Proper sealing of the building envelope is an important means of removing infiltration routes into and out of the building. If the wind hits a well sealed façade then it will be more difficult for infiltration to take place and the effect of the wind speed on heat loss will be less severe.

- The corner of a building is always the area with the greatest wind speed because here air flow separates and moves around the building forming a negative pressure peak. Therefore, this area is not a suitable location for the entrance doorway because strong wind forces need to be resisted

- The higher the wind speed, the higher the heat loss from the outside surface of building due to convection. So in order to slow wind speed across the site, a group of buildings should not be arranged in a line or lines or long parallel rows as the long channel will offer the wind good opportunities to build up its speed [13, P31].

- The wind flow only re-forms itself at ground level some distance behind a building. This means that the distance between buildings should be sufficiently long, otherwise the building which is beside the lee of another building probably experiences lower or even negative wind pressure [24, P182].

3.3.3 Atrium

An atrium is a large open space running through a multi storey building with a glazed roof or large skylight. Nowadays, the atrium has proliferated and is seen with increasing frequency in new, renovated, and converted public buildings as an integral component. It appears to provide the most attractive of combinations: reviving the indoor space, admitting natural light, simulating the outdoors and increasing interaction between people. It also has the potential to be environment-enhancing and energy-efficient. Their use as a buffer space and as a means of providing natural light and ventilation has been exploited in many large, deep and complex buildings [27].

Although the word 'atrium' can be used to describe the covered spaces that extend to or border the exterior of building or occur between buildings, there are four main patterns in use (Figure 3.9). Depending on the design, they all have their own specific aesthetically architectural features, indoor environment conditions, thermal loads and daylighting performances. The difference between these lies in the number of external surfaces through which daylight can enter the atrium and the arrangement between the atrium and the spaces adjoining it [13, P99].

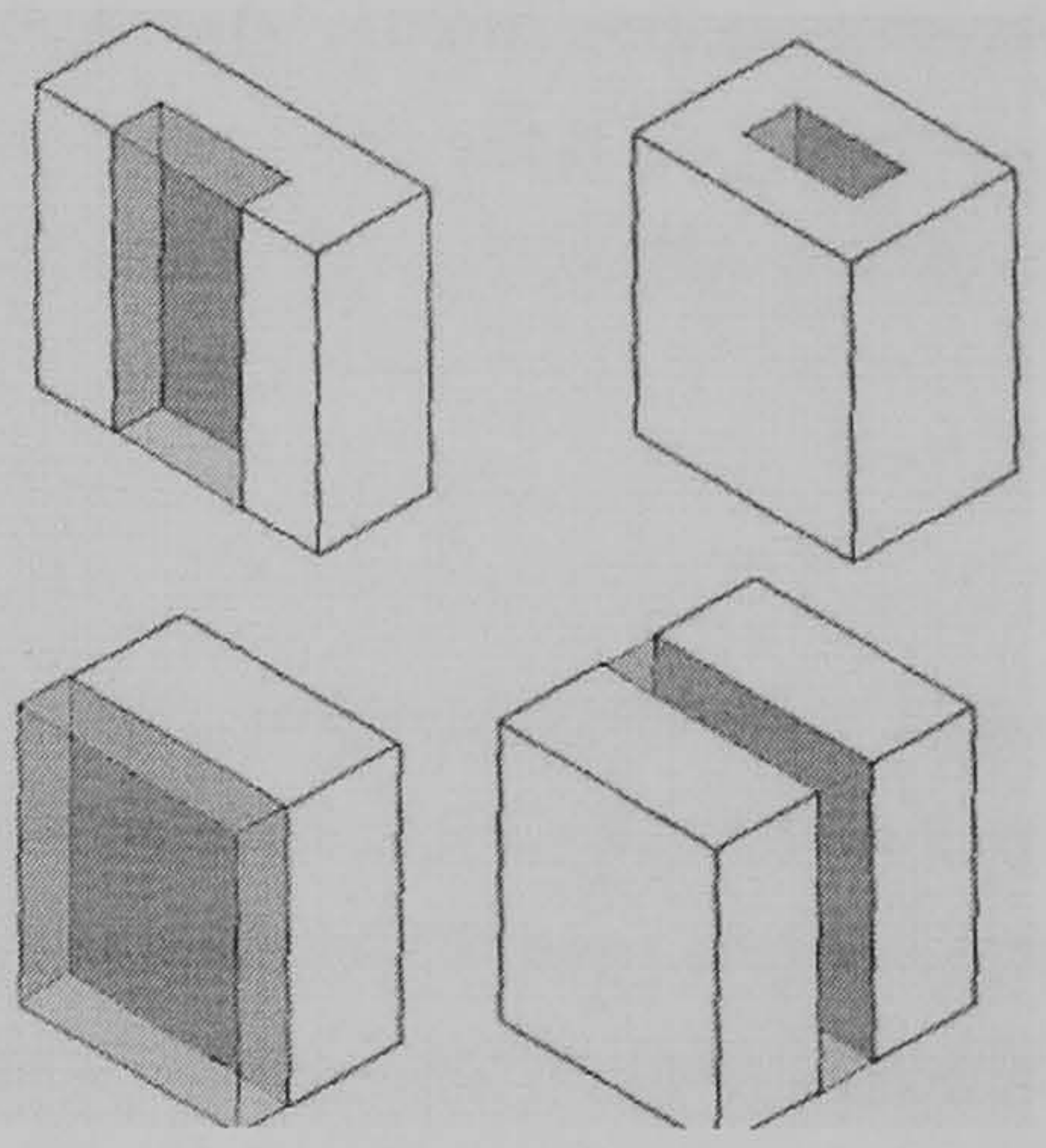

Figure 3.9 Various atrium positions

The transmission characteristics of the atrium shape, form and aperture have a major impact on the availability of natural light entering the atrium and space adjacent to it. There are many factors that affect the degree of sunlight and skylight transmission. Structural elements, bars, smoke damper etc. lead to reduction of available daylight by about 20% between the outside and the inside of the atrium roof. In some extreme cases, the loss may be as high as 50% [28, P40]. If the open space is very high, it is often difficult for the base level to receive enough natural light or, if it does receive enough, it may not do so for a sufficient period of time. In such cases, widening the atrium with successive floors can improve the daylight access to lower floors. If the surrounding spaces at each level also require the atrium to provide natural light, the internal structure of the enclosure has to be finished with light and highly reflective surfaces in order to encourage the daylight distribution inside.

The atrium allows the ventilation to be optimized. The openings are located at each floor level toward the atrium and glazed areas on the roof can be opened in variety of combinations in order to provide a kind of vent with the aim of offering draught-free air movement. In summer, the hot air is allowed to vent naturally to the exterior through the openings, and sometimes a sunscreen is installed with several functions in mind, such as providing shading and reflecting daylight. In winter, the enclosed atrium can work like an environmental buffer space, preventing heat loss from surrounding spaces.

3.4 Building Envelope

Where environmentally responsive approaches are employed, the building envelope itself is the aspect of design that modifies the exterior microclimate as well as the environmental conditions inside the building [20, P1]. The properties of the building envelope are the basic determinants of the indoor climate and also of the demand for supplementary heating and/or cooling energy. When the predominant physical environmental factors, such as heat, light and sound, are taken into account, the outcome will be a solution that depends on the thermal, visual and acoustic features. The objective here is to provide comfort conditions with lower mechanical energy consumption and requires a design of the building envelope as an element of a passive system with optimal value and performance in accordance with the prevailing outdoor microclimate [29].

3.4.1 External Wall

The type of construction used to form vertical elements of the outer envelope varies depending on its function. Many environmental design strategies have been proposed to improve and optimize the external wall's environmental performance e.g. to prevent overheating, to reduce heat loss and cooling loads, to control the visual environment such as glare, contrast, the view and to provide noise isolation and so forth. The ability to do all these things depends upon the materials they are made from, the nature of the exposed surfaces and where they are located. Their 'optimal' design always requires a trade-off of between all visual, thermal and aural comfort factors.

3.4.1.1 High Thermal Mass

The thermal mass of a structure is a function of the density and quantity of the building materials in combination with the ability to store heat. High thermal mass is typically the case when buildings are constructed with materials like poured concrete, bricks, tiles, stone and earth [30]. This has a very positive effect on the indoor conditions both during hot and cold periods. The energy of high solar radiation gain during the day is stored and then is slowly released into the indoor environment at a later time. The time shift of the peak load and time lag of the heat released are actually desirable since in winter, the stored heat is transferred back into the room during the late afternoon and late evening hours when it is most needed, taking on part of the heating load. In summer, heat is stored in the thermal mass, thus reducing the cooling load peaks and avoiding overheating [31].

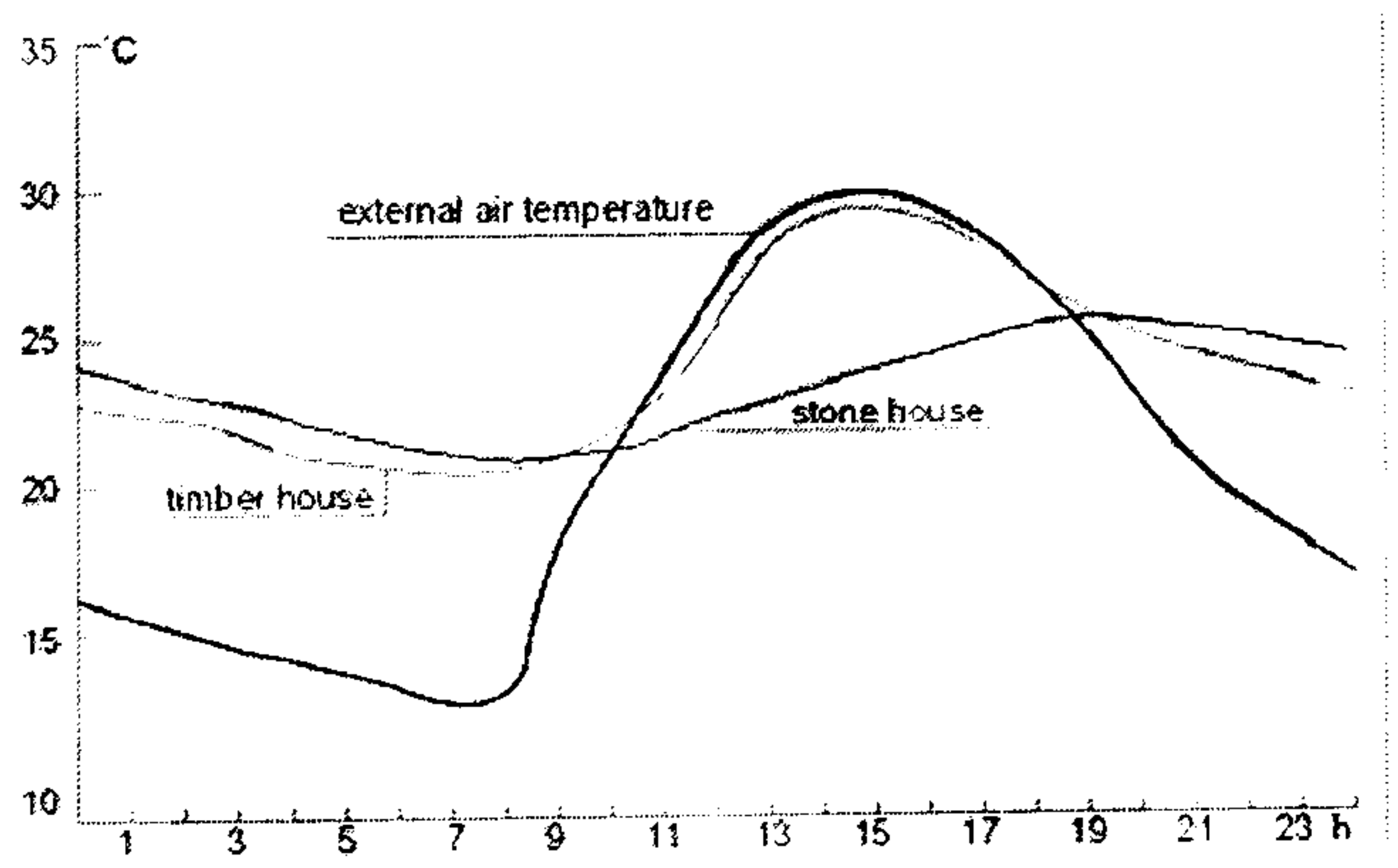

Figure 3.10 Temperature between low and high thermal mass building

Broadly speaking, the high thermal mass prohibits the occurrence of high interior air and wall temperature variations and sustains a steadier overall thermal environment thus increasing the level of comfort. As a result, indoor air temperature variations often remain within the comfort range for most hours during the day [32]. Figure 3.10 shows the impact of a high and low thermal mass on the indoor environment. This experiment was carried out in Kenya on a hot day in February. The findings show that when the maximum outdoor temperature was over 33°C, the maximum indoor temperature in a high thermal mass building of natural stone was 25.4°C, which is within the comfort zone, while the low thermal mass one with timber panelling shows the peak indoor temperature reaching above the peak outdoor temperature by 4-5°C [33].

In cases where the role of high thermal mass is mainly to do with cooling control, it is found that the impact on the indoor environment can be further improved by utilizing night ventilation to allow the structure to cool down. It is also reported that in California on an extremely hot day with a maximum outdoor temperature of 38°C, in the case of a high thermal mass building, the maximum indoor temperature was only 24.5°C (Figure 3.11) [34].

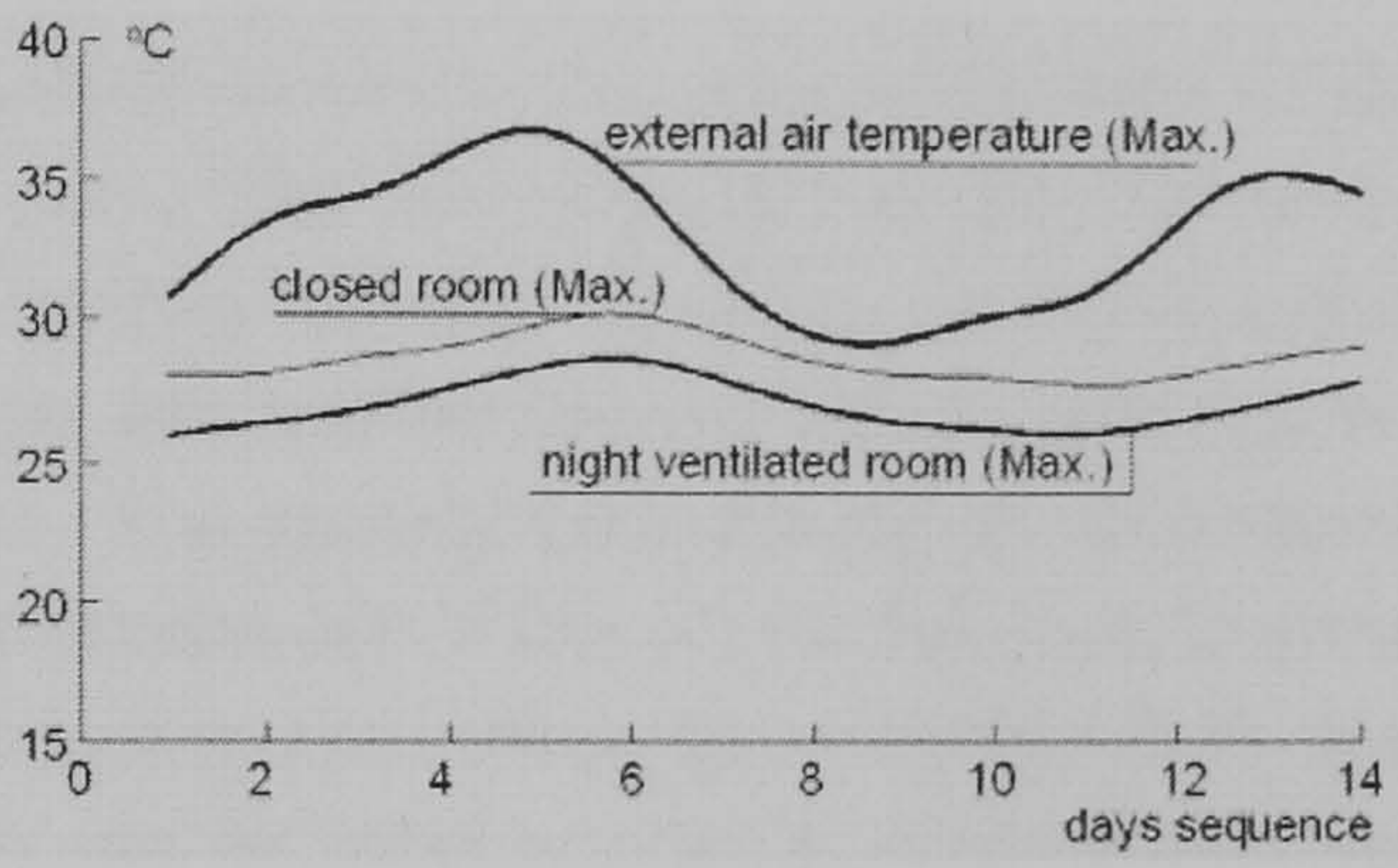

Figure 3.11 Temperature with and without utilization of night ventilation

A trombe wall is an environmental strategy that is developed and modified by conditions of high thermal mass. The required elements for a trombe wall system are a wall with high thermal mass, formed, for example, of masonry, concrete, adobe or water tanks, and covered by a glazing outside. There is a gap between wall and glazing in order to circulate the air between the inside and the outside. Normally, dampers are installed at the top and bottom of the air gap between the glazing and the location of the 'thermal mass, both having one-way flaps which controls the air flow directionally.

In a trombe wall system, the 'mass wall' is normally south-facing (northern hemisphere) in order to receive and store more solar heat. The time-lag and the dampening effect on the temperature wave depend on the type and thickness of the storage material: masonry is better than concrete and water is better than masonry. Based on the ambient environment, by adjusting the air flow through dampers, heat can either be introduced in winter or facilitates room air movement for summer cooling (Figure 3.12). Its efficiency is strongly influenced by the operation of heat distribution, storage, insulation and reflection from the

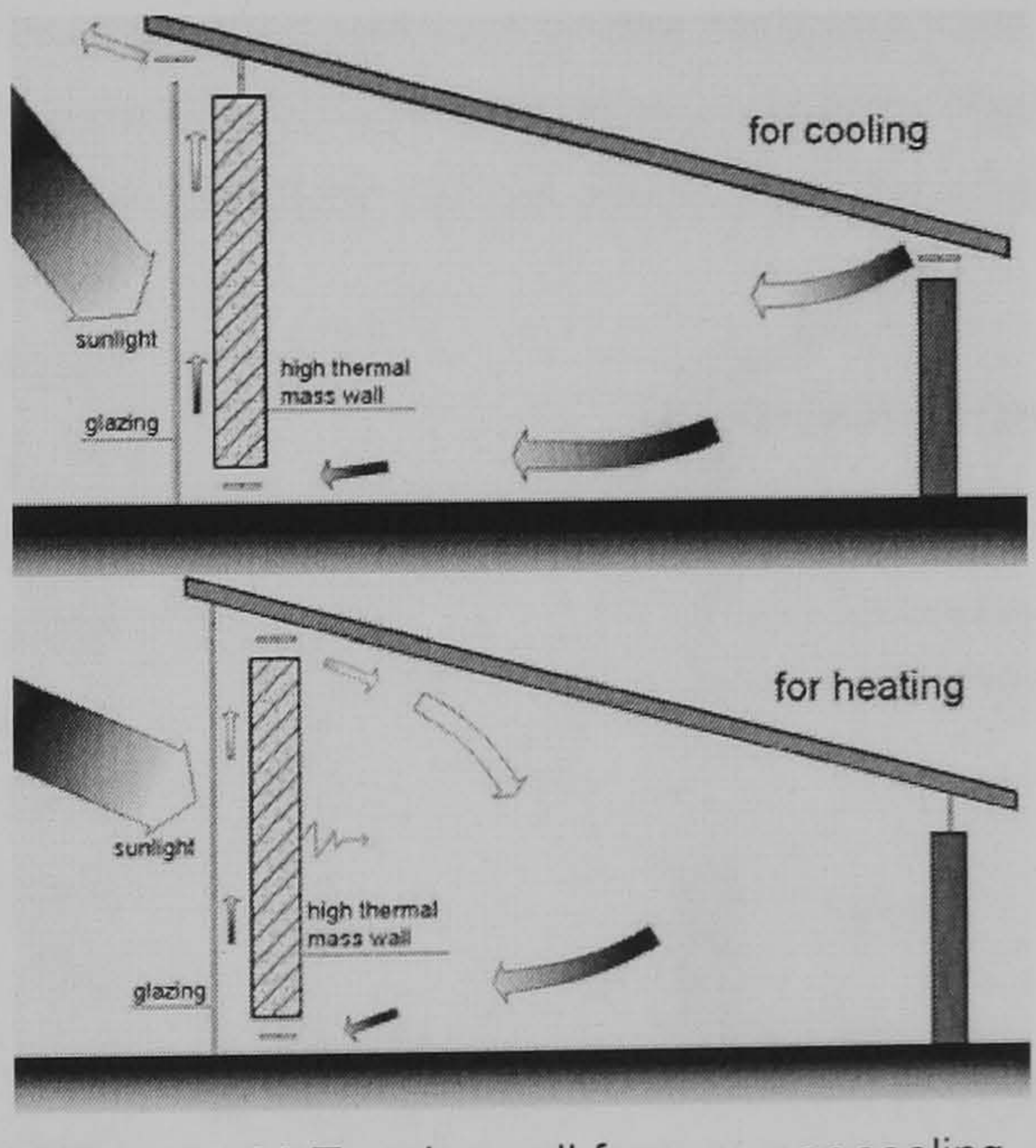

Figure 3.12 Trombe wall for summer cooling and winter heating

external air and solar radiation [20, P68].

3.4.1.2 Attached Sunspace

Attached sunspace is a design strategy that exploits solar heat gain in buildings. It usually consists of a glazed enclosure, facing south (northern hemisphere) so that much direct solar energy can be received, running the full width and/or full height of the house. This is now widely favoured in practice and variations serve many other functions, such as providing extra living areas, or acting as a solar heat store, ventilation pre-heater, buffer space or an entrance vestibule. The gain approach is simple and inexpensive: when the incident solar radiation is transmitted through the façade glazing to the sunspace and falls on the internal surfaces, part of the solar energy is absorbed by the surfaces. Thus they are warmed up and the heat re-radiated. Because the temperature of these surfaces is not normally high enough, the wavelengths of the re-radiation are much longer than those of the solar radiation. The glazing can prevent much of these going through and reflect them back into the interior [28, P18], and in this way thermal storage can be achieved. The heated sunspace can either be a comfortable and habitable environment in winter or ventilation can be used in order to channel the heat into the living space to provide necessary heating. The sunspace also works as a buffer zone between the living space and outside conditions. It buffers the main spaces from extremes of exposure, thus reducing the potential temperature fluctuations, fabric and ventilation heat loss, glare, fading of fabrics and furniture that may result from excessive indoor sunlight [35].

In most climates conditions, except on sunny days in winter, additional strategies have to be put in place in order to make the indoor environment pleasant all year round to override the effect of outside weather. For example, a heat storage wall with high thermal mass has to be located between the main house and the sunspace. This serves to stabilize the temperature in both the sunspace and the house in winter and summer. Operable insulation on the sunspace glazing is needed to prevent unnecessary heat loss at night and on an overcast day the sunspace is probably below the indoor comfort level and thus unable to provide positive heat to the building attached [20, P70]. Also double or triple glazing is recommended for cold climates [36]. In summer, sunspaces often encounter overheating issues, and in these instances moveable insulation or light coloured coverings are needed to prevent solar radiation access and sunlight glare, and fans may also be installed to increase air movement. This is especially important at night because the glazed roof of the sunspace can be sufficiently cool at night to cause condensation on its internal surface (Figure 3.13) [20, P70].

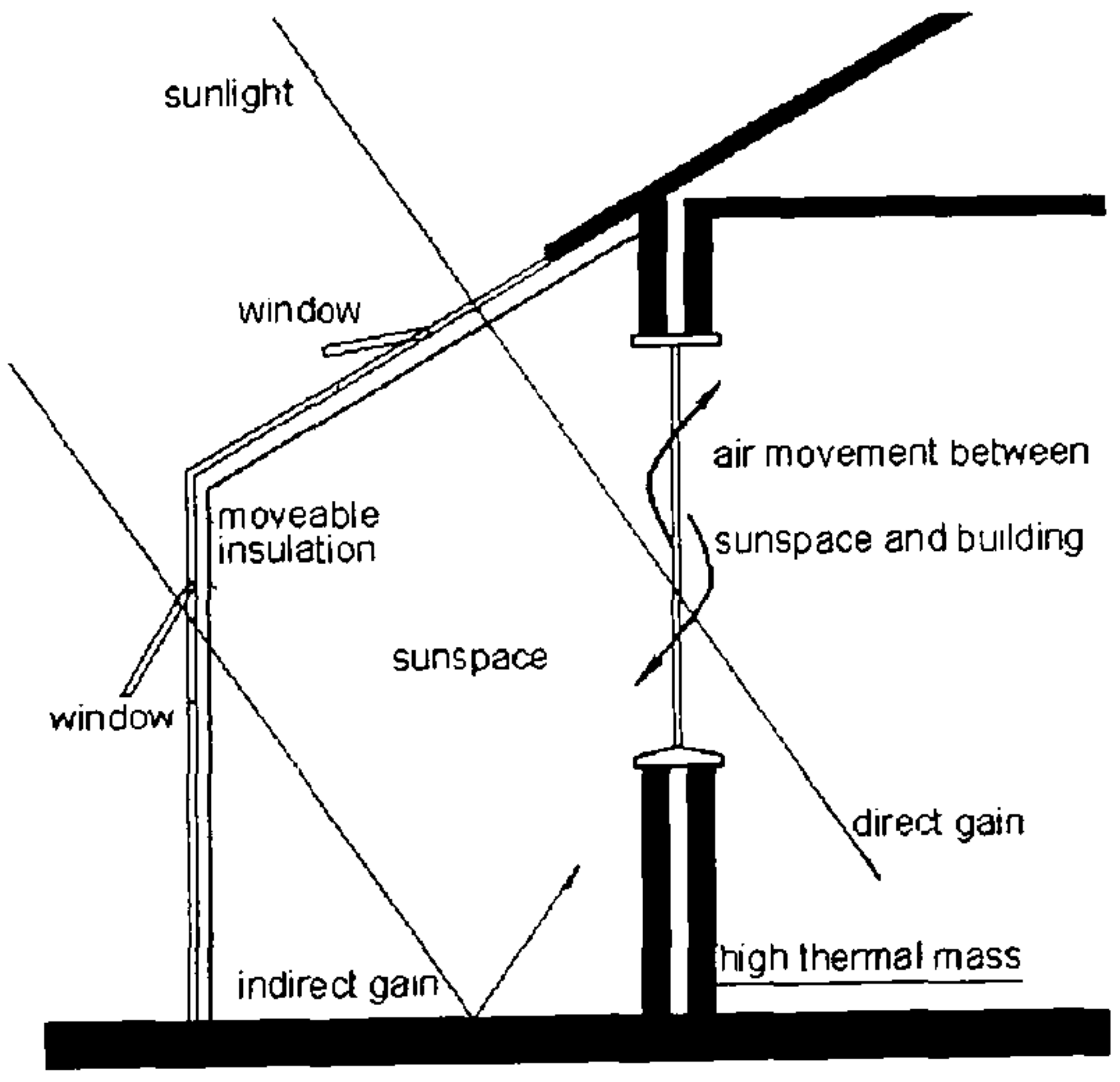

Figure 3.13 An attached sunspace

3.4.1.3 Wall Insulation

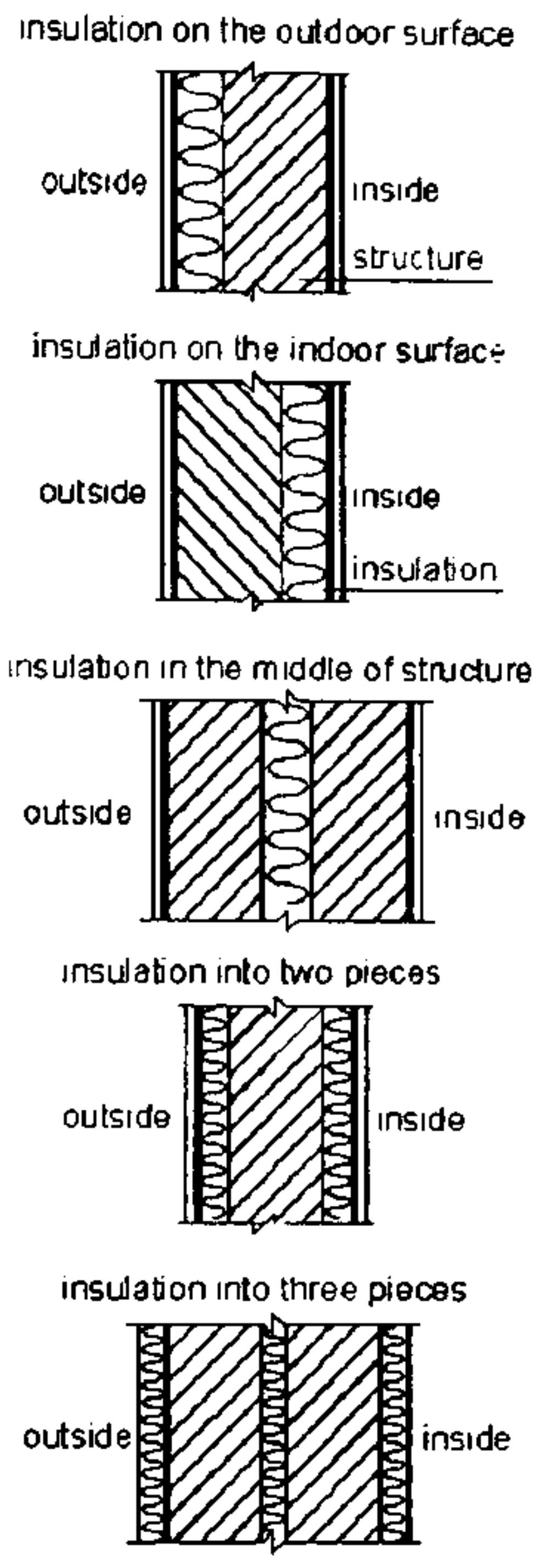

Figure 3.14 Position of thermal insulation on the wall

Thermal insulation is used to reduce the magnitude of heat flow in a 'resistive' manner. Since air provides good resistance to heat flow, air cavities within walls efficiently reduce heat loss. But where thickness is greater than 20mm, the resistance to heat flow remains nearly constant [8, P133]. Generally, the higher the density is, the greater the heat flows. Thus the structural components themselves are not able to provide a high level of resistive insulation due to their higher density, which is usually an absolute necessity given their load-bearing roles. Insulation materials are used then to further improve the thermal insulation characteristics of buildings, including artificial mineral fibres, foamed inorganic and organic insulation and cellulose, which are all based on the idea of numerous layers or pockets with air trapped within them.

Where the material is to be used and applied has to be given careful consideration in order to take maximum advantage of the physical characteristics of the materials in achieving indoor comfort. In practice, insulation is usually applied as single piece on the outdoor surface, in the middle or on the indoor surface of a wall. However, recent developments in research have shown that better thermal performance can be obtained by dividing an insulation layer in two and applying these as two separate layers of insulation on top of each other. This will provide better insulation than a single layer of the same thickness as the combined one, and if the insulation is combined of three levels the insulating effect is better still (Figure 3.14) [37]. In the last few years, a vacuum insulation panel has been as introduced into building technology as a high performance thermal insulation component for building envelope application. Its high thermal resistivity provides new solutions for slim but still energy efficient building envelopes [38].

At present, attention has been focused on the possibility of insulating buildings to such an extent that no heating system is required to maintain comfortable conditions. This technique is known as 'superinsulation', and the application of it will mean that a house will have an average U-value of less than $0.2W/m^2K$ for all major non transparent elements. This means that the house is so highly insulated and draught proofed that the space heating requirements on a domestic scale can be met from casual gains from the sun, occupant activity and the operation of appliances etc.

The use of high levels of insulation can eliminate the need for a space heating system, although some technical risks are unavoidably associated with achieving this. Since they are dense, highly thermally conductive elements are needed to provide the structure of the building, and, in practice, this can create a thermal bridge between the inside and outside [13, P63]. A thermal bridge may also occur at cavity closers, joints between intermediate floors, cavity walls, and across the lintels above windows and doors. A consequence of this is that condensation is likely to occur, which can lead to serious difficulties, such as rotting or rusting, and once insulation materials absorb moisture and get wet, their insulation effect is very much reduced. Additionally, outer leaf damage, rain penetration, and the freezing of loft pipework are all factors to which attention must be paid and given careful consideration in the design process [28, P25].

3.4.2 Glazing

No matter how well HVAC and artificial lighting can provide ideal, healthy and comfortable living conditions, window glazing cannot be substituted even if the natural means by which glazing actually operated involve many conflicting problems in the provision of heat, light, ventilation and sound. Most importantly, windows give a connection between the inside and the outside. Amongst other things, the direct view make it is possible to know the time of day, sounds are carried through the window, and thermal changes are also sensed, as well as varying patterns of light. In short windows provide the room and the built environment with an irreplaceable richness [39, P75]. Glazing design involves many variables that affect the built environment: size, shape, position, fitting, covering and insulation treatment etc. A sensible and acceptable balance has to be achieved between all these variables, which control heat input, light penetration, sound transmission, ventilation, security and privacy, not to mention the overall and detailed appearance [40, P200].

3.4.2.1 Glazing Area and Position

Generally the size and position of windows depend on where the sun, wind, and noise sources are. The extent to which all these align or conflict depends on the microclimate of the site area. If, in the case of a hot climate, they are aligned, small sized windows are desirable because excessive heat and very bright light can be eliminated during daytime. In a moderate climate, however, large south facing windows may usefully contribute to solar gain in underheated winter conditions. But the large areas of glazing may conflict with the need to exclude high noise levels existing outside and summer overheating. Lastly, in a cold climate, a balance has to be achieved between natural lighting and heat loss bearing in mind that either one of these considerations might be of overriding importance at any one time.

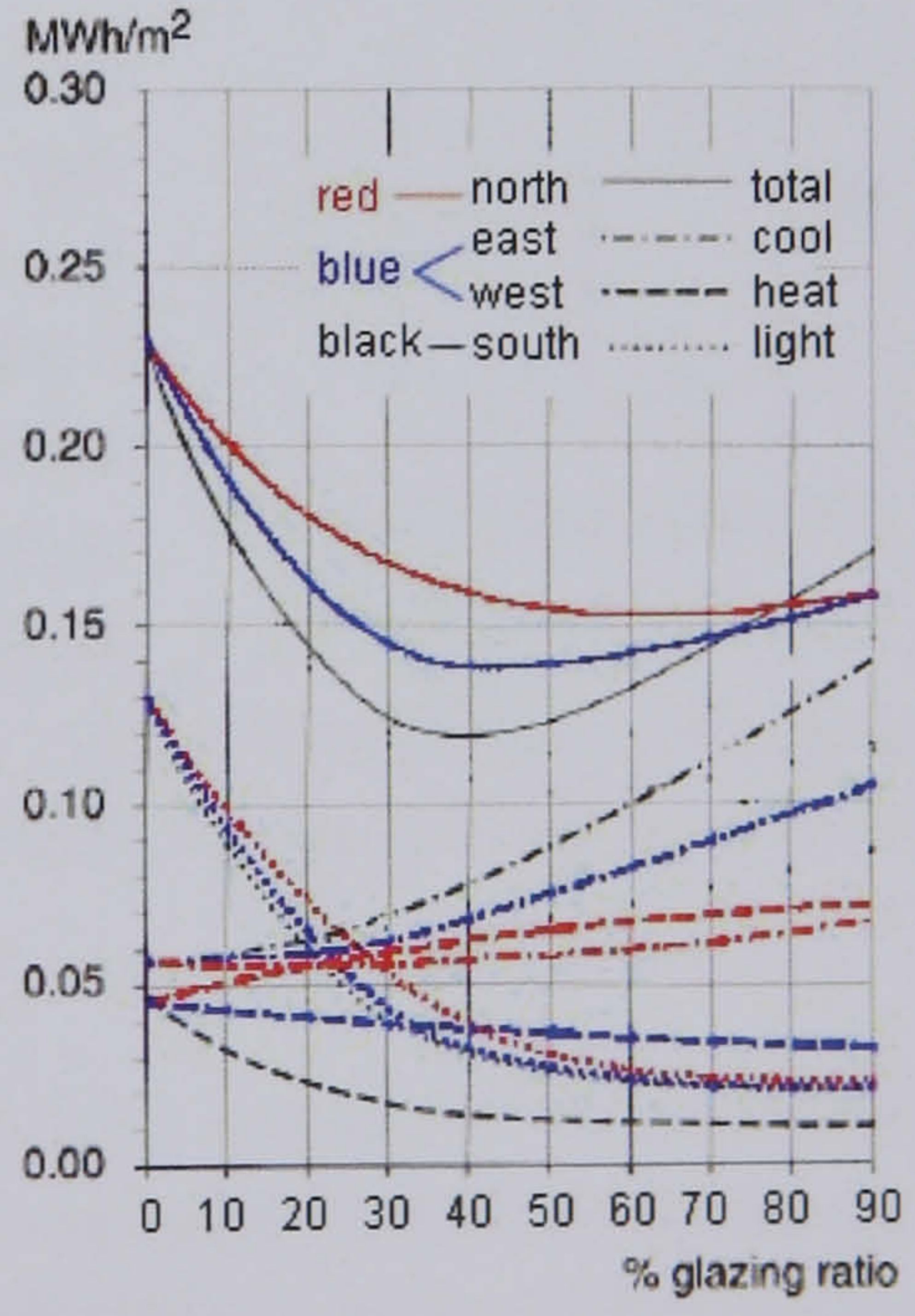

Figure 3.15 LT Method used in a typical office building

The amount of solar radiation admitted is directly proportional to the fraction of an area that is actually glazed: the larger the glazed area, the greater the amount of solar energy that can enter, and the greater the heat loss from the inside to the outside. The central argument here is how much of the incoming radiation is useful [25, P63].The Lighting and Thermal (LT) Method is a technique that can be used to make comparisons between glazed windows of different areas and directions in terms of the heating, cooling and lighting requirements of a given building. For example, Figure 3.15 shows an example of a typical office building with five storeys located in southern Europe [41]. The horizontal line represents the glazing ratio. It is a percentage of the total external wall which is glazed. The vertical is the annual energy consumption in terms of megawatt hours per square meter broken down into lighting, heating and cooling energy.

It can be seen that as the glazing ratio increases solar gains increases so the demand for space heating falls. This is especially true with east, west and south façade glazing. Compared with other façade windows, the south one requires the least heating energy by mechanical means, while the north one needs the highest. This result is reversed when it comes to cooling: a room in the north façade consumes the lowest amount of energy compared with all the others, while the south one consumes the most.

For lighting, the energy used for artificial lighting is reduced as the available daylight input goes upward with the increase of the glazing area. But the curve is decreasingly dramatic until 60% is arrived at. Thereafter, no evident saving can be made, and this causes the curve to flatten out. The total energy curve has a U shape indicating that initially energy consumption falls as use is made of natural lighting and solar radiation. However, this curve shows a distinct minimum total energy consumption at around 40% glazing ratio on the south, 50% on the east/west and 60% on the north façade.

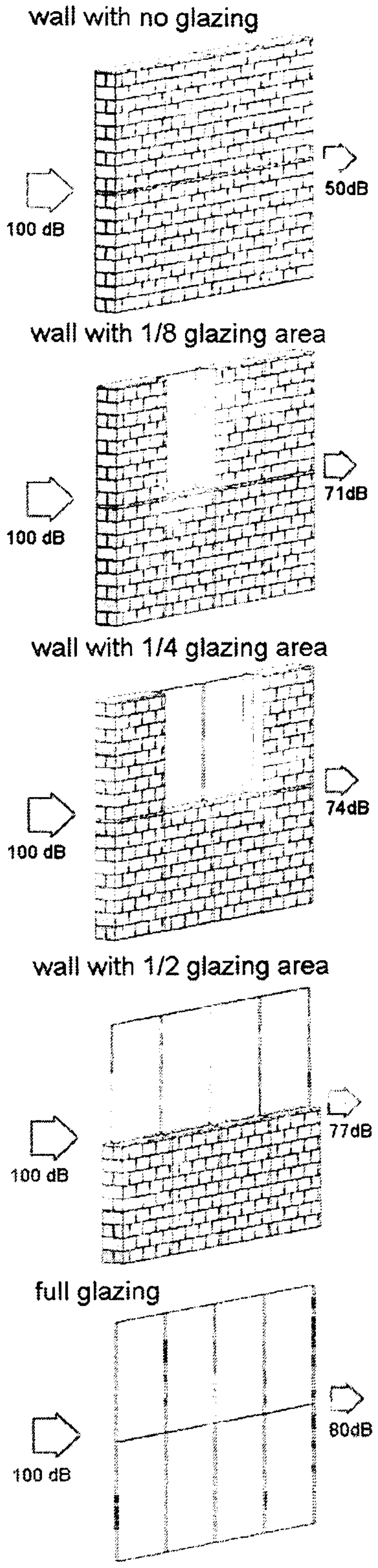

Figure 3.16 Noise reduction with different glazing area

Furthermore, windows are usually the main source of natural ventilation. In the majority of buildings with small rooms, it is easy to achieve an acceptable level of ventilation with controllable openings except where external noise levels prevent window opening. In a room with a large area, cross-flow ventilation is straightforward: primary inlet and outlet windows are located in opposite pressure areas. However, the position has to avoid the predominant wind direction as this allows infiltration air to pass easily through the windward to the leeward [22, P39].

The window is often a 'weak' element when it comes to noise control, compared with the solid and opaque walls. When it comes to their composite construction, the effect is usually closer to the weak window than to the strong wall. For example, a wall with whole bricks can reduce the sound level of the noise from 100dB to 50dB while a single pane of glass can just reduce 20dB. The combination of these two, depending on the glazing ratio is shown in Figure 3.16. It can be seen that because the sound isolation provided by the glass is so much lower than the brick, only one eighth glass will reduce the overall effectiveness of the composite construction to 29dB [42, P188].

3.4.2.2 Light Shelf

The majority of rooms are daylit using vertical side windows. Among the deficiencies in this system, daylight is mostly available near the window and excessive light may produce glare discomfort, and encounters difficulties in spreading to the points furthest from it. Various methods have been proposed to solve these problems. The light shelf is considered innovative and this is a plane element normally placed horizontally or inclined in an intermediate position within the window system, dividing the upper and lower glazed areas. It can be either internal, external or both. Figure 3.17 shows a light shelf projecting partially outwards and partially inwards into the room.

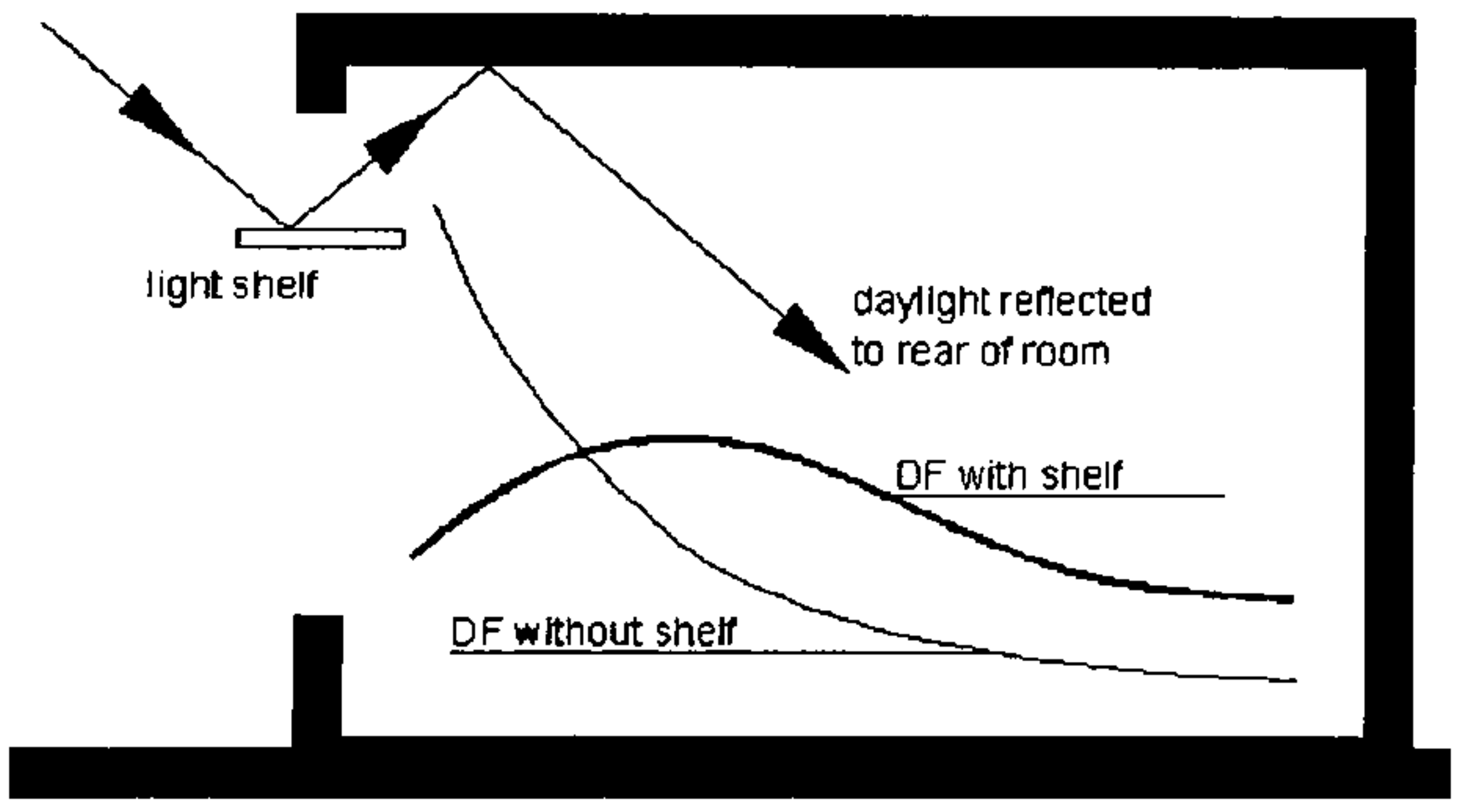

Figure 3.17 Schematic of a light shelf system

The light shelf can reduce the solar radiation incident upon the window thus reduce the glare risk, especially when the solar altitude is high. Usually, the surface of the light shelf has a light and smooth surface in order to have high reflectance. The upper side can re-direct skylight and sunlight to the ceiling inside the room. The higher the reflectivity of the shelf surface is, the better the light redirection will be. Although there is some increase in the skylight and sunlight reflected to the outside, in practice this is offset by ceiling reflection to increase the illumiance at parts of an interior distant from the window. The higher the ceiling above the shelf, the deeper will be the penetration of re-directed light. However, the shelf has to be located above eye level at both standing and sitting levels so as to avoid obstruction of the external view [23, P25]. The under side of the shelf can also be made reflective to re-direct light from external paving or obstructions into the room. Therefore, a better and more even distribution of light is further improved to provide uniform illumination. Such devices can also be used in an atrium where strong downward light needs to be reflected into surrounding rooms [39, P83].

Light shelf operates most effectively in sunlight. Under a diffused and overcast sky, the value of the light shelf is only a relative redistribution of light that can not increase the lighting level. In this context, the ceiling is usually made higher than normal for best impact and operation [21, P147].

3.4.2.3 External Shading Devices

A shading device is one of the most commonly and fundamentally used design strategies. It is usually exploited as a supplement to control the degree of sun heat and sunlight penetration when necessary. This device also gives rain protection to walls and openings [8, P121]. Fixed shading systems includes overhangs, balconies and projecting fins on the external facades, while the movable one is also available to overcome the unpredictable daily variation and responds better to the dynamic nature of weather than do static devices. The orientation and shape of the window, relative to the position of the sun strongly influence the appropriate choice of shading device.

Usually the shading device, used as a partial screening, blocks the solar radiation before it reaches the building, particularly the glazed, but sometimes also opaque surfaces including the door and wall. Then the radiation is partly absorbed by the shading system surface and partly dissipated to the outside air, harmlessly re-radiated and air-convected away. Each orientation needs to be dealt with separately, taking account of direct and diffuse or reflected components of the overall solar radiation throughout the day and year. Horizontal shading devices are appropriate for shading south-facing windows while the vertical one is appropriate for east- or west- facing facades because the solar altitude is always low. Based on these two patterns, an egg-crate type is developed to deal with the radiation in a more flexible way [20, P100].

A comparative study presents the performance of daylighting with these three shading device patterns (Figure 3.18). From this it can be seen that every shading device reduces the daylight penetration to a certain degree especially near the window area. With the increase of distance from the window, the efficiency drops, with the egg-crate being the most efficient in terms of daylight distribution. Furthermore, daylight factors decrease when the depth of the horizontal device is increased in all three shading forms. Especially in the case of the one with egg-crate, the daylight factor drops from 12% with 150mm to 5% with 900mm depth where 1m away from the window. [43].

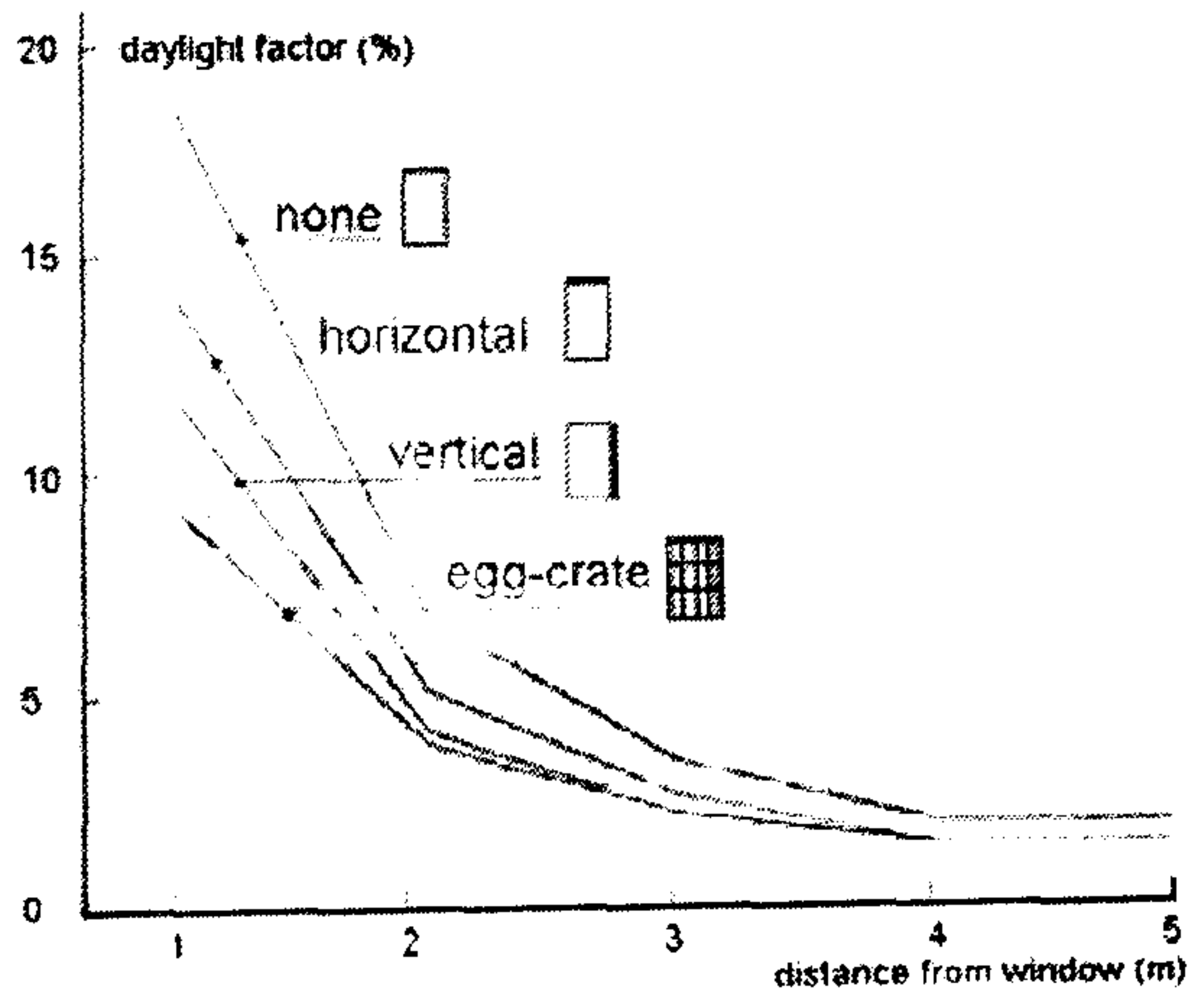

Figure 3.18 Comparison of shading devises patterns on daylight distribution

Another study shows the impact of window shading devices on the difference between radiated and ambient temperatures in Singapore, which is a country in the tropics with very strong solar radiation [44]. In this study, an external shading device of 300mm is located on all façade directions of the building. The difference of temperature is dramatically decreased in comparison with cases in which there is no shading device. Figure 3.19 illustrates the measurement result on the east façade window. It is reported that the 300mm horizontal shading device is enough to maintain a good level of indoor thermal comfort and that the difference between radiated and ambient temperatures is always below 2°C except at 7am from the east façade window room due to the low solar altitude that is the source of direct solar radiation for the room. However, since 7am is sunrise and solar radiation is not strong, the high temperature difference doesn't have a serious effect on the indoor comfort environment.

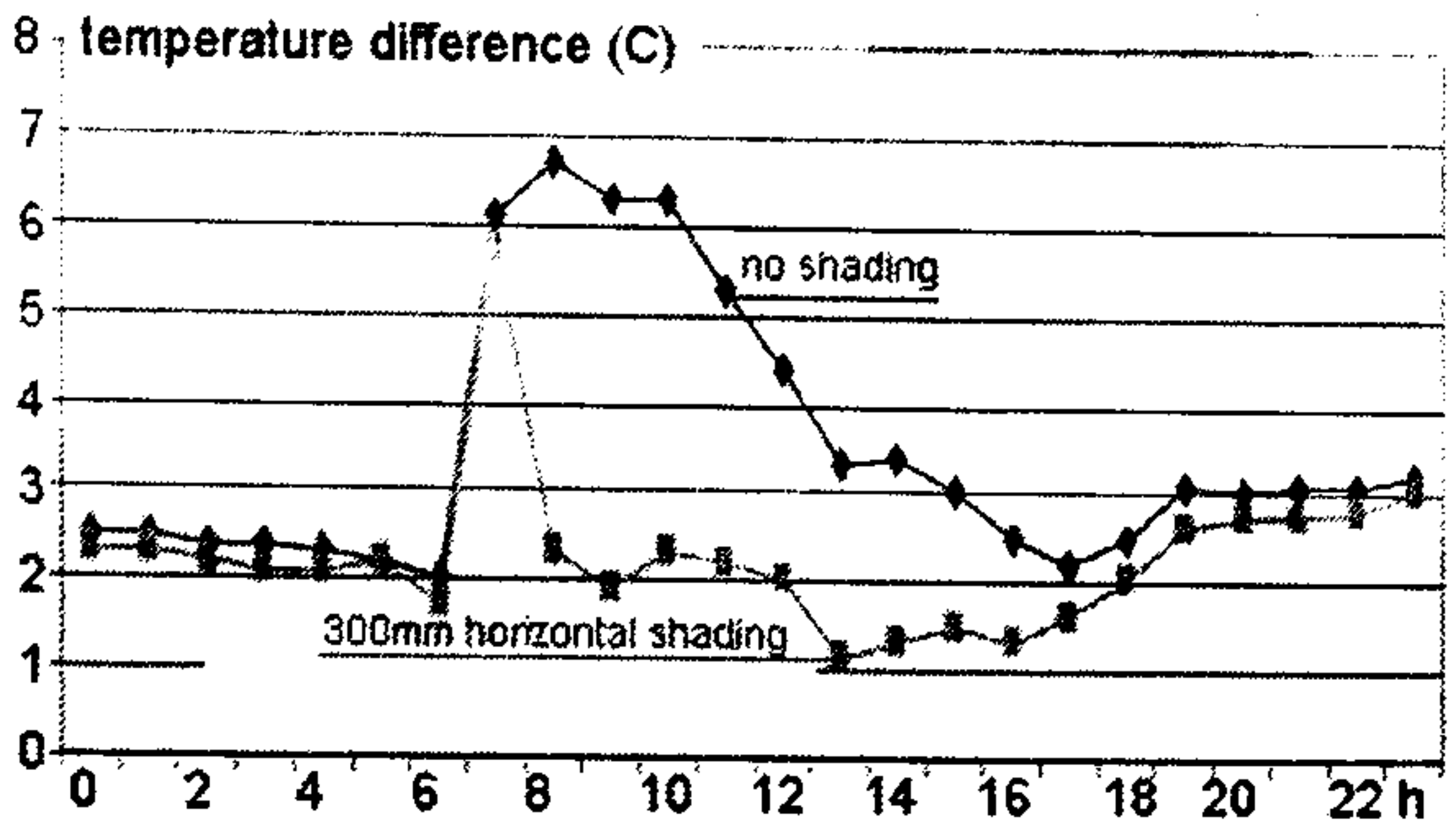

Figure 3.19 Temperature difference between room with and without shading device

3.4.2.4 Internal Shading Devices

With a fixed external shading device the solar exposure of the window is not a function of temperature but rather of sun angles, which change in a very predictable manner throughout the year. Therefore, such devices are very efficient in controlling overheating in summer and allowing solar radiation penetration during the underheated periods. However, the sun angles and temperature are not completely in phase, because the daily weather patterns vary widely. Especially during the transition period, the day may be too hot, while the next may be too cold. Even in winter, the exposure to direct solar radiation can easily cause discomfort and the strength of solar radiation may lead to glare disturbance. This can be intensified by the asymmetry between the exposed side of the body and the side in the shade [20, P61].

The external shading device may not respond to these changes to prevent intense glare, overheating and fading of surface colours [45, P142]. In contrast, internal shading coverings are very adjustable and movable and this allows them to respond easily to the changing requirements, such as current radiation levels, daylight or thermal need. Interior shading mechanisms include roller shades, venetian blinds, curtains, drapes and so forth. These are all very capable of converting direct sunlight into a softer, reflected light and reduce its intensity to illuminate the building rooms when exterior shading is not designed to work [40, P76]. The efficiency of the shading device is measured as the fraction of the total incident radiation transmitted through the opening. This parameter is known as the solar factor of the opening or its transmitted radiation impact (Table 3.3) [46]. Besides shading, these devices

Shading device	Solar factor
Venetian blind	0.75
Roller shade	0.62-0.81
Tinted glass	0.52-0.66
Insulating curtain	0.36-0.60
Coating on glass surface	0.20-0.50

Table 3.3 Efficiency of some internal shading devices

are also used for some other benefits such as privacy and glare control. It is reasonable to assume the presences of these shading devices also affect the solar heat gain and thermal performance (U-value) of the window system [47].

One of the main drawbacks is that they are not always 'discerning', which means that they do not block the sun and let in the view at the same time: they fail to discriminate between wanted and unwanted light. On the other hand, since they work primarily by blocking the solar radiation only after it has arrived through the inside of the glazing, much of the heat remains indoors regardless of how reflective they are [9, P189]. Even a fairly light and shiny blind will only reflect about 40% of the incoming radiation back through the glass, absorbing the rest, heating up, and becoming a radiator for the room [48, P45]. In warm and humid climates, where air flow is desirable, they seriously impede ventilation. Internal blinds and curtains can reduce the solar heat input by reducing the direct radiation, but they, in turn, become heated and will re-emit that heat, thus causing convective gains [12, P65].

3.4.2.5 Glazing Insulation

Transparent insulation materials have developed quickly over recent years. Normally they are made of special fabrics with relatively low U-values such as multi-layer polycarbonate sheets, aerogel and fibre glass panels. Indeed, they are actually translucent rather than transparent. For instance, glass reinforced plastic is widely used in factory roof lights with only around 50% light transmission: the daylight can get through them, but it is diffused; they provide no view of the outside world [13, P55]. Apart from these special insulation treatments, most glazing materials are glass, which has poor resistance thermally and acoustically. Usually it is responsible for a large proportion of heat loss and noise transference. In response to these disadvantages, the insulation properties of glazing have to be improved. Generally, the qualities of glazing insulation treatment are constant both in respect to thermal loss and noise control, and a good thermal insulation strategy can also decrease the level of noise transferred from the outside to the inside. The performance of some strategies is shown below:

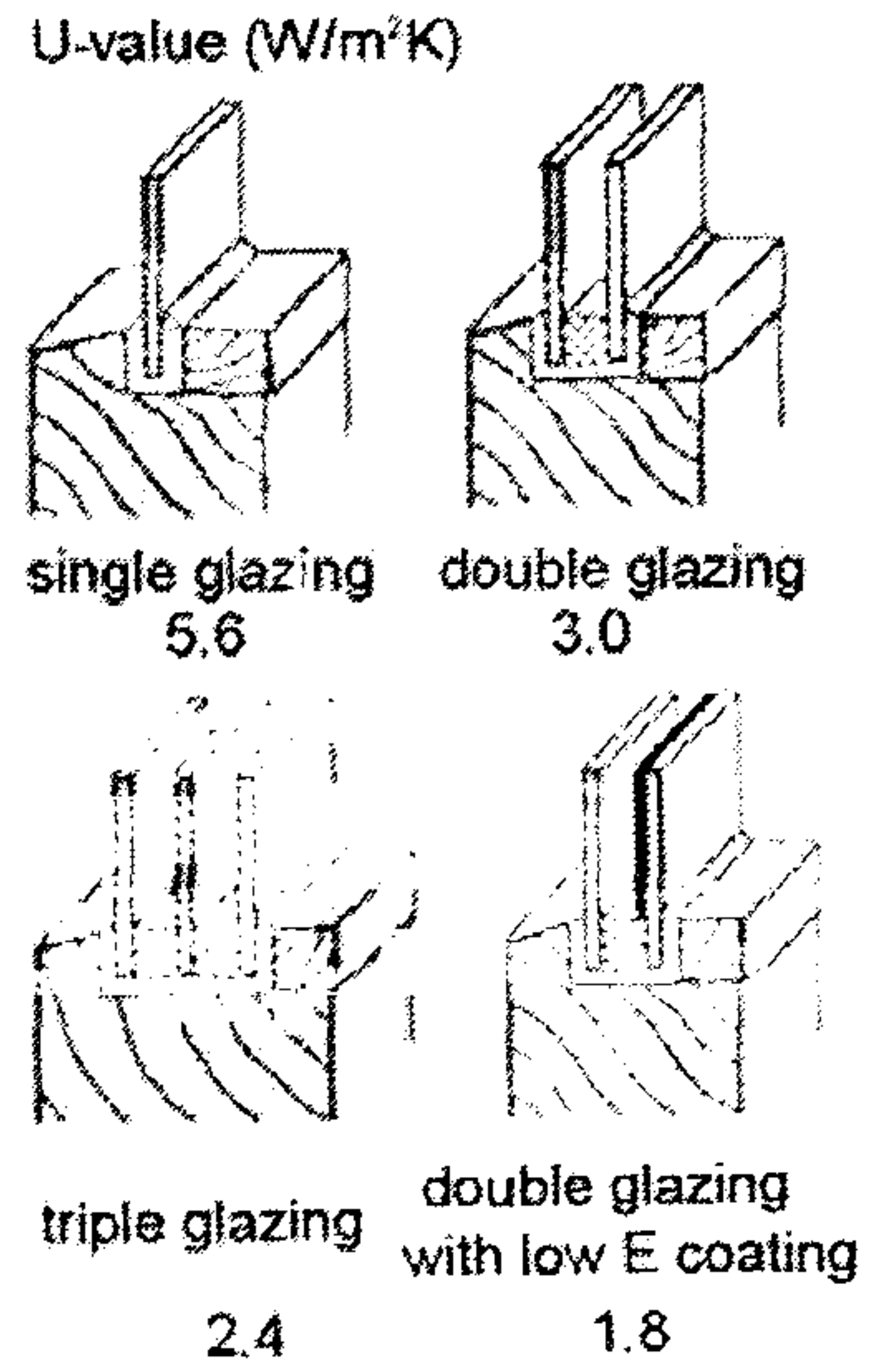

Figure 3.20 U-value against cavity width for double glazing (4mm glazing, no coatings)

Sheet of glass Increasing the thickness of the glass is the simplest way of increasing insulation. With clear glass reducing outward thermal transmission, it does not significantly alter the extent of solar gain. The U-values for single, double and triple glazing are 5.6, 3.0 and 2.4 W/m^{2}K respectively (Figure 3.20). Also double and triple glazing may increase sound reduction by 10 -15 dB [49, P46]. More than three sheets are certainly better but become impractical due to weight or the dimensions of the unit [13, P56].

Cavity Increasing the width of the cavity between the sheets of glass reduces the U-Value as well. For example the U-values of double glazed units with 6, 12, 16 mm air gaps set in a timber frame are 3.1, 2.8 and 2.7W/m^{2}K respectively [13, P57]. The optimum performance is 12mm as the reduction in effectiveness is approximately 2% comparing with 20mm. Over 20mm, the thermal performance is practically constant. If the noise reduction is the main consideration, the cavity needs to be much wider than is normally required and preferably 200-300mm. Sometimes, the different thicknesses are located to further improve sound reduction particularly at higher frequencies [50, P40].

Low emissivity coating A low emittance coating inside a sealed double glazing unit can reduce the radiant heat transfer. Normally, by coating double glazing, a fine layer of metal oxide is placed on the outer surface of the inner pane (Figure 3.20). It has a minimum effect on the transmission of solar radiation from the outside to the inside. The inner pane of glazing absorbs the heat either from solar radiation or from the heating system, causing its temperature to rise and re-radiate thermal radiation both into and out of the building. Because of the low emissivity of the coating, the radiation outwards is reduced thus the heat transfer is reduced [13, P58]. If the blind is in the cavity when aluminized, the effect can conserve 45% of the normal heat loss [25, P110].

Frame sealing The frame can form as much as 15% of the window opening area. The thermal characteristics of the frame therefore have a strong influence on the overall impact. Generally, the metal with around 3.6 W/m^{2}K U-value is better than wood with 2.8W/m^{2}K. However, the most important aspect of improving the thermal performance of all window frames regardless of material is to incorporate proper sealing. Even very small gaps can severely impair the performance of all the special treatments applied for the sake of glazing insulation effects. This principle also works for acoustic performance. Gaps around the edges of frames have to be sealed tightly, using weatherstripping, sound-absorbent lining etc [49, P46].

3.4.2.6 Wing Wall

The wing wall is a building structural element that is built onto a building's exterior along with inner edges of all the windows and extending from the ground to the eaves. For modern natural ventilation, windows are used to control the volume, velocity and direction of airflow. Insofar as airflow is concerned, a pivoted and hinged window can exert a deflecting, turning effect on incoming air currents. While sliding one can operate in the plane of the wall and thus avoid steering incoming flows. In both cases, they are designed so as to offer an inlet and/or outlet of given size to provide better natural ventilation. However, when these two methods are not practical, for example, when no significant ventilating breeze will enter an opening that is parallel to the wind flow, particularly if the opening is narrow, the use of wing wall is an alternative way of creating effective natural ventilation.

Figure 3.21 shows how the provision of wing walls in a building façade vertically between two openings changes the air flow through room. The locations of external fins act by means of a damming effect that causes the fluctuations and changes the direction of the natural wind direction. This produces moderate pressure differences across the window and thus deflects the air stream in useful directions. In this way, it can increase inflow of breezes and channel the direction of incoming flow currents [9, P195].

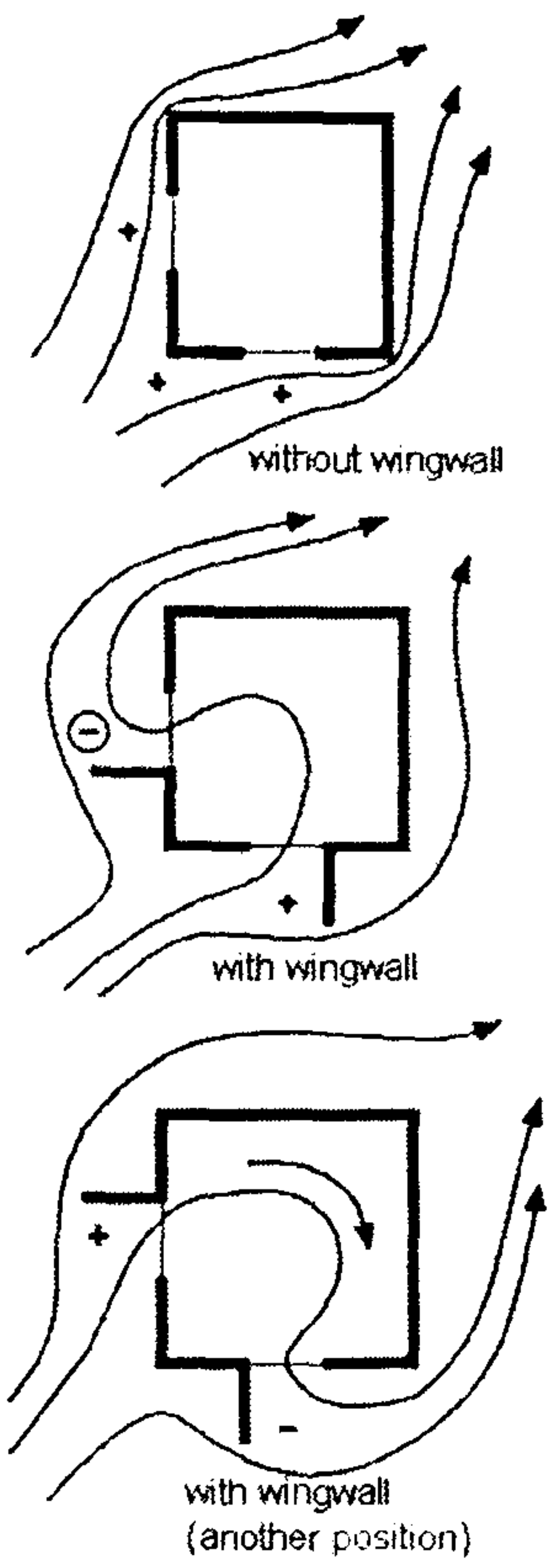

Figure 3.21 Influence of wing wall on air flow

Givoni conducted experiences on room models with and without wing walls in a wind tunnel to study its effect on ventilation. It has been shown that, depending on the wind direction, in rooms with only one opening window the average air velocity is about 3.3 to 4.7% of the wind velocity, and that the window size has little effect (Givoni 1981). Two openings in the same wall will improve matters. The average velocity then increases to between 4.3 and 15.7%. If wings are added externally to the window openings and the wind blows obliquely to them, then the average velocity will increase to 35% [23, P28].

3.4.3 Roof

The roof top covering of a building may be pitched or flat depending on the local microclimate and the function of the building. In terms of environmental control, the pitched roof construction can use the attic as an intermediate space between the ceiling of the living room and the part of the building shell envelope that takes the brunt of both summer and winter stresses. Necessary ventilation strategies and insulation are sometimes needed to prevent humidity and enhance buffering ability [9, P115]. On the flat roof, not only can the high thermal resistance prevent the heat exchange between the outside and the inside, but also the reflectance of the outside surface can be utilized to affect the thermal performance by radiation from the sky and to the sky. The design strategies that are exploited on roof element are all developed on these principles.

3.4.3.1 Stack Effect

There are two impetuses of air motion through the building. One is the aeromotive or wind force that produces high and low pressure on the building façade, leading to air influx and outflow through openings, gaps and cracks. The other one is temperature forces or stack effect. The thermal ventilation due to the stack effect operates when a temperature difference exists between the outside and inside air of a building. This difference is created between their densities and a pressure gradient developed along the vertical direction over the walls of the building. If the temperature inside is higher than that outside, the building will have higher pressure on the top part while lower pressure on the bottom. When openings are provided in these regions, air enters through the lower openings and escapes through the upper. When the indoor air temperature is lower than the outside, the positions are interchanged and the flow direction is reversed (Figure 3.22) [8].

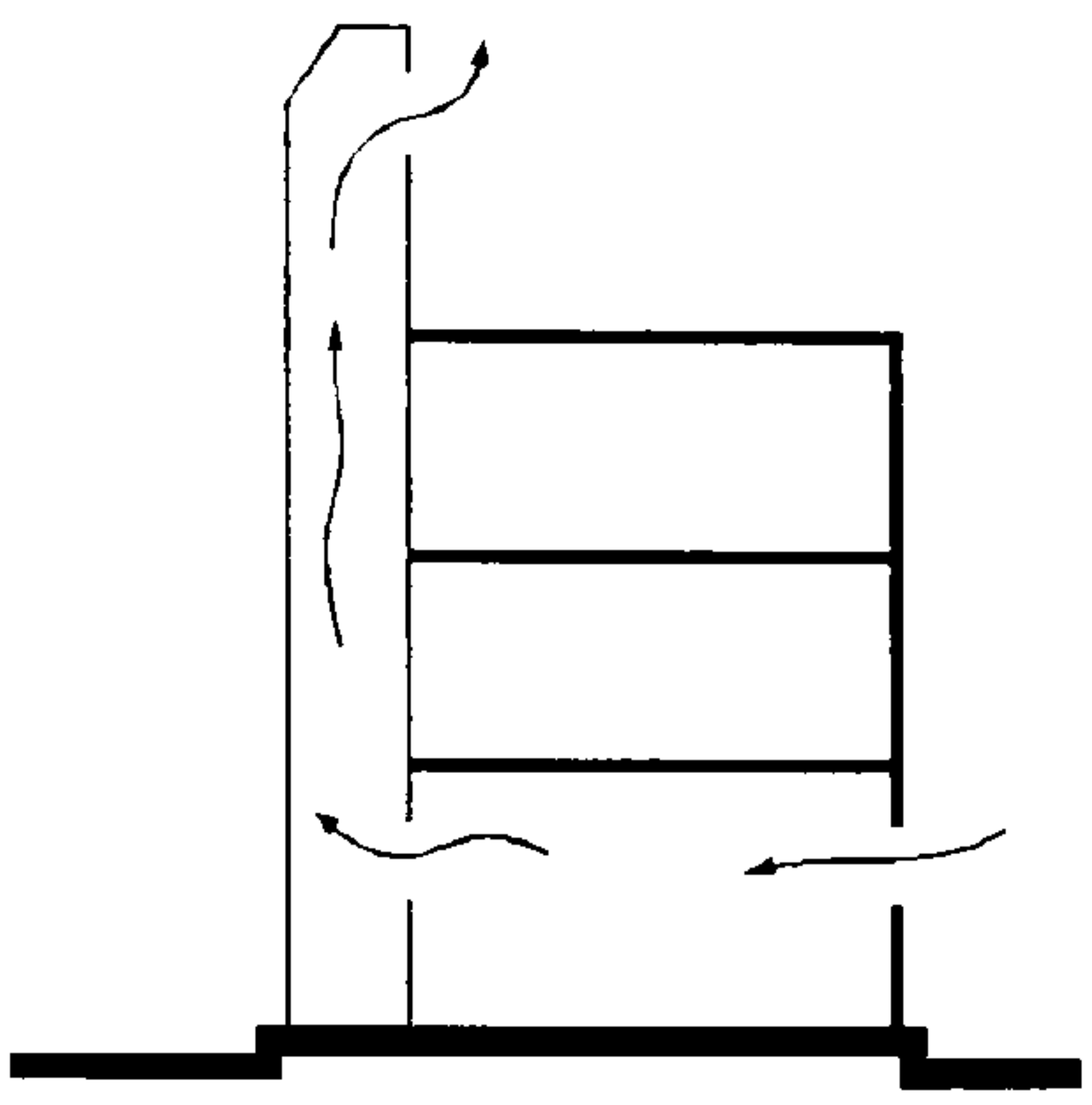

Figure 3.22 Schematic of stack effect system in the building

As the height of the ventilation path affects the thermal force greatly, a high-reaching projection above the roof is exploited to have sufficient magnitude and enhance the performance of the stack effect for natural ventilation. Normally it serves as a suction zone to exhaust the air through the top. Because of the random nature of the driving force, the stack action may be reversed with the intended outlets serving as poorly located intakes. Often an extractor fan is installed to ensure the rate is controllable and adequate air movement can be introduced more uniformly across the space.

Figure 3.23 shows the result of a field survey on the application of the stack system to enhance natural ventilation in a public housing scheme in Singapore [51]. Measurements are taken at the nearest point to the inlet opening both with and without fan effects. It can be seen that the bigger the stack size the higher the air velocity is and the average speed of air velocity is around 20% lower with the fan switched off than on. It can be concluded that passive stack ventilation with the combination of a necessary extractor can lead to a substantial increase of the air velocity in the room and thus meeting human thermal comfort needs.

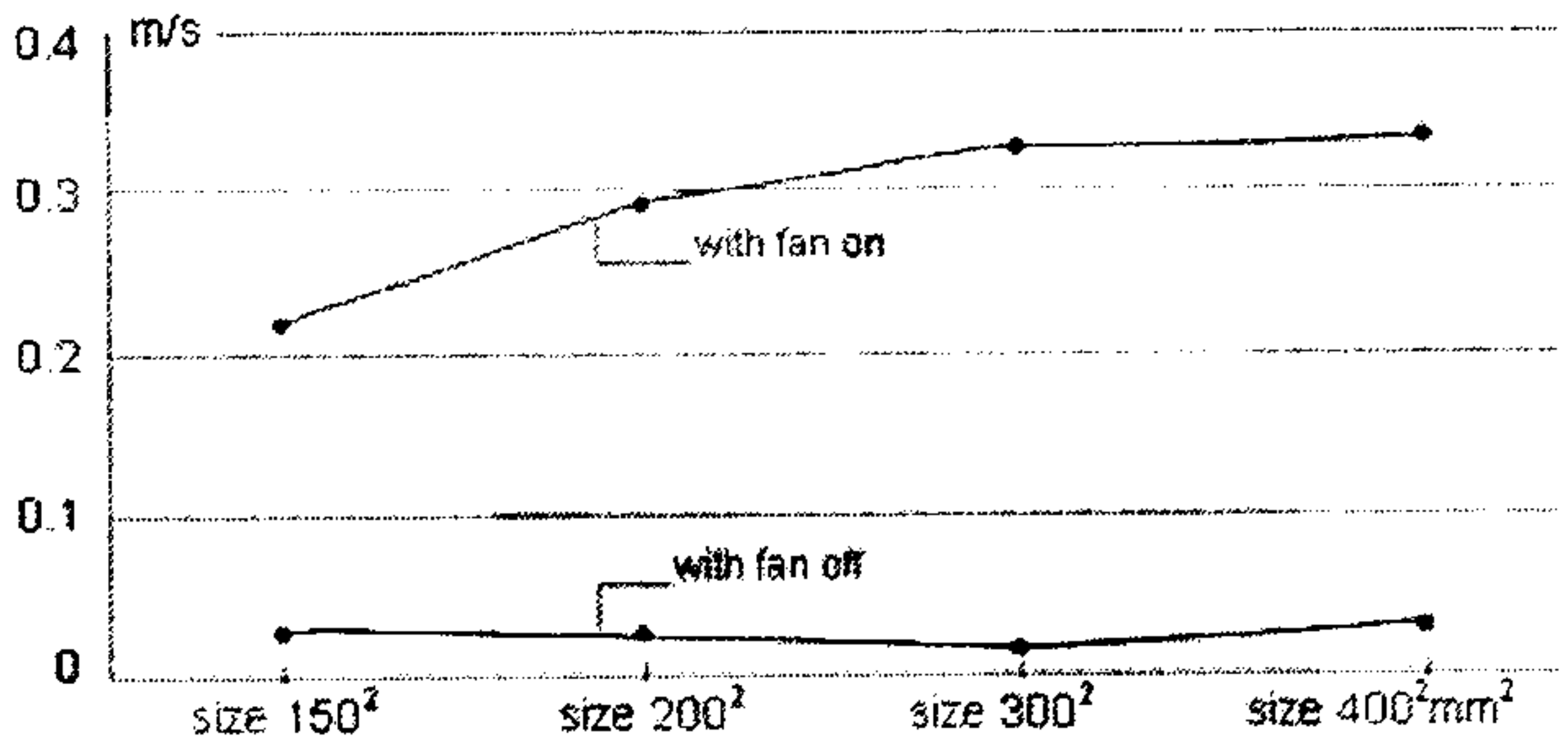

Figure 3.23 Application of stack system to enhance natural ventilation

3.4.3.2 Roof Water

Because the property of water has a very high thermal resistance value (Table 2.1) and enormous latent heat is needed for evaporation, roof water is a very efficient way of both cooling in summer and heating in winter, especially in a predominantly dry area. The most widely used system employs a shallow pond of water in a thermal contact with a strong but highly conductive flat roof and ceiling structure. If the main intention is just evaporative cooling, flowing water layer or spray over the roof can also be used with the same effect. In the daytime in summer, the pond has to be shaded by a removable insulation to cut off the excess solar radiation to the living place. At night, movable insulation is taken out and the water is cooled. By air movement from the water surface and longwave radiation to the night sky, heat from the building is transferred to the environment through the tank to the ambient environment, and the cooling effect is obtained (Figure 3.24).

Figure 3.25 shows the results of experiments conducted in India that examined the effect of the pond roof for cooling on a typical clear summer day [52]. In this experiment, the shallow pond has a 100mm water column and 40mm thick movable thermal insulation over the roof. The water is covered by insulation during daytime and exposed to the sky after the sunset for nocturnal cooling. The average air temperature inside structure is 13.2°C lower than the ambient temperature which shows the evaporative cooling is significantly efficient to keep building structure cool in summer.

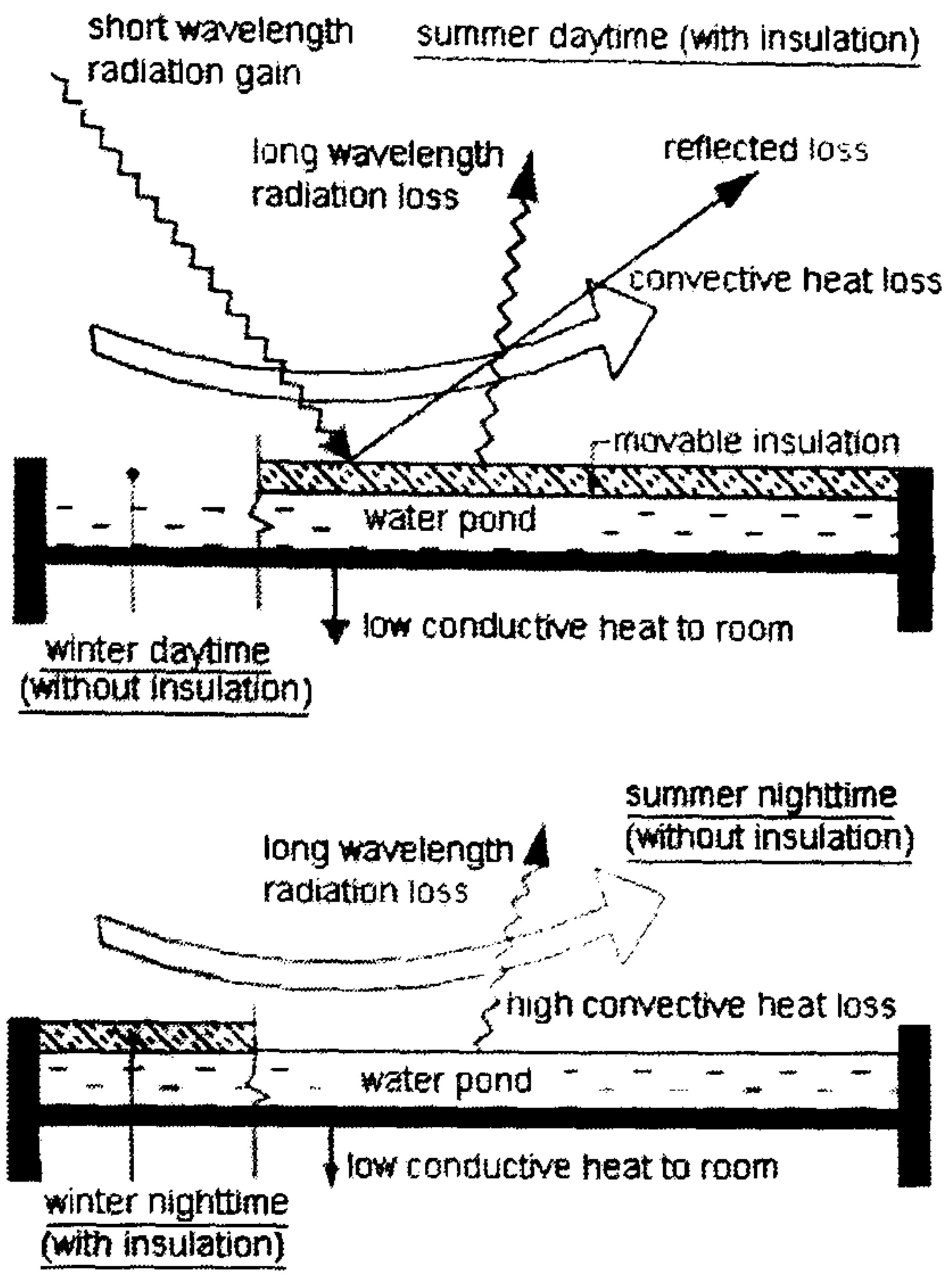

Figure 3.24 Schematic of roof pond in summer and winter

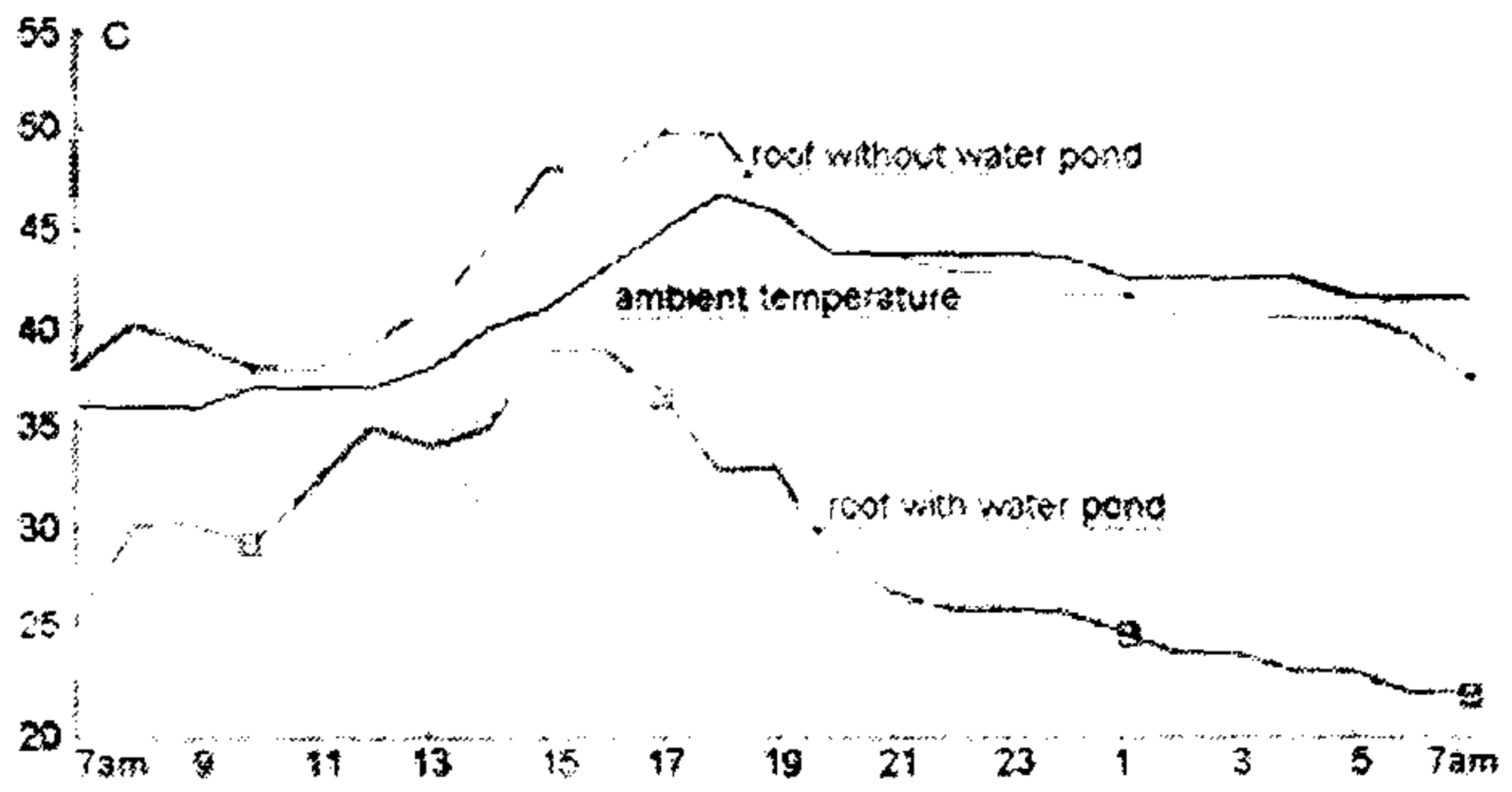

Figure 3.25 Performance of a roof pond in summer

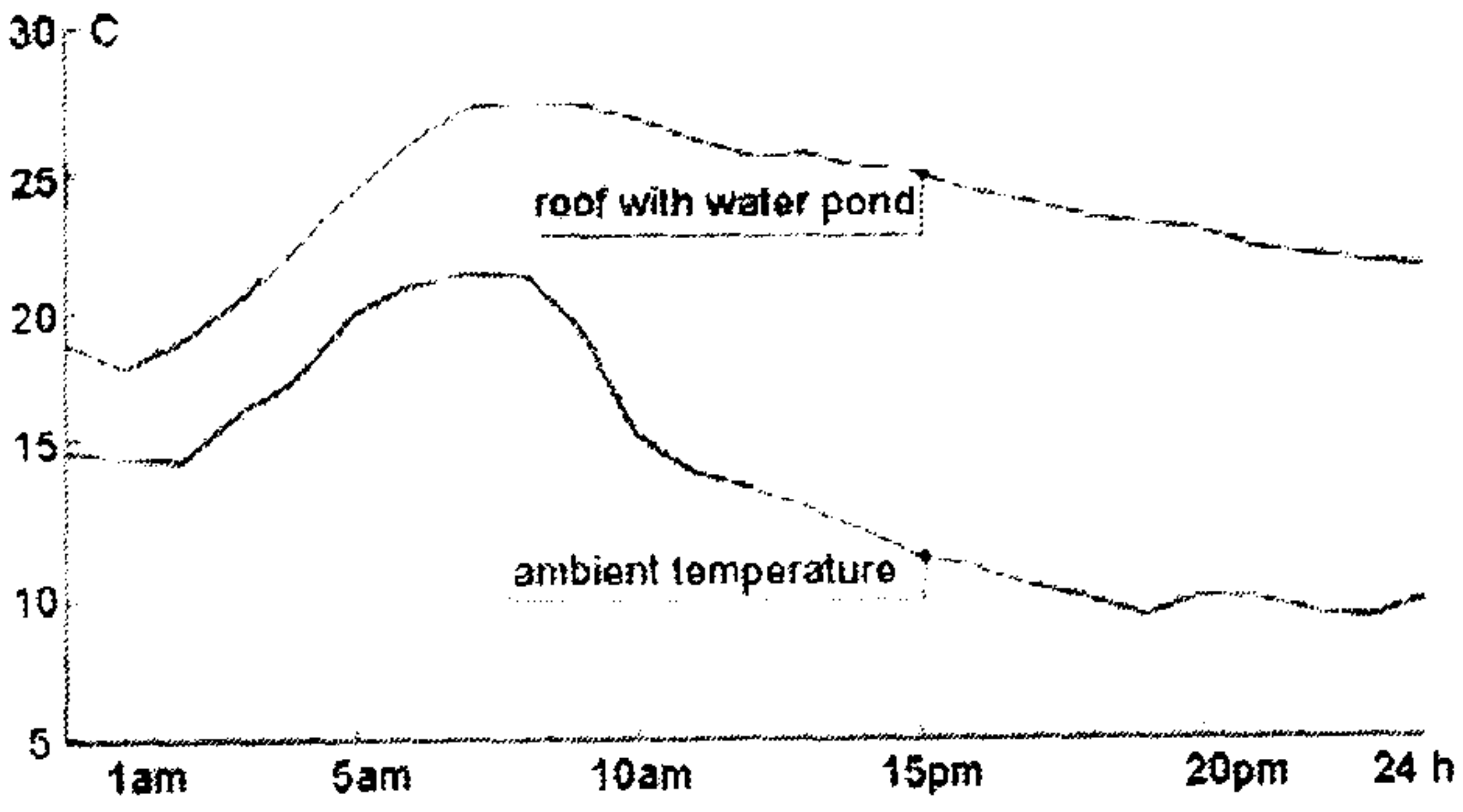

Figure 3.26 Performance of a roof pond in winter

In winter, evaporative loss from the water surface has to be minimized. Thermal insulation is taken out during the sunshine hours to let the water in the tank get heated up by incoming solar radiation, while it is covered with thermal insulation during the hours without sun. The heated water in the pond serves as the source of heat going into the building and the environment inside the building gets heated. Figure 3.26 shows an experimental model on a typical cold day in January [53]. The pond is 100mm deep with 5mm of expanded polystyrene insulation. The cover is removed during the sunshine hours from 8am to 5pm. It is observed that with moveable insulation cover, average water temperature is around 9°C higher than the air temperature, owing to the fact that the fall in water temperature during the hours without sun is retarded by the insulating cover.

3.4.3.3 Roof Plants

Sod with plants on the roof amounts to a complex thermal system that can provide benefits in both summer and winter climates. Most of the heating effect is through the thermal mass inertia of a soil cover which damps out temperature variations. It is recorded that only 30% of the daily fluctuation is felt at a depth of 45mm. Also as a result of its mass, a typical soil possesses a time lag of about 9 hours per 300mm. While for cooling effects, there are two measures. One is to provide protection against overheating. Grass and other leafy ground covers intercept most radiation received, reflecting 20 to 30% and absorbing the remainder at leaf-level. The roof surface, therefore, is shaded and receives much less heat gain than a conventional roof [9, P157]. The other one is related to evapotranspiration. Large amounts of solar radiation can be converted into latent heat and thus the temperature doesn't rise. A study on the energy performance of the green roof was carried out in Athens, Greece [54]. Figure 3.27 shows the temperature difference with and without planted surfaces on the roof. The average temperature of a roof surface with plants is much lower (33.2°C) than the one without plants (43.5°C).

Green roofs can be categorised as 'intensive, 'semi-intensive' or 'extensive', depending on the depth of planting medium and the amount of maintenance they need. An extensive green roof has between 50 and 150mm of growing medium to support plant life. It is designed to be virtually self-sustaining and requires a minimum of maintenance. This limits the size of plants that can be used on the roof, thus limiting the weight of the green roof on the building structure [55]. Intensive green roofs generally have from 150 to 1200mm of growing medium, which will support larger plant life. Large bushes and even trees can be planted on the intensive green roofs. It is on the contrary, are labour-intensive, requiring many careful maintenance which are often called 'roof gardens' to provide recreational opportunities [56].

One of the main disadvantages in the use of roof plants is that more demanding structural standards are required to support soil and vegetation. Green roofs also demand more exacting standards in terms of what is to be installed beneath them, as finding and repairing a leak under 100-300mm of soil and vegetation is an expensive endeavour [55].

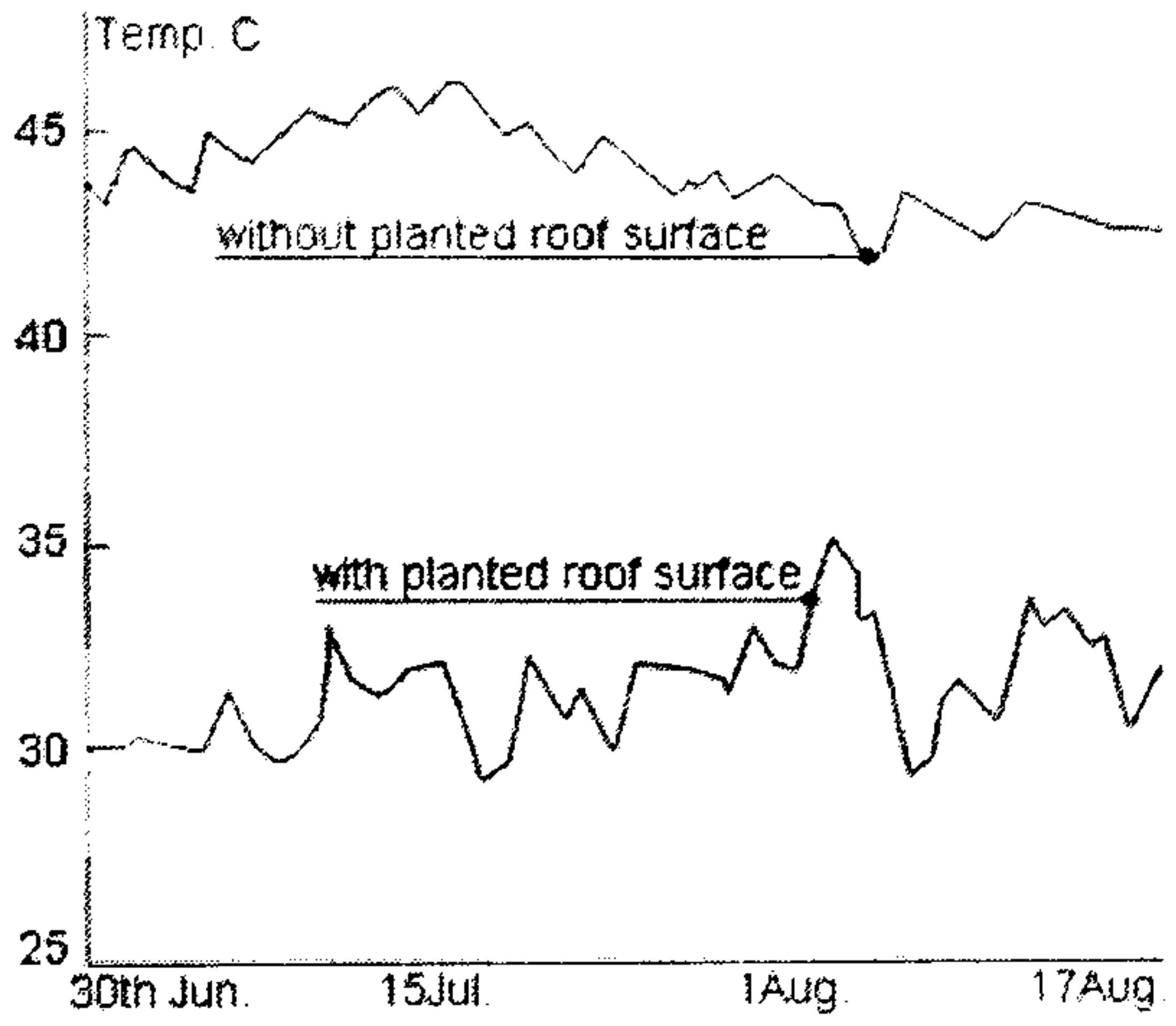

Figure 3.27 Temperature difference between rooms with and without plant roof

3.4.3.4 Roof Radiation

The roof surface is the part of the envelope that has the best view of the sky dome and represents the most appropriate surface for radiative cooling. Therefore, it is selected in order to take both the maximum advantage and minimum disadvantage of the outside situation. In winter, when more solar radiation and heat loss is desirable, a high absorptance surface material is preferable in order to receive and store as much heat as possible. On the contrary, in summer, opaque surfaces should have a maximum reflectivity in the shortwave region of the spectrum so as to reflect solar radiation in order to limit the impact and a maximum emissivity in the longwave region to favour the radiation from the building to the cold sky thus producing an appreciable net heat flux between two bodies.

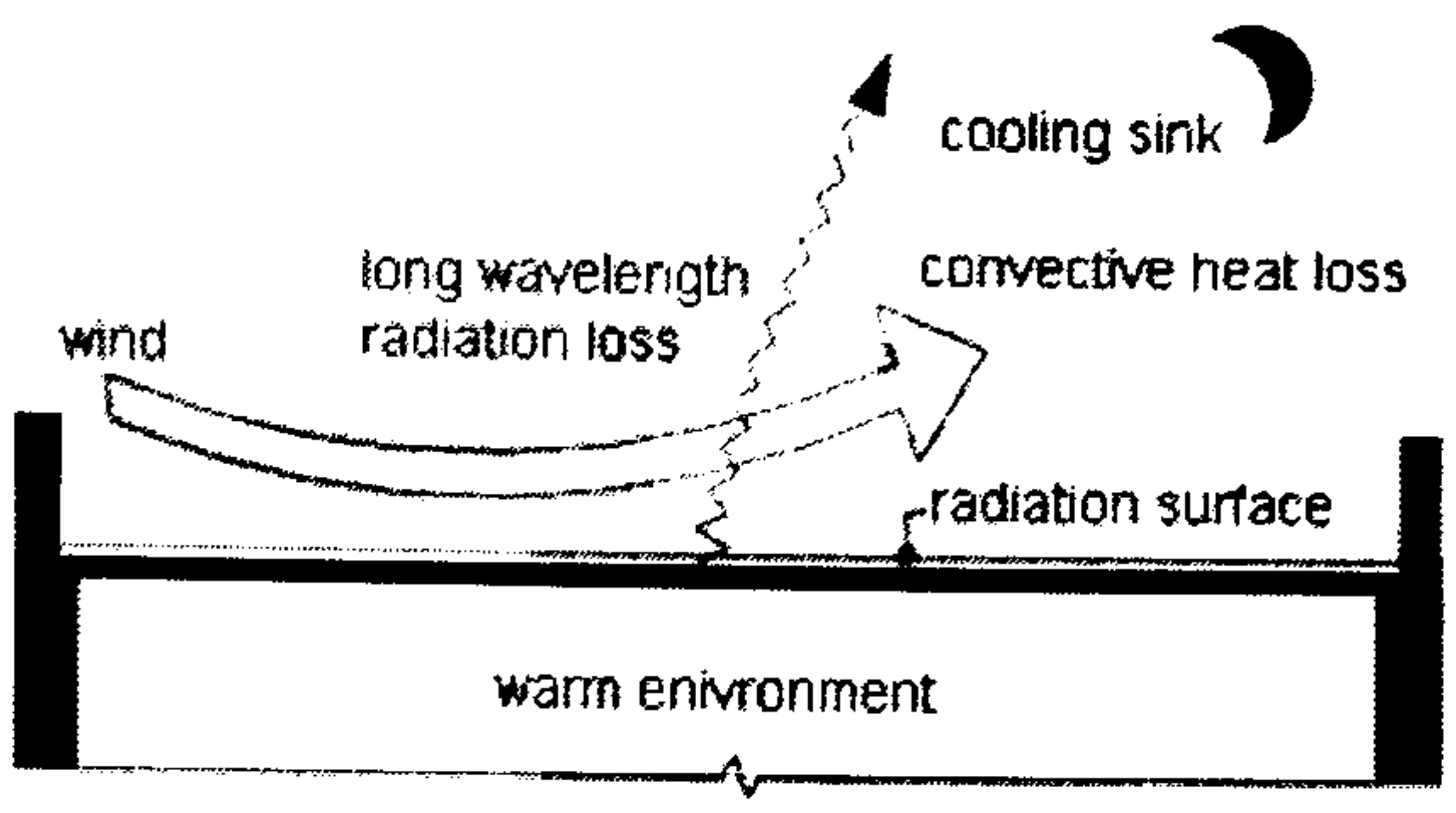

Figure 3.28 Schematic of radiating room for cooling effect

This physical principle forms the basis of nocturnal radiative cooling in an area that is predominated by a hot climate: by allowing heat built-up in the building fabric during the day to be lost by radiation from the external surfaces to the clear night sky, an intermediate heat sink occurs (Figure 3.28) [20, P107]. White paint coating or aluminium sheeting is popularly used since it has the good spectral properties required for radiation. However, highly selective surfaces have been proposed but the potential for radiative cooling of buildings is inherently limited, because the wavelength of nocturnal radiation is quite low (100W/m^2) under ideal meteorological conditions from most architectural materials.

Moreover, there are other two problems identified: one is the convective heat gain from the ambient air and the other one is the transfer of the cold to the building. To improve the efficiency of the system, a thermal storage mass is necessary to be incorporated in the building to carry over the benefits of nocturnal cooling to the warmer daytime hours when they are most needed. On the one hand it can function as a heat sink, absorbing day-time heat gains thus enabling cooling from nocturnal long wave radiation. Furthermore, it maintains the radiator cooling rate in case of the condensation and the indoor temperatures no lower than the design temperature [57].

3.4.3.5 Roof Light

If the building encloses a large floor area and is provided only with site lit windows installed on the wall, the solar radiation and daylight received may be too limited and result in uneven distribution over the floor area. This can be practically solved by placing the roof light to provide a uniform illuminance of daylight to the core of a single storey or the upper floor of multi-storey building [58]. Furthermore, the daylight from roof lights is less likely to be shaded by external trees, surrounding building obstructions and internal columns and furniture. On an overcast day, the advantage of providing daylight can even be significant. The CIE standard has a defined luminance distribution which is considered to be three times brighter when looking directly overhead than when looking at the horizon under a uniformly overcast sky. The horizontal window on the roof face is, as a consequence, the brightest part of the overcast sky and lets in three times as much daylight as the equivalent area of vertical glazing.

On the other hand, the negative impact on the thermal environment of the roof light has to be overcome in that it causes high heat losses in winter and high heat gains in summer. The heat losses are greater than through vertical glazing because warm air rises, creating an elevated temperature difference between the inside and the outside. In such cases, transparent insulation can be used as a view to the sky. In addition, this can also be solved by tilting the roof glazing to an angle depending on the latitude of the site under consideration. For maximum year round collection, the glazing is recommended to be tilted towards the equator at an angle slightly greater than the latitude of the site by approximately 5 degrees [58].

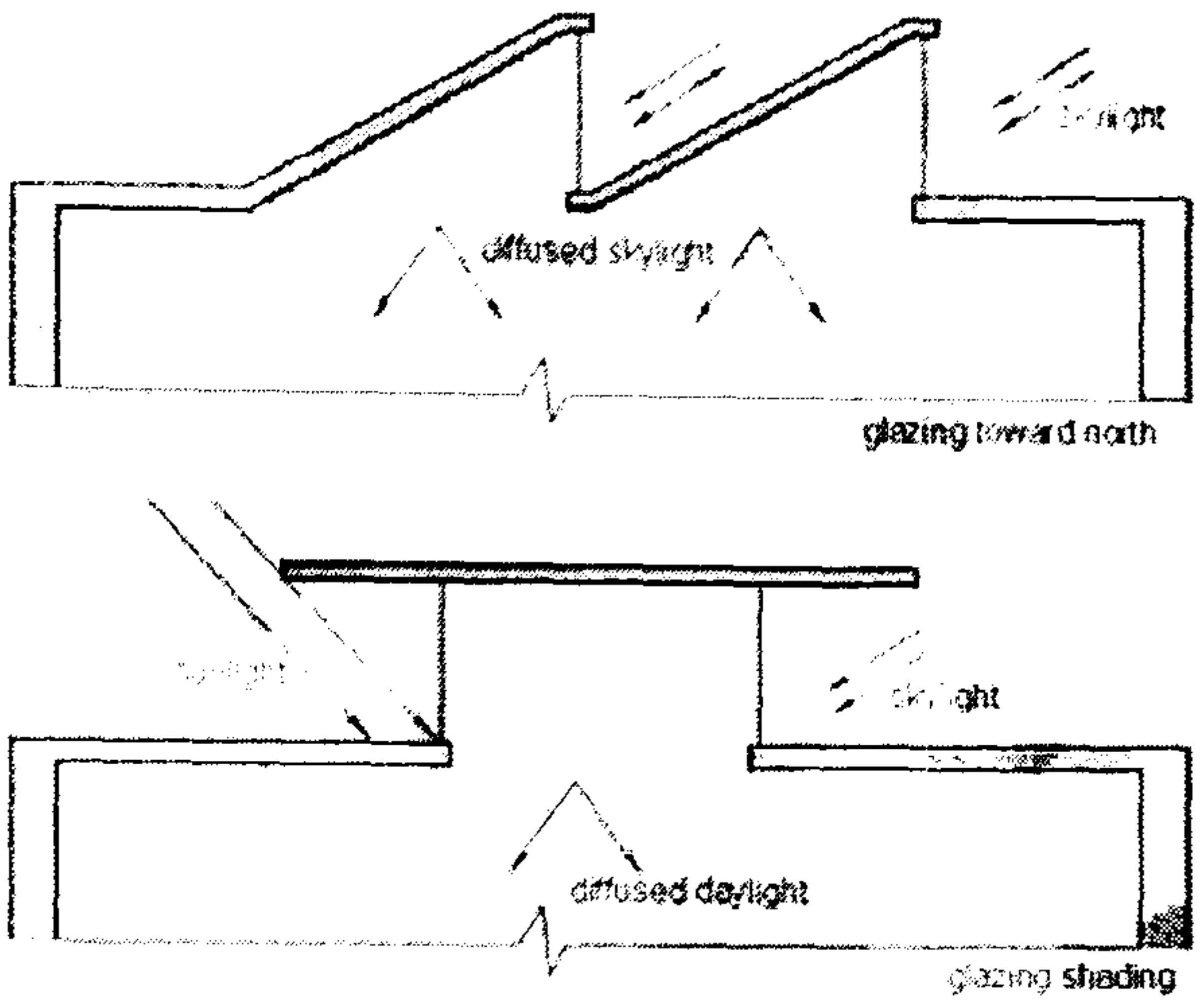

Figure 3.29 Protection of roof glazing from glare and overheating

An alternative can be attempted by using a protection to shade roof glazing or separate the heat component of the solar radiation from the light by locating the glazing towards the north when glare and overheating are the main concern in the design, although this will greatly reduce the amount of daylight entering the building (Figure 3.29) [13, P97].

3.5 Summary

Virtually every aspect of building construction and service has an effect on the indoor environment to a certain degree. Depending on the regional climate and the predominant need for heating or cooling, for the best heating effects are essentially a matter of reducing the heat losses and increasing the solar heat gain inside a building. On the contrary, for the best cooling effect it is important to utilize natural cooling, increase ventilation and reduce unnecessary thermal loads. The impacts of built environmental control strategies are summarized below:

- The landscape may not be easily modified on a large scale, such as the nature of surroundings and topographical features, while the treatment of a site area does have an important impact on the outside environment of the site, such as its surface reflectance, roughness and vegetation. These can be created and adapted in order to modify and improve the microclimate around the building.

- The form of the building dictates the size and shape of the surface area and volume. These two factors determine the general heat exchange rate between the inside and the outside. It also affects the full advantage to be made of natural energy flow. The orientation of the building toward the sun and wind is directly related to envelope heat loss and heat gain.

- The envelope of a building has a significant impact on its energy consumption to meet the requirements of a comfortable indoor environment. In the pursuit of the optimization of natural sources of energy such as solar gain, daylight and air movement, the various strategies may conflict and in such cases compromises have to be made. Therefore, the characteristics of the building envelope and its fabric have to be taken into account and deployed in an efficient and well controlled manner.

From the review undertaken in these two chapters, it is clear how the indoor environment affects occupant sensation and comfort, and how design strategies affect the indoor environment. However, seldom has it been noted how occupants respond to their comfort conditions in order to operate those environmental control strategies. To bridge the gap between occupant operation behaviour and environmental control strategies, this study can be seen as an attempt to deal with such matters and push discussion in this direction. In the next chapter, the way in which this study is designed to test the hypothesis generated in Chapter One will be presented.

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Chapter Four

Research Methodology

- 'Data, data! Data!' he cried impatiently.
- 'I can't make bricks out of clay.'

Sherlock Holmes
The Adventure of the Copper Beeches

Chapter Four
Research Methodology

4.1 Introduction

This chapter attempts to provide a clearer picture of how the study was conducted. First it describes the areas of study. Two naturally ventilated buildings are carefully selected for investigation on the basis of their architectural and occupant characteristics. Based on the scope of the problem mentioned in Chapter One, various data are required in order for case study analysis to be conducted. However, most of this data is scattered in an array of different places thus making the collection of it time consuming. Therefore it is necessary to use a number of different methods in order to obtain the required data.

Broadly, there are three major sections adopted. Section one deals with the parametric analysis of the impact of control strategy on the built environment in these two naturally ventilated buildings, which was mainly carried out through environmental simulation using computer models and physical measurement. Section two, meanwhile, focuses attention on issues of occupant perception and comfort [1]. It mainly describes the techniques adopted and also provides some insight into the testing of the hypotheses. Accordingly, physical measurements were taken, questionnaire surveys and door-to-door interviews administered [2, 3] with occupant control behaviour being directly recorded throughout the conduct of field work and site observation (Figure 4.1). After the cessation of the information collection period, methods of statistical analysis were followed.

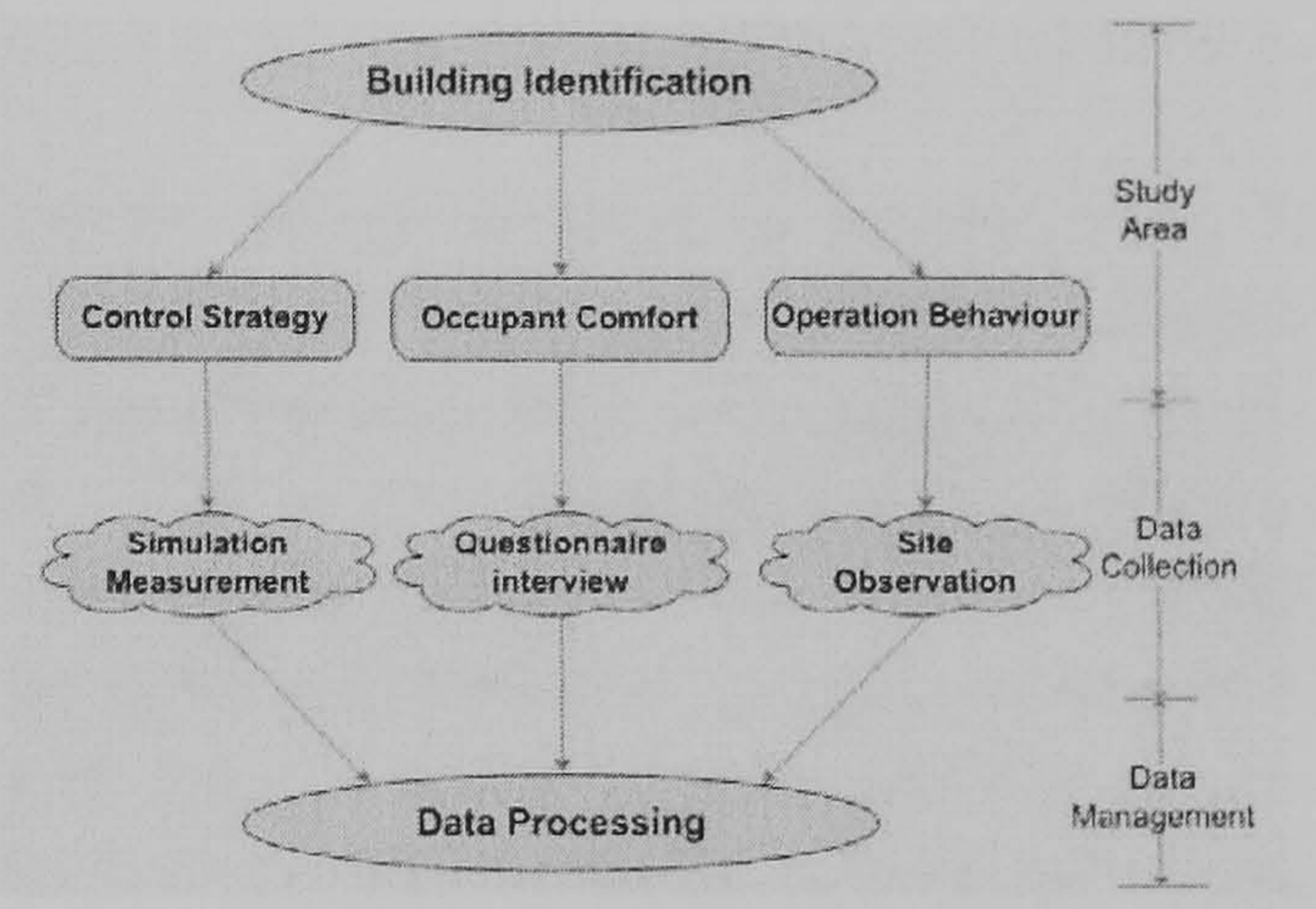

Figure 4.1 Main methods adopted in the study

4.2 Study Area

The main aim of this study is to explore the impact of environmental control strategy, the effect of the built environment on occupant perception and comfort levels and the occupant operation behaviour. Therefore, the study area is restricted to the following:

Building Pattern Indoor environment in the building with air conditioning applications is predominantly stable and automatically controlled by a series building management systems, regardless of internal energy loads and external weather conditions [4]. As a consequence windows are normally sealed and occupants have limited control over the internal climate. On the contrary, the indoor environment in a naturally ventilated building is much harder to control because it normally follows the local microclimate and the temporal and changeable weather variables. Thus occupants play an active role in influencing their environment [5]. Therefore, in this study only naturally ventilated buildings in which occupant-related aspects are major issues are considered, thus, for the purposes of this evaluation, excluding artificially air conditioned buildings.

Building Volume Naturally ventilated buildings are, have been, and will continue to be very common and widespread among contemporary buildings [6], ranging from small domestic dwellings to large commercial or public halls. In this study, the buildings are initially selected on the basis of their provision of various common types of naturally ventilated environments. However, the degree to which the owners and managers of buildings have been willing to accept the study has obviously placed limits on the overall selection criteria. Ultimately, for each type of representative design feature it was possible to target and obtain agreement for the study of two naturally ventilated buildings that possessed these.

Environmental Design Strategy Environmental design strategy is a wide topic. In Chapter Three, various design strategies are reviewed in terms of both their theoretical aspects and practical applications. Although their applications in architecture to improve the indoor environment are manifold, from points of view of adaptive opportunity and control, this study only concerned itself with, those strategies that actively involved occupants in the normal role of the operation. Even with the limitation of the involvement of only two buildings for each category of design feature being imposed on the investigation, it was still prudent to further limit the field of study to occupant-related issues, especially those simple, easy-to-use, robust, and, importantly, visible means of control by the use of which occupants almost immediately experience the results of the actions taken to assert control.

4.2.1 Building Identification

Two institutional buildings, the Arts Tower and ICOSS Building, were selected. Both of these belong to The University of Sheffield, and each building is meant to be viewed and examined independently of the other: no comparisons are drawn between them. Their inclusion was prompted, aside from their possession of typical representative features of naturally ventilated buildings, mainly by two factors.

One is ease of access, which means the building and occupant information can be collected in as detailed a way as possible. The basic building information, such as design, structure and materials used in construction could be obtained from the Estate

Department of the University. The large occupied floor areas and high density of users also provided a sufficient quantity of data samples. In addition, the occupancy period in these institutional buildings changes in a predictable manner throughout the year and thus increases the study's reliability. At the same time the fact that it is a university building makes it easy to get permission from occupants to conduct internal physical measurement, interviews and questionnaires. The other important factor is that occupants in these two buildings have both a closed and sensitive relationship to the outside environment. In order to quickly respond to the unpredictable weather variables, their working and/or study environment provides them with a convenient manual control system with which to satisfy their changing requirements, both easily and simultaneously [7].

The Arts Tower is one of the academic buildings of the University of Sheffield (Figure 4.2). This building was selected because to a certain extent, as far as the provision of a pleasant indoor environment is concerned, it has failed as an acceptable design. In short, this building represents the 'despair' side of a naturally ventilated building. Although on the surface, taking a conventional building standard as the measure, it might not appear to represent a desperate situation, within the context of its own physical built environment in hot summers and cold winters, its glare and noise control, from the interviews with many occupants it seems that conditions are often uncomfortable and, sometimes even unbearable. The investigation of this case is a study of occupant response and behaviour under such circumstances, and what design elements, if any, may be contributing to its negative reputation.

Figure 4.2 Photo of one of the study case: the Arts Tower

ICOSS (the Informatics Collaboratory of the Social Sciences) building also belongs to the University of Sheffield (Figure 4.3). This building is selected because it represents the 'hopeful' side of the naturally ventilated building. It is considered to be a very successful example of the energy efficient of a building use in which sustainability is a fundamental aspect of the architectural concept. In 2006 it was the winner of the national gold award at the International Green Apple Awards for its low-energy use and visually striking appearance [8]. The post-occupancy observation and survey explore occupant comfort perceptions and windows with internal shading roll operating strategies.

Figure 4.3 Photo of one of the study case: the ICOSS Building

4.3 Impact of Environmental Control Strategies

Much work has been done on the impact of environmental control strategy, especially in terms of the building's environmental optimization, energy and comfort performance. Parametric analysis is a common method that has been used in many studies [9-11]. It involves varying one factor in the model while holding all other factors constant. Thus the change in results is solely due to the change in the factor. The method is taken from simple mathematical calculation to complicated computer program simulation based on different purposes and requirements. The reliability of results is usually evaluated and validated with either experimental measurements on a scale model or field measurements performed in real life buildings. In these two case studies, two methods are used in order to demonstrate how control strategies affect - and to what level they can affect - the built environment.

4.3.1 Environmental Simulation Using Computer Models

An attempt is made to do some simple parametric analysis. Computer simulation is used to examine the contribution of each specified control strategy on the built environment of these two buildings. Although the simulation only occupies a small part of the work, it is a very powerful tool adopted to find out whether the built environment may have performed better if different strategies are controlled in a beneficial way [12].

ECOTECT is a building design and environmental analysis tool that covers the broad range of simulation and analysis functions required to understand how a building design operates and performs. This simulation tool is mainly used in these two buildings to analyse the thermal and luminous impact due to the position change of electric lighting, windows and/or blinds.

Radiance is a distributed raytracing package which is optimized to simulate the diffuse distribution and propagation of light in a built environment. It is currently a very popular system for computing the effects of architectural lighting and daylighting. In this study, particular focus is on the model of the visual impact of side glazing and original ways to control the internal shading device. This special focus makes it possible to take into account some complex situations, such as different position of internal shading devices, sky and sun contributions and the orientation of rooms in the building.

4.3.2 Physical Measurement

Since control strategy has been, and still is, involved in the maintenance of environmental comfort conditions within the building [13, 14], it has been decided to carry out some environmental measurements in the buildings. The indoor physical measurement data are mainly derived from two methods: one is the use of a portable meter, and this was employed during the interview based on the survey sheet. The other part only applies to the case of the ICOSS Building. Here a fixed and advanced thermoscope was placed at different primary occupancy floor levels. The choice of equipment for environment measurements during the questionnaire survey was based on the following criteria:

- degree of accuracy
- ease of use and set up
- portability
- ability to measure the variables required

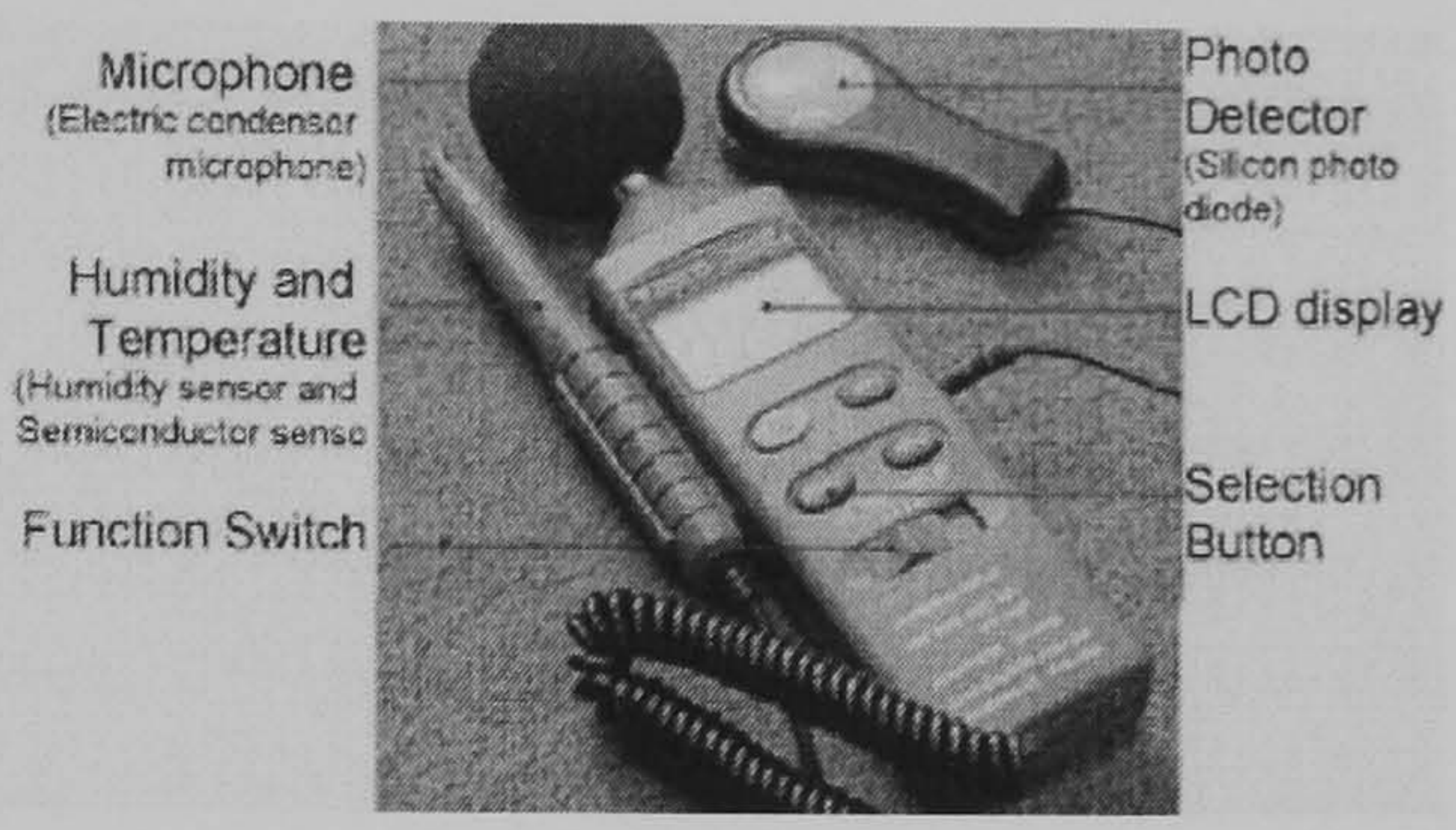

Figure 4.4 Environmental meter used

Ultimately, a four in one digital multi-function environment meter was used. This is a portable test instrument designed in order to combine the functions of the Sound Level Meter, Light Meter, Humidity Meter and Temperature Meter which has scores of practical applications for professional use. The sound level function in this case is used to measure noise level in the room and outside through an electric condenser microphone. The light function is measured by lux level which is fully cosine corrected for the angular incidence of light. The light sensitive component used in the meter is a very stable, long life silicon diode. There is also a semiconductor sensor for humidity measurements and a K-type thermocouple for temperature measurement. A fast time response LCD display with units of lux for illuminance, °C for air temperature, % for relative humidity and A level decibel for sound level indication. Special caution is taken to ensure accurate and representative measurements (Figure 4.4).

A HOBO Temperature logger is located in every main working area of ICOSS building. It is a basic single channel temperature recorder, measuring and recording up to 7943 temperature readings. Its reading rate is user selectable with sampling intervals being 0.5 seconds to 9 hours, recording for durations of up to 1 year. A HOBO Shuttle is needed to readout and relaunch the HOBO data loggers and brings the data back to computer. It is a quick response meter with an accuracy of to ±0.7°C from 0 to 40°C (Figure 4.5).

Figure 4.5 Thermoscope equipment

4.4 Occupant Comfort and Perception of Built Environment

There has been a call for the standardization of field surveys for people's environmental comfort to make them not only easily replicable in different parts of the world but also to make the results of different surveys comparable [15]. The work of Nicol et al in Pakistan is a good example of how a field survey can be conducted [16]. In Nicol's survey, each subject is given a booklet containing questionnaires to fill in, including the sensation of comfort, preference, activity, skin moisture, clothing and controls. The answer to each question is indicated by a tick in the appropriate box. Physical parameters, i.e. air temperature, relative humidity and so forth, are simultaneously measured.

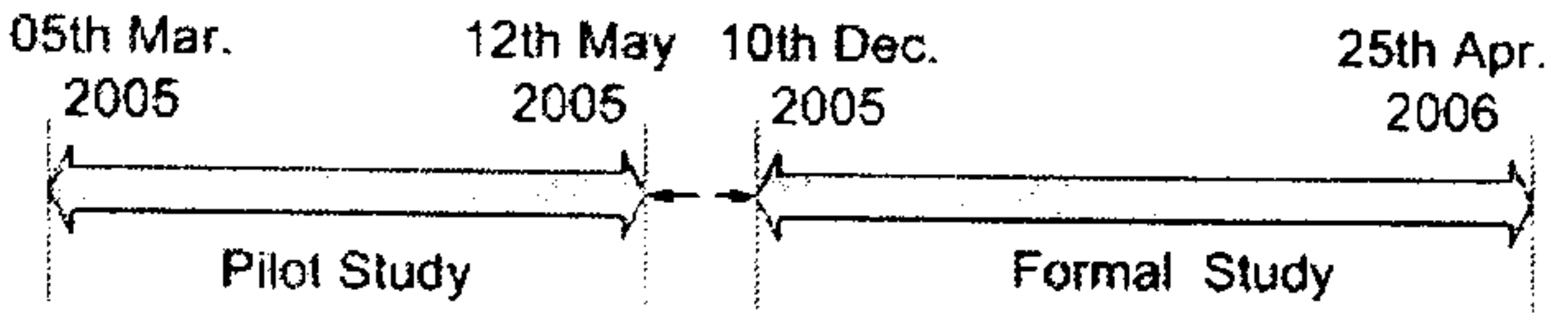

Figure 4.6 Two periods of questionnaire survey

The questionnaires applied in these building surveys are designed in a similar manner, differing slightly only because the two buildings are different [17]. The goal of the questionnaire surveys is to gain an understanding of the occupants experience and perception of their working place, and the control methods they employ to adapt to the changes in the environment in order to improve comfort or alleviate the discomfort. At the same time, the major physical parameters of physical environmental information measured while the interviewee was doing the survey sheet are also in association with the part of questionnaire's concerning respondent response and opinion. In addition, a short interview with respondents was carried out with the aim of providing an excellent way of exploring complex feelings, beliefs and attitudes. Thus the interview produces a richer and sometimes more accurate source of information. The whole questionnaire survey process was divided into two steps: a two-month pilot study from 05th Mar to 12th May/05, followed by a modified questionnaire version used from 10th Dec/05 to 25th Apr/06 (Figure 4.6).

4.4.1 Pilot Study for Questionnaire

Dennis and Kumar [18] stated that 'newly prepared questionnaires should be pretested on a few pilot respondents in order to identify weaknesses, ambiguities and omissions before they are finalised for the survey itself.'

Therefore, a pilot survey was carried out first in order to test the quality of the questions included in the questionnaire, to detect any problems that are commonly encountered during the proper interviews, and to find ways of solving or minimising them to ensure that these questions are not ambiguous and can be clearly understood by interviewers and respondents. Nevertheless, some explanations by the interviews are required to clarify certain points. In this way, a certain level of consistency can be achieved in the interviews. All the questions are designed as precoded because of the evident efficiency of such questions in interviewing, coding, tabulating and analysis.

Another reason for this pilot study is to select the nature and characteristic of the population to be surveyed. Because both case studies involve institutional buildings in the university, their occupancy densities are greatly influenced by the university semester schedule. In sample selection for the surveys, priority was given to occupants who were very knowledgeable about these buildings, having, for example, experience of routine and day-to-day changes, the status of the control system and the environment assessment for seasonal variations over the whole year. This was done to minimise the bias arising out of individual preferences. Furthermore, the choice of room occupant was greatly influenced by the availability of people willing to take part in the survey and also on the availability of people willing to have their rooms used in the survey.

4.4.2 Final Experiment for Questionnaire

After the pilot survey of 45 interviewees was finished, the amendments were incorporated into the final version of the questionnaire [19]. The content of the questionnaire was divided into two parts: the survey and the observation sheet. The observation part records respondent's personal information: their age, gender, clothing, occupancy identification and basic information about the room they stay in and any extra environmental controls used, such as plants, heaters or fans. The measurement data and interview information were also entered on this sheet. The survey sheet concerned the respondents' personal experiences and responses to the indoor environment which they were in. The main aspects of the survey covered by the questionnaires are:

- immediate (i.e. at the point of questionnaire completion) perception of individual indoor environment;
- immediate comfort level of the individual indoor environment;
- occupancy situation out of normal working hours;
- frequency of discomfort and noise level disturbance;
- current window and blind control status;
- preferred situation of window, blind, door and artificial lighting under different weather conditions in the case of the Arts Tower survey;
- overall comfort level in the room month by month over the course of the whole year (in the case of ICOSS building, the question is framed in terms of seasonal variation);

Finally, a probe question was posed which was designed to reveal what were the crucial building environment features to different people from a broader perspective. This question was the only open-ended question, since these had to be kept to a minimum in this study, as they are often off-putting, difficult to answer, and require reasonably extensive written responses [20].

Except the last question mentioned above, the other questions all use a rating scale to measure respondents' preferences with regard to the built environment. This approach is frequently used to measure perceptions of the environment [21, 22]. By standardising the scale, the need for judges is eliminated, by getting subjects to place themselves on a linear attitude continuum for each statement, and adverse effects minimised, thus increasing the reliability of the rating. In environmental perception research, there is a variety of rating scales available. The main scales used are a 7-point degree scale to describe feeling in the current situation while a 5-point degree scales for the perception in a general situation. Both can make it easy for respondents to distinguish the gradation.

The choosing of the target study population is guided by Nicol [23] and the main considerations are:

- to get an even ratio of males to females;
- to get an even mix of all age groups (although in an institutional building of a university it is difficult to find very young and very old people);
- to find subjects acclimatised to the environment

It is difficult to enough meet all of the above criteria, but especially so for respondents in university buildings. Age and gender information in this study was included for demographic validation reasons rather than for the purpose of correlation investigation. Also for the consideration of acclimatization to the environment, people who spent less than 80% of their work time within their own office space were excluded. Detailed information about the final version of the questionnaire is attached in Appendix A.

4.5 Occupant Operation Behaviour

Humphreys [13] and Nicol and Roaf [16] demonstrate that people use various control methods to adapt to the changes in the environment to improve their comfort. This study attempts to find out in what level and in what condition this adaptive model is applicable in terms of interaction between occupant and environmental control systems given the difference in weather and building room where this model has been tested. However, this case study is constructed on a design basis, rather than a social science basis; thus the validity of observation intent is paramount.

4.5.1 Weather Information

The external environment undoubtedly has a great impact on the extent of the interaction between the environmental performance of buildings and the comfort level of the occupants. As the research problem outlined in Chapter One has indicated, unpredictable weather influences the occupant comfort sensation and indoor environment with short-term fluctuations which may be the cause of many adjustments made by the occupants. Therefore, weather information during the on-site observation period time is one of the most important variables that relate to this study.

The major weather information during the investigation from 01st Jan/05 to 30th Apr/06 was collected from Weston Park Weather Station which is an official weather station for the Sheffield region [24]. The station is located in Weston Park, one mile west of the city centre, surrounded by the University of Sheffield and managed by Weston Park Museum

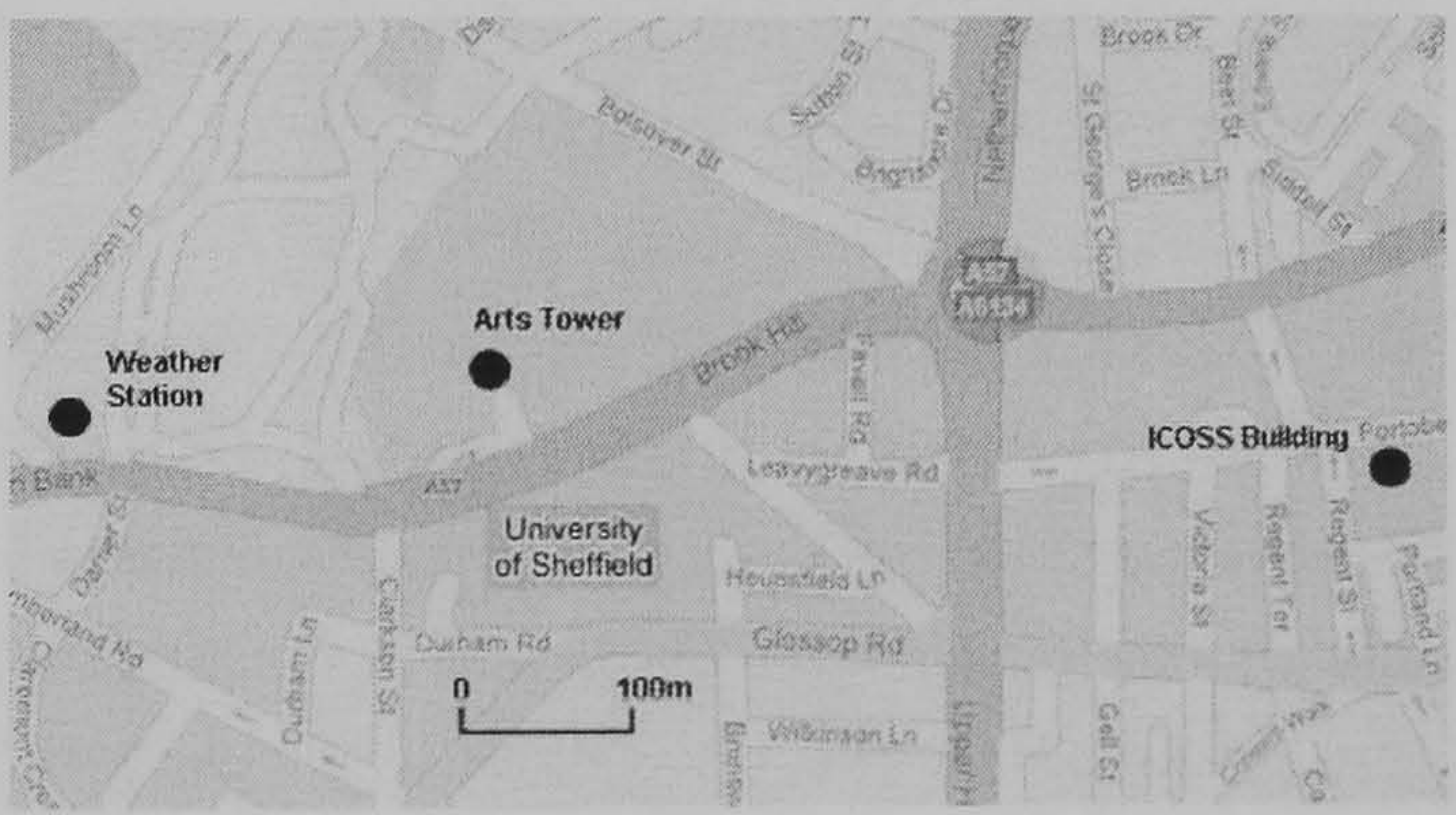

Figure 4.7 Location of weather station with the Arts Tower and ICOSS Building

that is to the left of it. Figure 4.7 shows the location of the weather station, the Arts Tower and the ICOSS building. Major weather parameters collected from Western Park Weather Station are:

- hourly maximum air temperature (°C),
- hourly minimum air temperature (°C),
- hourly relative humidity (%),
- hourly solar radiation,
- hourly sunshine hours (h),
- hourly wind direction and speed (knot) (1knot=0.51m/s),
- daily mean air temperature (°C),
- daily rainfall totals,
- daily sunshine hours,
- daily relative humidity and
- monthly major information in thirty years

4.5.2 Field Observation

The intention of the site visit was to observe the way occupants seek to maintain equable comfort conditions in the face of variations such as the room feature and the ever-changing weather in order to address the following question: what do they do and how do they do it? Because a system of glazing with internal shading devices performs quite a complicated multi-purpose function, often, as illustrated in Chapters Two and Three, having to accommodate conflicting requirements, its operation to a certain extent reflects the occupants' adaptations of the built environment in order to suit their needs. Therefore, the field observation in this study focuses attention on the operations of the windows and internal shading devices of both buildings: windows with venetian blinds in the Arts Tower and windows with roller shades in the ICOSS building.

Figure 4.8 Window and blind in the Arts Tower

Figure 4.9 Window and shading roll in the ICOSS Building

The works of M.S.Rea in Canada [25] and Michelle Foster et al in UK [26] are good examples of how a blind-operation-related field survey can be conducted. A thorough photographic record is taken, so that information gathered can be verified away from the site. Necessary equipment with a digital camera is used to collect the position information of all the blinds and windows under investigation. When the photo is taken, the date and time are automatically stored in the photo information. Figure 4.8, 4.9 shows part of the photo image of windows with venetian blinds in the Arts Tower and windows with roll shading in the ICOSS building.

The field work lasted sixteen months and the whole process was divided into two steps. The first took place from Jan 2005 to April 2005. Among the total of 120 days during this period, 90 days worth of records (75.0%) of the window and blind position were taken, one per day. There are three main reasons for the initial work. One reason is the opportunity for testing the method applied and finding potential errors that can be 'ironed-out' in the final study set-up. The other reason is to explore the feasibility and efficiency of the method itself i.e. whether yielded data can be applied to test the hypotheses of this study, in terms of both time and resources.

After identifying as well as locating the ideal place for recording data, both in terms of its capacity to inspire confidence in the final set-up and the results themselves, the second step keeps to the original method. In order to have an overall view of the impact of ever-changing weather conditions on occupant manual operation, the observation lasts for a whole year from May/05 to Apr/06. Internality and constancy were achieved during this period time with only two days of recording missing: 05th Jul/05 and 08th Jan/06. In addition, based on the occupant's specific working schedule in these two institutional buildings, photos were taken twice in the standard semester day: around 10am and 3pm; once during in weekends, public and bank holidays and vacations (including Christmas, Easter and summer vacations).

4.6 Method of Data Processing

Once data had been collected, the editing of data gathered was conducted. This involved data organisation and data manipulation in order to demonstrate the relationship between research variables so that the phenomenon being studied can be explained. Statistical analyses are used to establish the significance of these relationships through hypotheses testing [27]. Due to the many variables involved it was very time-consuming and demanded a reasonably advanced computer effort in terms of both processing time and storage capability in this research

Before statistical analysis, the collected data were cleaned and put into the proper format via database management programs. There are lots of computer programs available for data processing. Due to the amount of the records stored in the database, two of them were evaluated and used in the different scenarios. Microsoft Access is a light-weight database management program, running on the Microsoft Windows platform. It allows for relatively quick development and is suitable for the building of prototypes. The friendly user interface and handy help system makes it fairly easy of use and quick learning. However, the relatively slow speed of data processing, and the limitation imposed by the total number of records, limits the data scale to be processed. In this instance it was used in the pilot study and for the detailed analysis of certain selected data sets, such as weather data, building room information, questionnaire results and physical measurements.

However, the processing of information concerning window and blind operation is a task beyond the limitations of Access, as well as many other popular database packages such as SPSS. Therefore, PostgreSQL was introduced in this case. This is an 'open source' database system, which means it is free and also that it supports various operating systems. The speed of PostgreSQL is greater than that of Access, and it also has a rich variety of function features which supply an array of adequate tools for the querying and manipulation of data. Nevertheless, the weak point here is its simple interface (the official 'off-the-shelf' release only has a command line interface), which prevents the beginner from taking full advantage of its capabilities. All the same, in this research it is used to filter, calculate, query and manipulate large scale data. The structure of all the tables in the database is designed to make it easy to access corresponding information and perform calculations.

4.6.1 Weather Information

The weather information gathered is dealt with in two ways. One concerns an analysis general weather trends in Sheffield over the thirty years from 1971-2000. The situation during the investigation period (Jan/05 to Apr/06) is then compared with the previous records in order to have a close up view of the data provided, like temperature, humidity and hours of sunshine etc., highlighting notable irregularities within the general pattern. Table 4.1 shows part of the structure and content of hourly weather information.

Date	Time	Max. temp. °C)	Min. temp. (°C)	RH (%)	Rainfall (mm)	Wind speed (m/s)	Sunshine (h)	...
01-Jan-05	06:00	7.15	6.6	81.8	0	8.09	0	
05-Jan-05	15:00	8.54	8.14	73.6	0	11.61	0	
...								

Table 4.1 Part of the structure and content of weather information

On the other hand, due to the fact that hourly weather information from weather station involves all the 24 hours of the day and the 7 days of the week, the data have to be further filtered with reference to the occupancy times and daily routines in these two buildings. Because the occupants are inside mainly on working weekdays during the daytime with a standard starting and finishing time, beginning at 9am and ending at 5pm. Before and after that range, the occupancy density is significantly reduced and nears zero in three hours. Therefore, only the period lasting from 6am to 8pm is focused on, especially when analysis is related to the built environment and observation survey. The average daily value, here, is recalculated due to only 14 hours per day being involved.

4.6.2 Building Occupation

The investigation only concentrates on the passive zone of the two buildings. The 'passive zone' is defined as the space on the perimeter of the building and which can make use of daylight, solar gains and natural ventilation. Conversely, the non-passive zone normally has to be artificially lit and ventilated and, in many cases, cooled as well. The depth of the passive zone is limited to twice the floor to ceiling height. The whole of the top floor can be a 'passive zone' if a skylight is provided [28]. In these two case studies, 6m for passive zone depth is used.

In the ICOSS building, when exposed to the consideration of such criteria, the study was further limited in order to focus the attention on the working areas where most of the daily activities of the occupants were taking place. It includes one east room on the second floor, six rooms toward the north and open-plan labs from the second to fourth floor. There is no personal office in this building. Apart from the open-plan offices, all the others are multiple-occupancy office rooms. These are shown in Figure 4.10 (shown in grey).

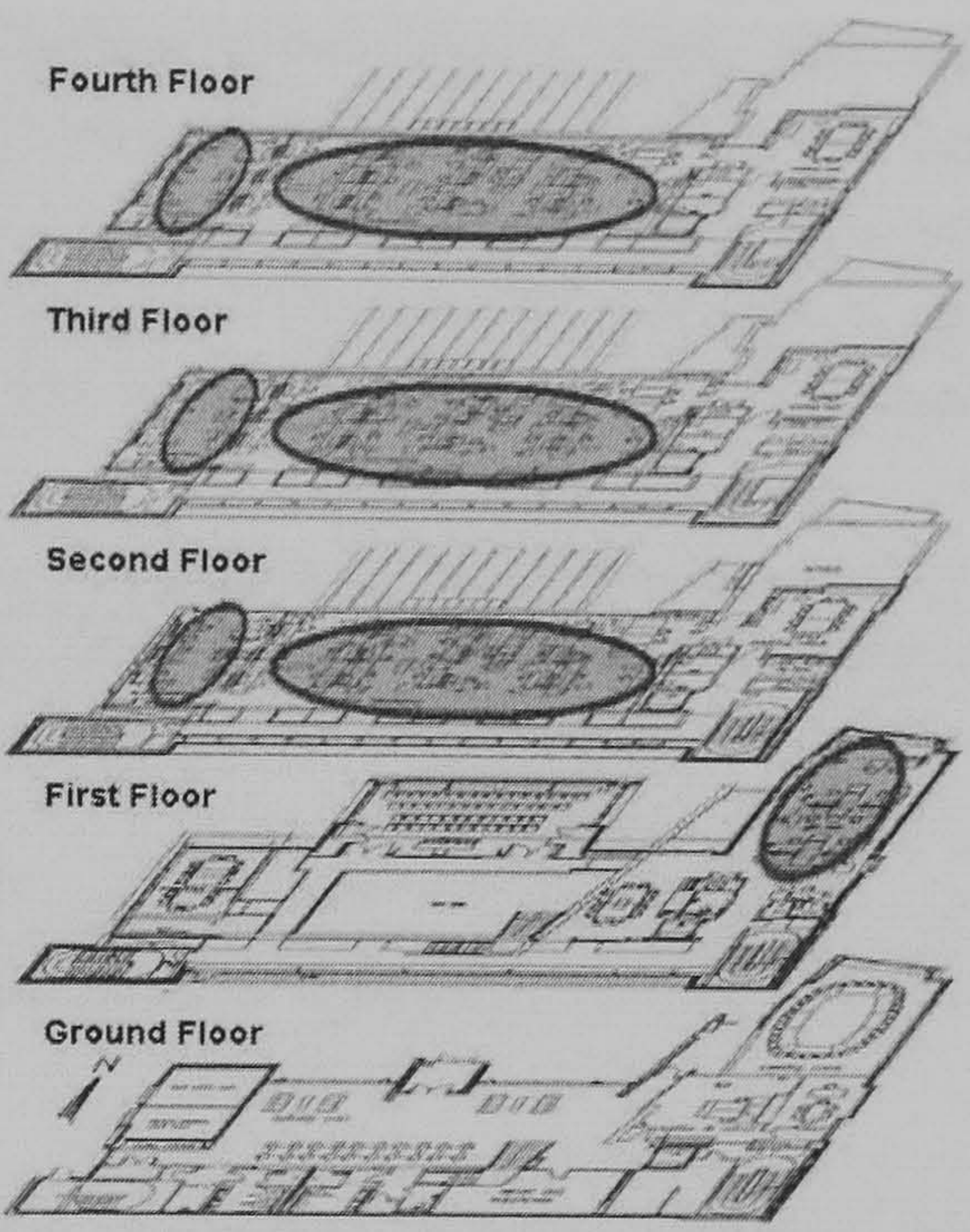

Figure 4.10 Area mainly for working activity in the ICOSS Building

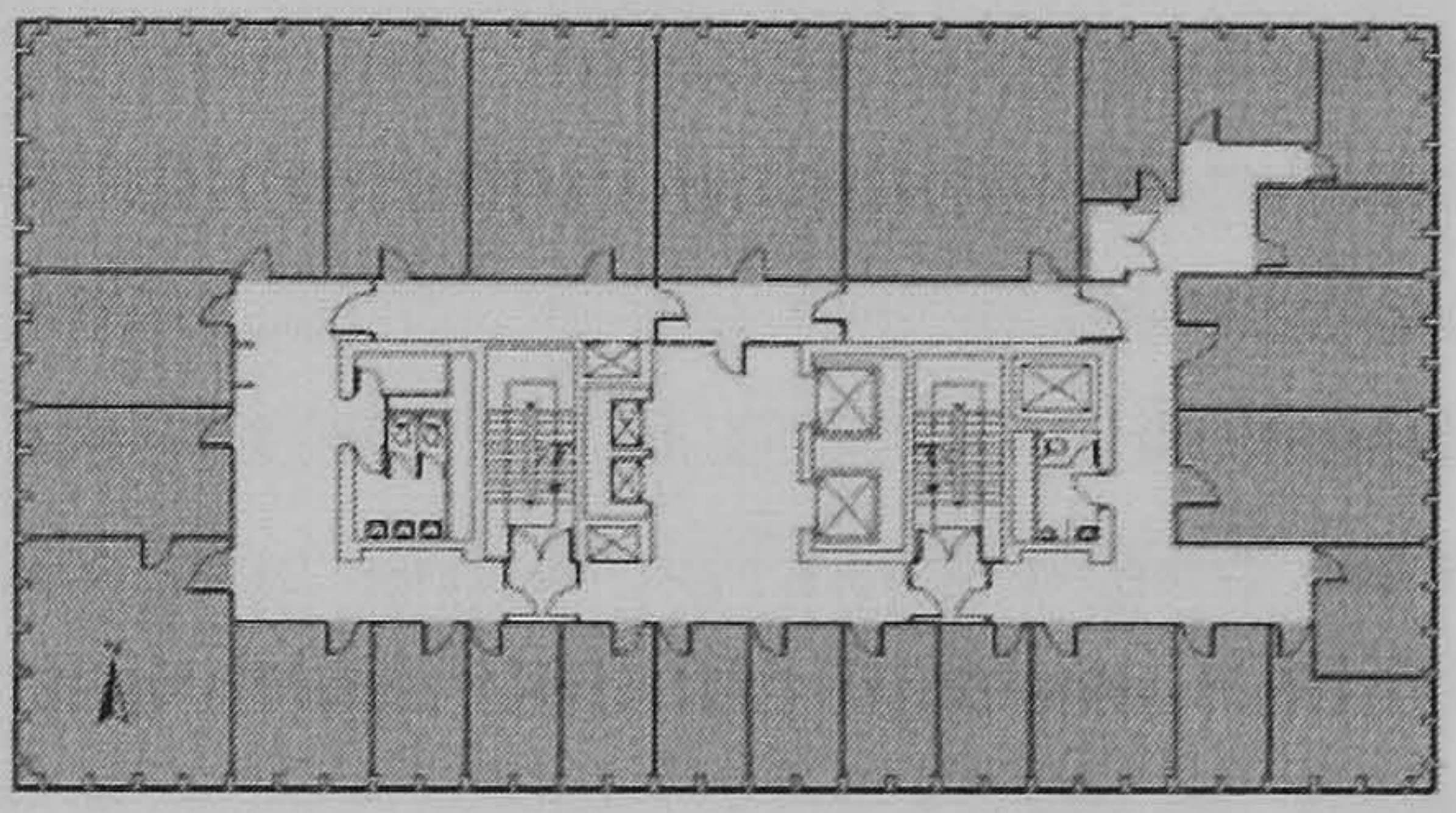

Figure 4.11 Passive zone in a typical floor in the Arts Tower

In the Arts Tower, only the passive zones from the 1st to the 18th floors are considered in this study. Figure 4.11 shows the passive zone considered on a typical floor. The ground floor and the mezzanine floor are used mainly for entrance and transition. There are no rooms on the perimeter of the building so these two floors are not included in this study. In addition, the underground floors have lecture rooms towards the north and the east which are in the passive zone, while the whole of the 19th floor is covered with the metal shelter built around the perimeter of the building. But in these instances the windows could not be reached and observed easily without first obtaining permission to go into the underground area and the outside of the top floor from the University authorities. Considering this was a project involving long-term observation, from a practical point of view, the rooms in these floors had to be excluded from the analysis.

After identifying the areas to be studied in these two buildings, all the rooms under investigation were assigned with a unique identification number from 1 to 370. The basic information about each room, like the accommodating building, floor, room number and so on, is also recorded in the database and associated with the identification number. Table 4.2 shows part of the structure and content of the presentation of room information. For example, room No.18 is on the second floor of the Arts Tower. It is an office whose official Arts Tower room number is 2.3, which is the number given by the department on that floor. Its area is 23.5m^2 with one person working in this room.

Room ID	Floor	Building	Room no.	Area (m^2)	Occupancy	Room feature	...
18	2	A.T	2.3	23.5	1	Office	
65	8	A.T	8.5	35.3	3	Office	
...							

Table 4.2 Part of the structure and content of room information

4.6.3 Photo Record

All the windows under the investigation in the two buildings are coded in a numerical order from 1 to 2094. The survey concentrated on identifying the position of the window and blind and each photo was analysed using the positional information. Two rating systems for evaluating the window and blind position from the photographic slides were developed [29]. Particularly for blind position analysis, the concept of the 'occlusion index' was introduced. This is a percentage value that is given to represent the proportion of the window area that is obscured (or occluded) by the blind and slat position. The shading devices were calculated in a similar manner, differing slightly only because one concerns blind slats in the Arts Tower and other shading rolls in the ICOSS building. The following steps are the process how to get the occlusion index of each blind position and window position:

1. The value for blind position is ranked from 0 to 7 respectively. This decision was due to a series of factors such as building height, amount of space available in front of the building and the resolution of the digital camera. The range from 0 to 7 can be evaluated accurately in the photo with bare eyes from a realistic and practical point of view. Above the 8-level this becomes difficult and the difference from the photo can be hardly recognised unless advanced measurement tools are used. Given that the 8-level standard is precise enough for reflecting occupant's blind operation situation, using advanced measurements for the sake of accuracy way was not necessary.

2. These values are divided by their maximum values (7) respectively to obtain the proportion of occlusion. In the case of the Arts Tower, the pitch of the blind louvers is also considered with a 2-evel rating scale to evaluate the angle of the blind. So when it comes to those slats with an angle, it further multiplies 51%.

The value of 51% instead of 50% is used because each value can represent one unique blind position thereby avoiding repetition. The 2-level standard is also selected due to the same reason as the 8-level position of the blind. In total the proportion of the window covered by a blind is taken into account in 15 situations. Figure 4.12 shows the standard position models for two buildings' blind analysis. For example, a completely lowered blind is given a value of occlusion index 100% while the occlusion index with a completely elevated blind is 0%.

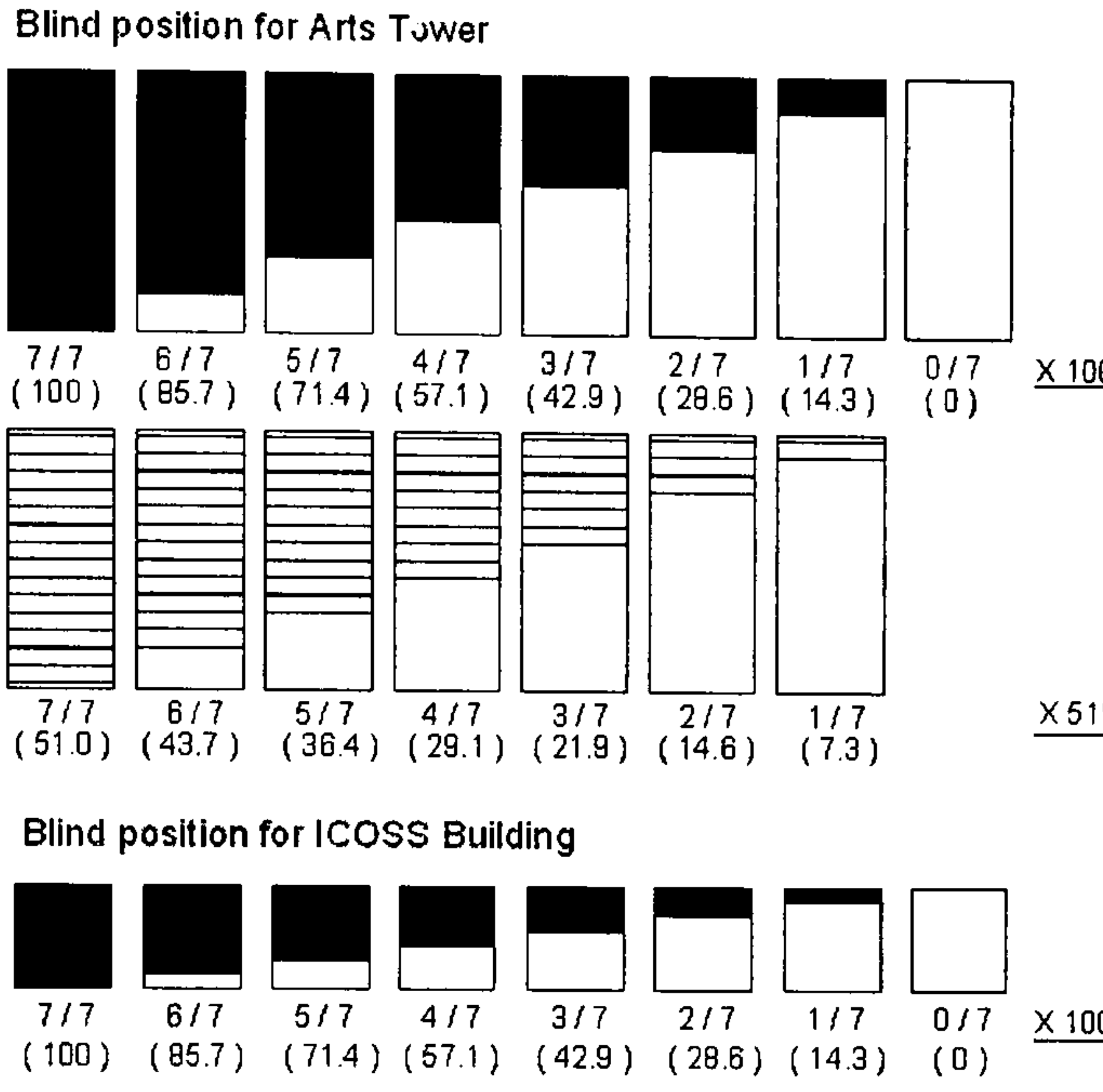

Figure 4.12 Models of blind position for the Arts Tower and the ICOSS Building

3. Almost all the windows under investigation include a white internal shading device, but there are still 11 windows towards the north and 6 windows towards the west in a corner room on the 12th floor of the Arts Tower with black venetian blinds, and this situation makes it very difficult to tell their positions from the photo. In this case, only the window position was considered while the analysis of blind position was not included at all. In addition, some rooms in the Arts Tower not only feature horizontal venetian blinds but also curtains. They are examined in a similar manner as was the case with the ICOSS building.

4. Although all the windows in the investigation have internal shading devices, not all the windows are openable. 144 corner windows in Arts Tower and 246 windows in ICOSS building are sealed, which occupies 8.2% and 74.5% of the total windows that are investigated in the two buildings respectively. For those windows not sealed, ways to open are different in each building. In the Arts Tower, windows are vertically sliding while in ICOSS building they are all top-tinged, allowing them to swing open towards the outside.

5. During the investigation period, usually all the windows were opened with a maximum 300mm height in the case of the Arts Tower, while a minimum adjustment level was selected for opening the ICOSS building windows. The differences in opened level size were not as recognisable as they were with the blinds. In this case, only three situations are considered and recorded as 'open' or 'closed' or 'fixed'. Figure 4.13 shows the standard position models for the two buildings' window analysis.

6. The date and time were abstracted from the photo when data processing is performed. In order to make these blind and window position data strongly linked to the outside environment, the time was selected with up to the minute precision.

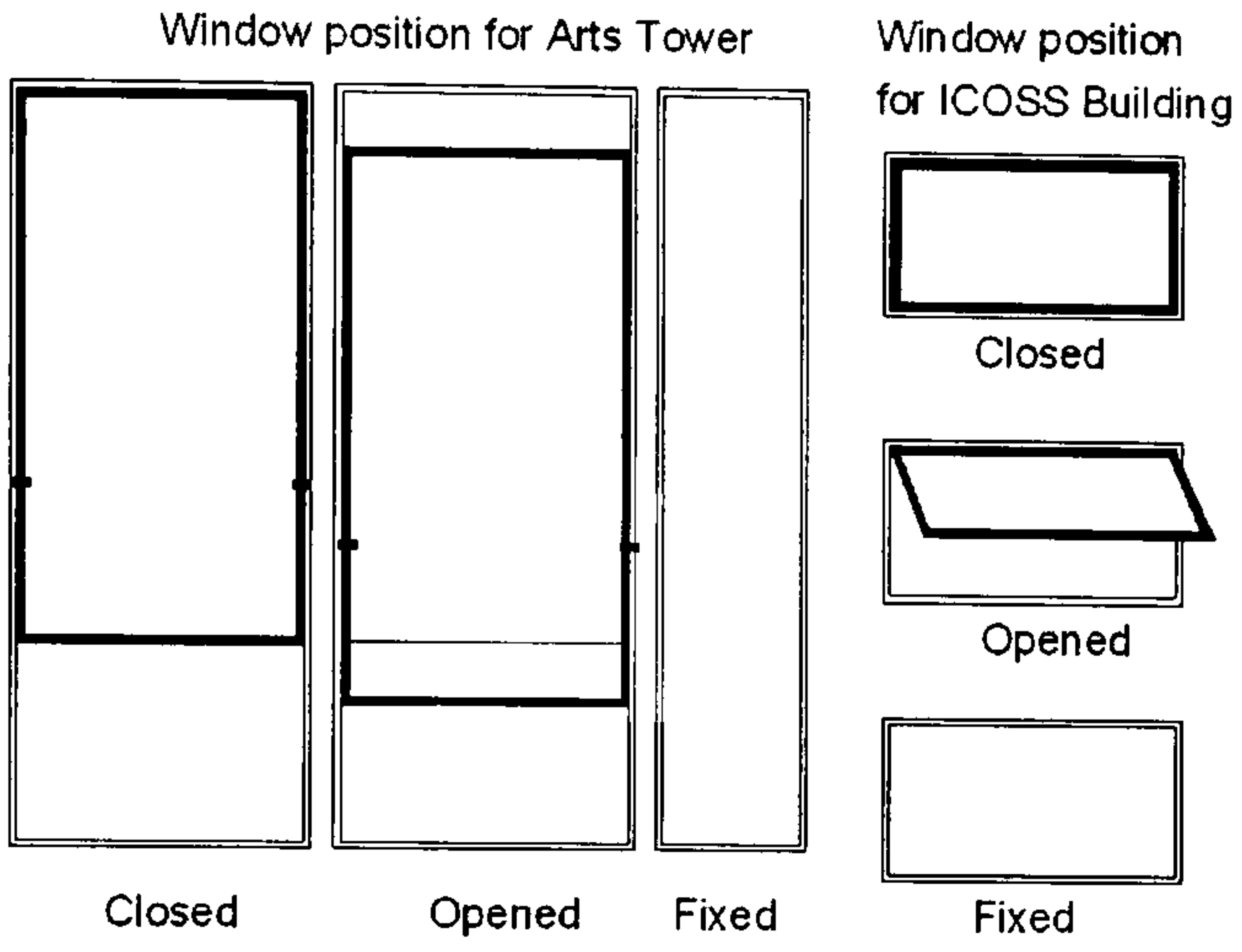

Figure 4.13 Models of window position for the Arts Tower and the ICOSS Building

Table 4.3 shows part of the final structure and content of the operation information below. The first column is the window code which can be traced to the room table to find out which building, floor, direction and room number it belongs to. The second and third columns are the dates and times when the values for window and blind information were recorded. And the fourth and fifth columns refer to the values for its window and blind position. These are also connected to the weather table. For example, the window with number 1 coded was open and its blind occlusion index was 16.7% on 2/Jun, 05 at 14:32:00.

Window ID	Date	Time	Window position	Blind position
1	02-Jun-05	15:02:00	Open	16.7%
72	25-Dec-05	10:15:00	Closed	51.0%
...				

Table 4.3 Part of the structure and content of operation information

4.6.4 Questionnaire Collection

Although cases involved are institutional buildings in the University of Sheffield, their different typologies lead to their own expected patterns of taking account of occupants. The ICOSS building is mainly an interdisciplinary research centre for the social sciences, which means occupants are here usually for work and have a standard working schedule living here. Right up until the time when the survey was finished, there were regularly around 45 occupants working in this building. The total number of subjects who took part in the questionnaire in the ICOSS building was 35 with a 77.8% sample proportion against the total population in the building. There were 12 males and 23 females (34.3% vs. 65.7%). The subjects age groups are as follows: 16 were between 20-29 years, 15 from 30-39 years, 3 ranged from 40-49 and 1 was 50-59 (Figure 4.14). In total there were 4 floors with 9 rooms involved in this survey. All of the subjects had their fixed working stations no matter whether they were in a multiple or open-plan lab.

Compared with the ICOSS building, the Arts Tower tells another story. In this case this academic building houses various different departments. A large number of occupants visit this building for for all purposes intermittently and temporarily. Although the standard semester day is fixed with a standard starting and finishing time, on average these people occupy from 20% to 120% of the total semester day and time. However, there are around 300 occupants who have fixed places to work and study in this building. Considering acclimatization to the built environment in this instance, the selection of samples was thus concentrated on these occupants. The proportion of the sample against the total population of this building is shown in Table 4.4.

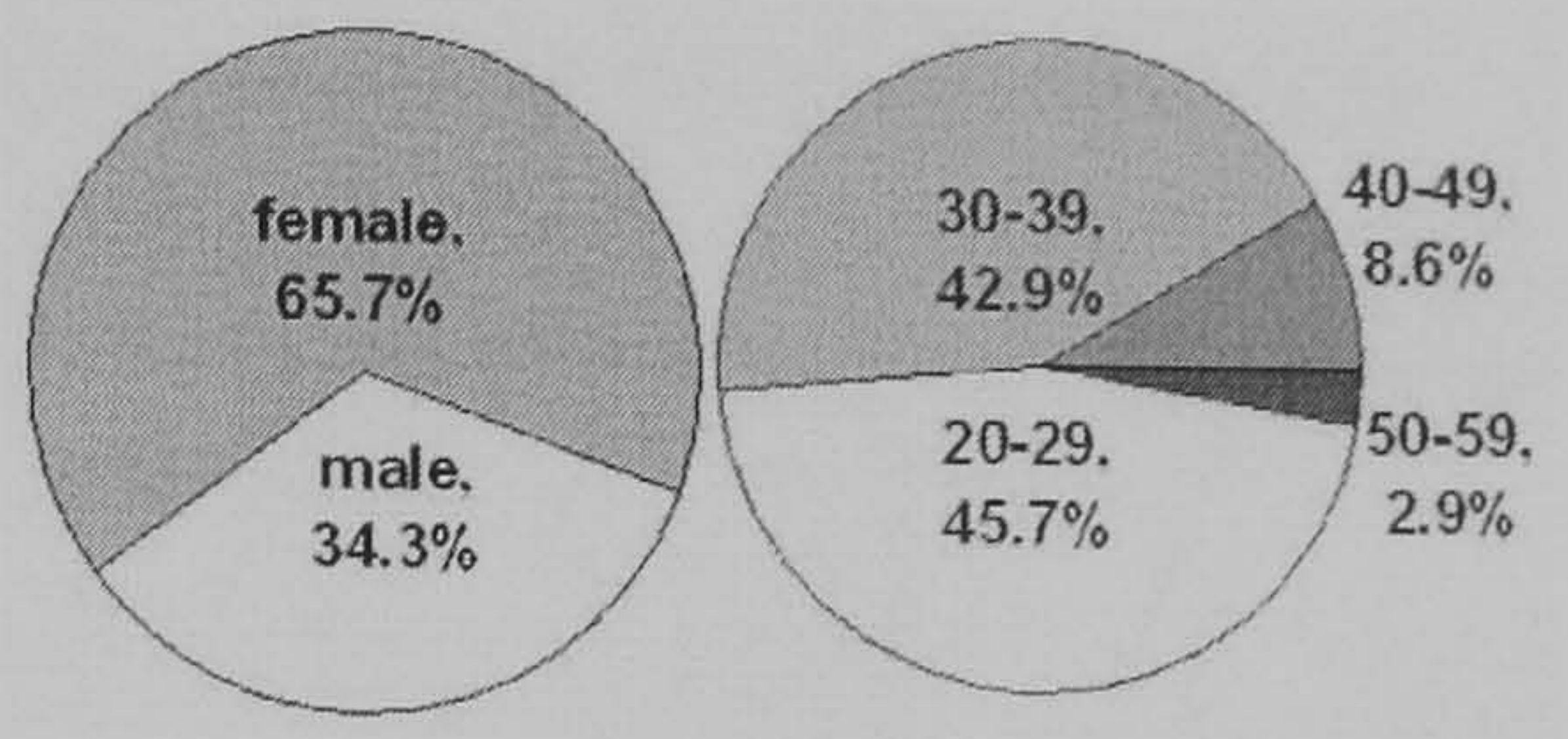

Figure 4.14 Distribution of survey subjects in the ICOSS Building

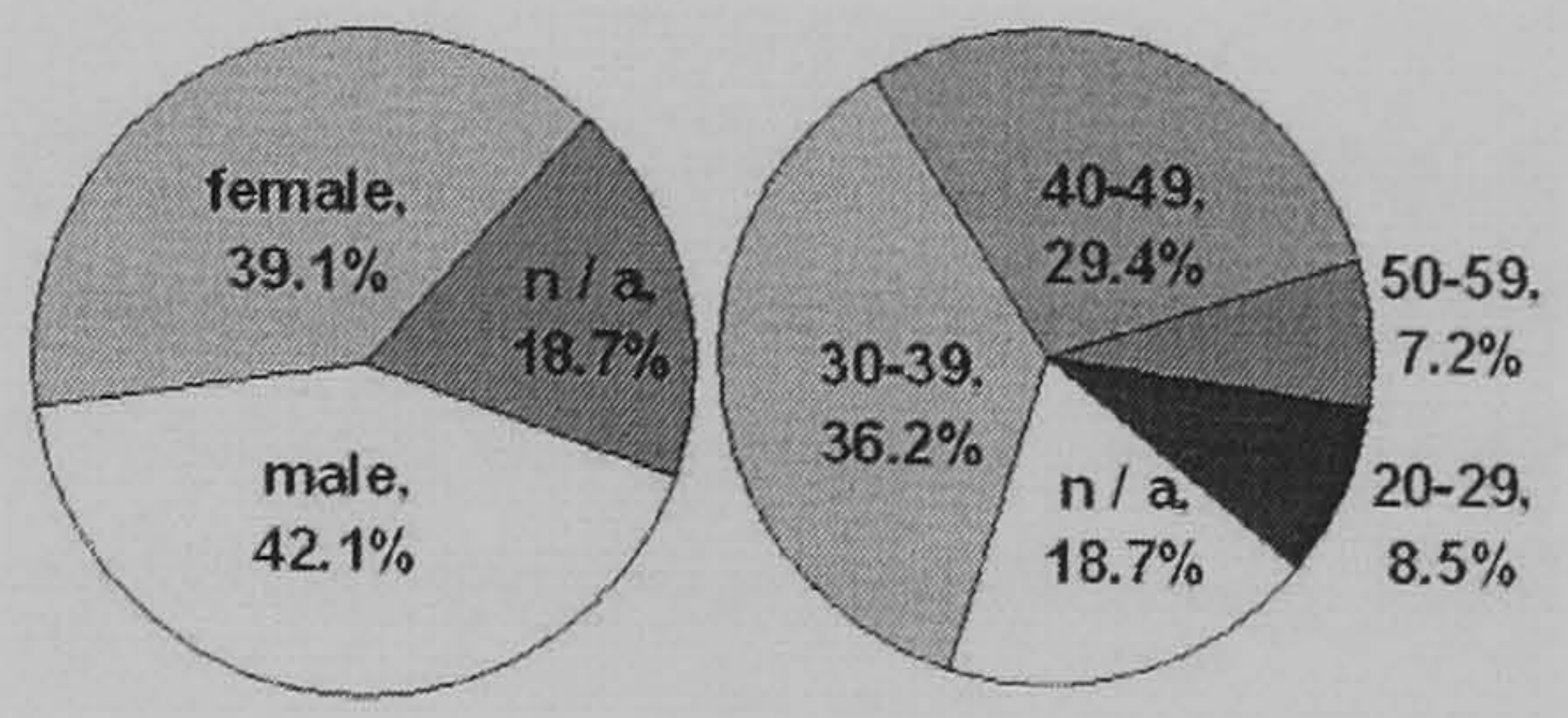

Figure 4.15 Distribution of survey subjects in the Arts Tower

A total of 235 respondents participated in the Arts Tower survey with 78.3% sample proportion (Table 4.4). They were 99 male and 92 female (51.8% vs. 48.2%) and the age groups were as follows: 20 between 20-29 years, 85 were 30-39 years, 69 from 40-49 and 17 were 50-59. Furthermore, 44 subjects omitted to indicate their gender and age. Of all these respondents, 225 had their fixed working or study places and rooms. The other 10 were students studying in the Arts Tower studio. 18 floors with 190 rooms were involved in the questionnaire survey thus ensuring that the investigation covered each floor and 57.1% of all rooms (333) (Figure 4.15). Of all these rooms, 32 are towards the north, 129 towards the south, 27 towards the east and 27 toward the west. It also has to be mentioned that 25 of them are either corner rooms or open-plan studios which have two or three oriented windows.

Building	Total population	Survey sample	Ratio
ICOSS	45	35	77.8%
Arts Tower	300	235	78.3%
Total	345	270	78.3%

Table 4.4 Proportion of the samples against the population in investigated buildings

Similarly, all the questionnaires were assigned a unique identification number from 1 to 270. The answers from these respondents were entered one by one into this table and associated with its identification number. Furthermore, the information from the observation sheet is also linked with the identification number i.e. the respondent's personal information: age, gender, clothing, when and where he or she did the questionnaire survey. The interview feedback was recoded as an appendix at the end of the database table. Additionally, when extra environmental control issues were found in these rooms such as a plant, heater or fan, they were added to the room information table. Table 4.5 shows part of the structure and content of the questionnaire information table. For example, No.3 respondent is a male with age from 30-40. He took this questionnaire survey on 15th May 2005 at 13:10:00 in room 2.3. His answer to question

1 is 3, which means that when he judged his thermal feeling, he felt a little cold [27].

Respondent ID	Gender	Time	Room number	Q-1	...
3	Male	13:10:00	2.3	3	
58	Female	10:25:00	4.8	2	
...					

Table 4.5 Part of the structure and content of occupant information

4.6.5 Physical Measurement

The data for physical measurement in the two buildings are presented in order to establish a general picture of the environmental performances of these two buildings. A detailed analysis is to examine the contribution of some control strategies and to explore the issues that produce the comfort and discomfort according to different room characteristics.

Aside from the aim of assessing how the environmental performance of the investigated buildings involving thermal (temperature, humidity value), visual (illuminance value) and noise control (sound level value) aspects, there are other two issues for which the data from physical measurement are needed. One is to evaluate and validate with environment simulation results so that physical parameters from both methods can be compared to check the method of performance assessment employed. The other is that they are also compared with those of the environmental questionnaire survey (subject response) to predict whether the conclusions drawn are consistent with the voting patterns of the subjects in the office used in the questionnaire survey and whether the results give a true picture of the performance of the house types in each building [13].

In order to achieve these aims, the table in this part is linked to three other tables: outside weather, room information and questionnaire responses. In fact, in total there were 7 tables created and associated with each other in the database for this survey. Through analysis of the results from this survey database, the aim of presenting a deep understanding of the impact of passive control systems on the built environment, the effect of the built environment on occupant perception and comfort level and the occupant's actual control of passive systems.

4.7 Summary

This chapter is mainly dedicated to the methodology used in this study. It can be seen from the foregoing sections that this research centres around three main areas i.e. environmental control strategy, occupant comfort level and occupant operation of control strategies. Thus, it is necessary to employ a multiplicity of methods in order to cover all the objectives of the study. In arriving at the methodologies, various methods that have traditionally been used are reviewed and in some cases the most appropriate one used while in other cases new ones were developed.

Environmental Performance of Control Strategy The method used involved the measurement of the internal climatic conditions of selected buildings. Another method used entailed the utilisation of computer environmental simulation tool to further investigate the performance of the environmental control strategies in two buildings [30].

Environmental Assessment from Occupant The questionnaire survey was used. The method is similar to the one used by Nicol et al [1994] in Pakistan. It entails the selection of buildings and subjects, the development and administration of questionnaires to get the subjective response to the environment of selected buildings. Simultaneous measurements of internal climatic conditions are also done [31].

Occupant's Operation of Windows and Internal Shading Covering Here, field observation was used. The method adopted is similar to the one used by A.I Rubin et al in US [1978], M.S.Rea in Canada [1984] and Michelle Foster et al in UK [2001]. Photography was used to record the position of windows and blinds on the façade of the building. The observation period time was 16 months so that an overall view of the occupant control behaviour could be presented in terms of different climates and weather conditions [32].

In the following chapter an attempt will be made at the detailed discussion of building information, building site geography and climate features, architectural identification and occupant working routines.

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Chapter Five

Background of Investigated Buildings

'... good for growing tomatoes in summer...'

- An Arts Tower occupant

'The ICOSS building's fantastic, environmentally-friendly design has made it an exciting building to work in.'

- An ICOSS Building occupant

Chapter Five
Background of Investigated Buildings

5.1 Introduction

In this chapter, prior to making result analysis, basic background information is explored in a preliminary description of the investigated buildings, the purpose of which is mainly to focus on issues like environmental, architectural and occupant features. It begins, however, with an overview of the characteristics of the Sheffield climate and weather conditions. In order to have a clear view of notable irregularities of weather within the general pattern of climate, it compares the main climatic factors such as temperature, relative humidity, rainfall and sunshine hours from a recent thirty year' period of statistical results (1970-2000) with the corresponding weather parameters that existed during the field observation period (Jan/05-Apr/06). Then the buildings are illustrated with respect to their backgrounds, basic situations, architectural and occupant features etc. in order to have a comprehensive understanding of the two selected buildings. The plan and occupant issues are highlighted as a basis for further analysis.

5.2 Climate and Weather in Sheffield

Climate and weather are primarily influenced by the sun's energy, and how this heats up land and water masses. At a regional level, climate and weather are influenced by altitude, topography, patterns of wind and ocean currents, as well the relation of land to water masses, geomorphology, and vegetation patterns. The Intergovernmental Panel on Climate Change (IPCC) provides the following scientific and semantic definition:

'Climate, in a narrow sense, is usually the 'average weather', or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. 'Weather' is the set of atmospheric conditions prevailing at a given place and time, such as sun, land and water. These interactions produce daily as well as seasonal temperature, humidity and wind patterns that can vary substantially between locations in close geographical proximity' [1].

Correctly defining the geography and climate of the target environment is one of the most critical steps in formulating a useful study of its influence on environmental comfort [2]. By describing the climate and climatic elements, the effects of the surrounding environment on people and buildings can be illustrated. Therefore, the following part provides a general picture of the UK's geography and climate with a more precise focus on the exact locality, the geographical area of Sheffield.

5.2.1 Geography of Sheffield

The United Kingdom (UK) is located in Western Europe and has a total area of approximately 245,000 km^2. It comprises the island of Great Britain (England, Scotland and Wales) and the north-eastern one-sixth of the island of Ireland (Northern Ireland), together with many other smaller islands. The mainland areas lie between latitudes 49°N and 59°N and longitudes 8°W and 2°E (Figure 5.1). Although the country is mostly an island bounded by the North Atlantic Ocean and the North Sea, Northern Ireland shares a 360 km international land border with the Republic of Ireland. The physical geography of the UK varies greatly, including cliffs, hills and mountains, uplands, fields, lakes and so forth. The country can be roughly divided into highland and lowland areas along the Tees-Exe line [3, 4].

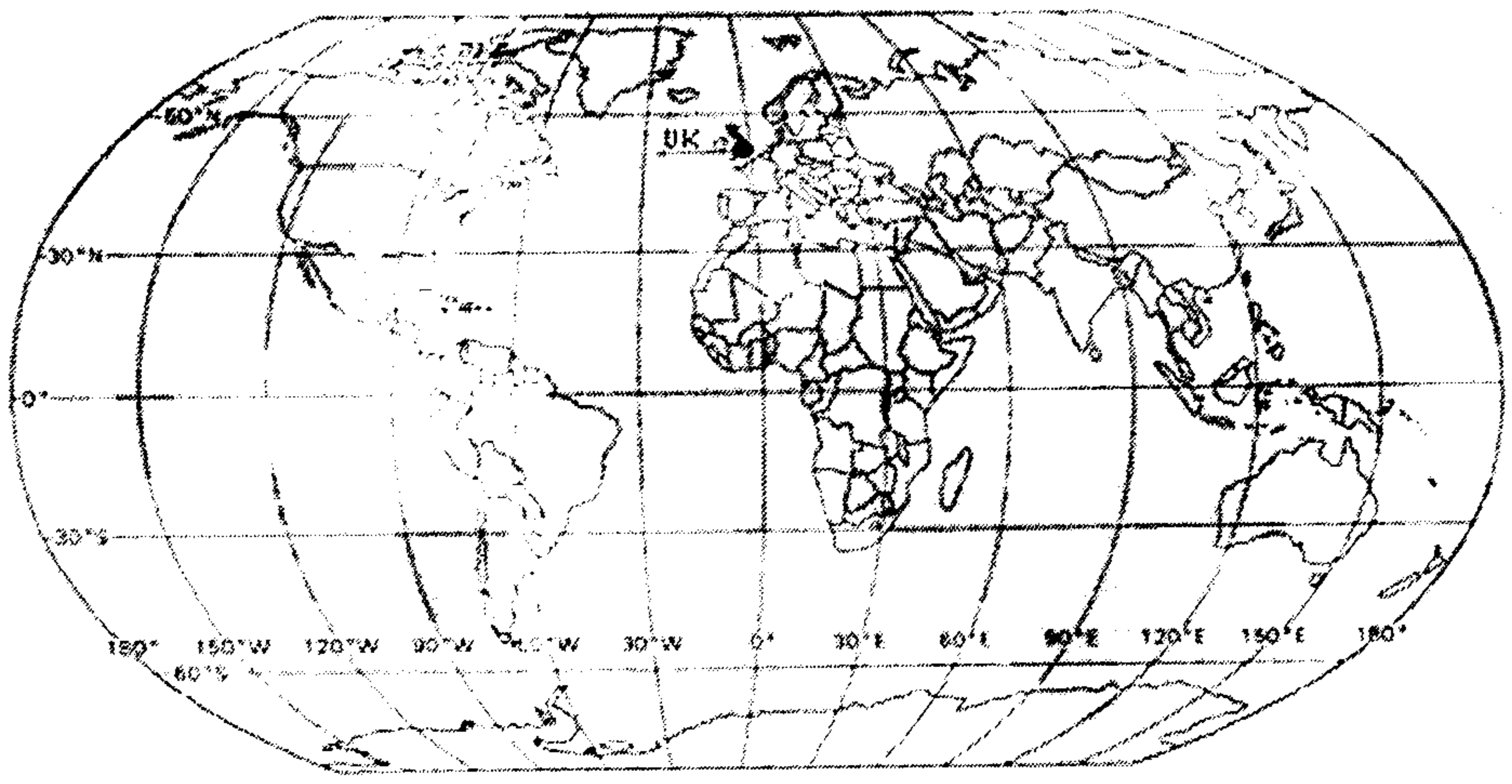

Figure 5.1 Position of UK in the world map

Mountains and hills Scotland is by far the most mountainous area, containing the ten tallest mountains in the UK, the highest being Ben Nevis measuring 1,344 metres high. England, on the other hand, is significantly less so, with its highest, Scafell Pike in the Lake District reaching 977 metres above sea level. Figure 5.2 shows the UK's topography. It can be seen that most of England consists of rolling lowland terrain, divided from more mountainous terrain in the north-west (Cumbrian Mountains of the Lake District), north (the upland moors of the Pennines and limestone hills of the Peak District) and south-west (Exmoor and Dartmoor) by the Tees-Exe line. Lower ranges include the limestone hills of the Isle of Purbeck, Cotswolds and Lincolnshire Wolds, and the chalk downs of the Southern England Chalk Formation.

Rivers and lakes The main rivers are the Severn and Thames. The River Severn is the longest one in the UK (354 km) and the largest in terms of water flow of any river that flows through both England and Wales. The Thames, on the other hand, has a length of 346km, and it flows mainly through southern England. The matter of the largest lake is a little complicated by the fact that many of the largest lakes in this country are man-made reservoirs or lakes whose size has been increased by damming. Lough Neagh, a freshwater lake in Northern Ireland, is the largest lake in the United Kingdom with an area of 388,000 m^2. Loch Lomond is a Scottish loch, located in both the western lowlands of Central Scotland and the southern Highlands. This freshwater loch is around 71,000m^2. In England, Windermere is the largest natural lake, covering an area of 14,700m^2 and is entirely within the Lake District National Park in northwest England.

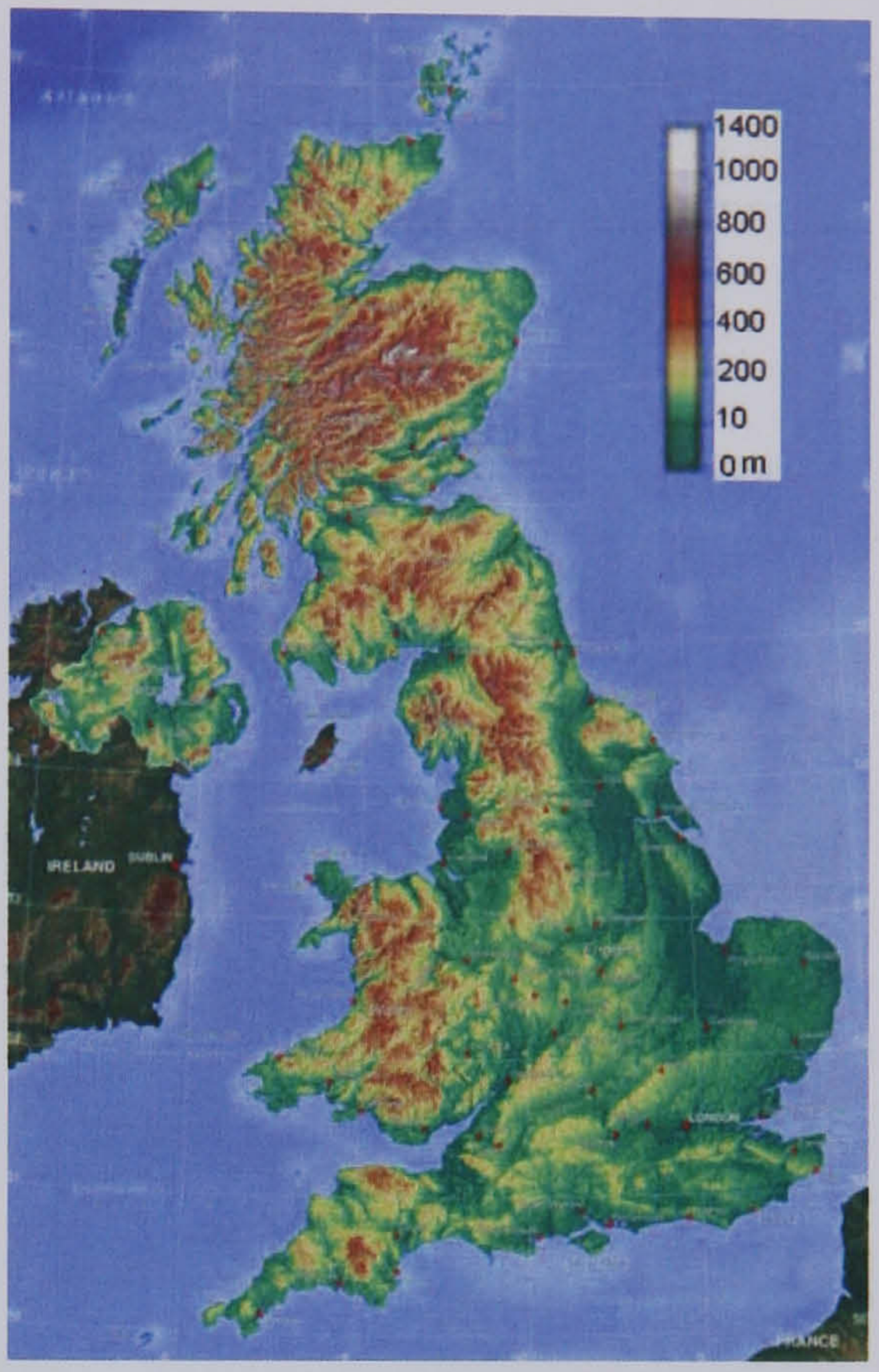

Figure 5.2 Map of UK's topography

Sheffield is located at 53°23′ N and 1°28′ W. It is a major city of the north of England in the county of South Yorkshire, (Figure 5.2). At the time of the 2001 census, the total population of Sheffield was around 513,000. It is quite geographically diverse and is situated at the foot of the Pennine highlands at a point where four streams - the Sheaf, the Porter, the Rivelin, and the Loxley - running in deep valleys converge to form the River Don. As such, much of the city is built on hillsides with views into the city centre or out into the countryside. The city is roughly one third urban, one third rural and one third in the Peak District. The lowest point is just 10 metres above sea level, compared with the 500-plus metres elevation of the highest parts of the city. However, 89% of the housing in the city is situation on sites between 100 and 200 metres above sea level [5].

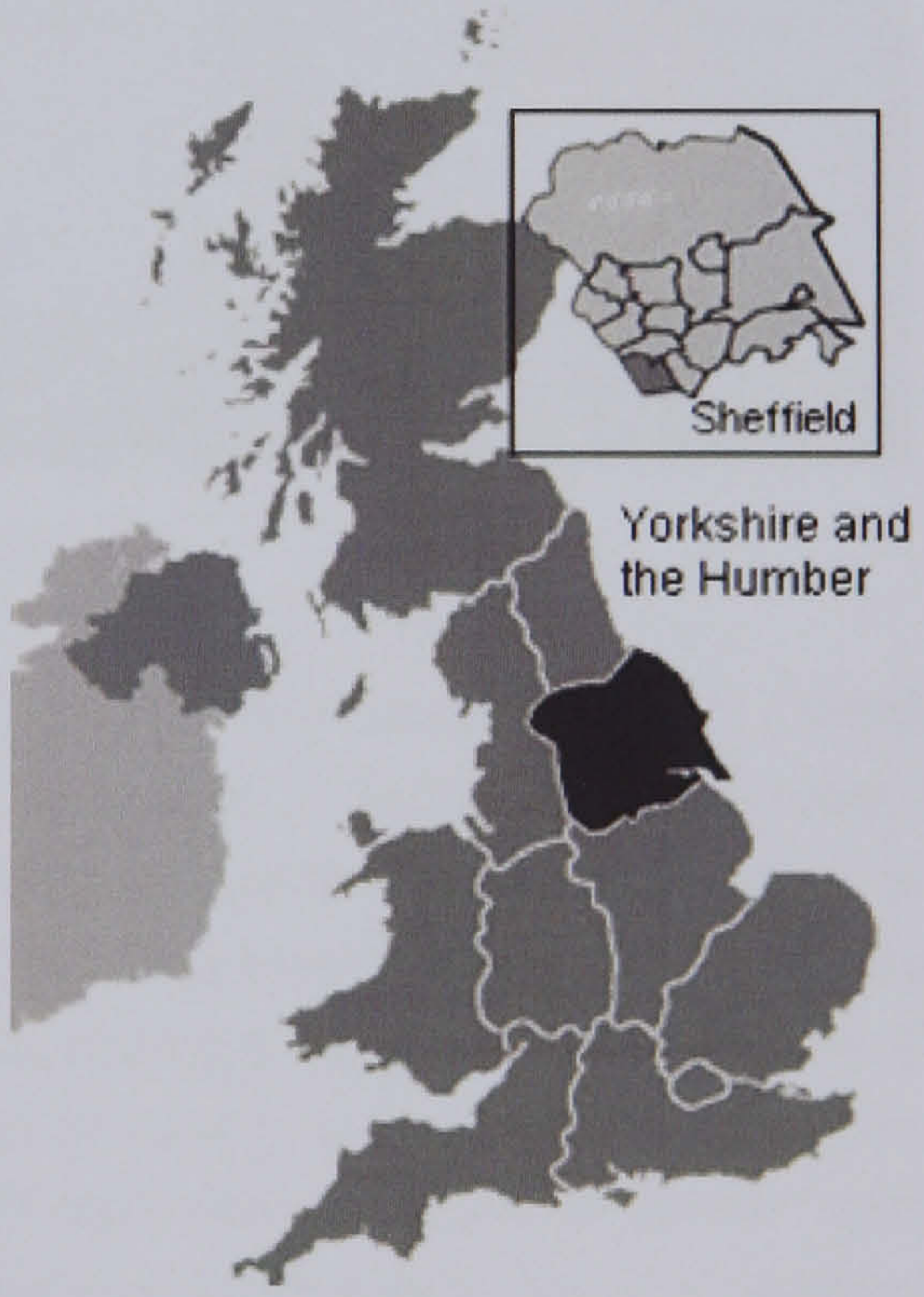

Figure 5.3 Sheffield Position in the UK map

5.2.2 Climate in Sheffield

Among many climatic classification systems, Koppen's [1936] system is generally the most accepted [6]. It was developed by Wladimir Koppen who established the method on the basis of organising the various types of climate into several classes; as such, this method exhibits the attractive characteristic of simplicity. The appeals of this scheme can be demonstrated in its use of numerical values to define the boundaries and symbols for major climatic types as well as lesser subdivisions. Generally, there are five basic climatic zones:

- hot-humid (tropical, rainy climates with no cool season)
- hot-arid and semiarid (dry climates)
- temperate (continental and maritime; middle latitude with mild seasons)
- cold (middle-latitude snow climates with severe winters)
- arctic or polar climates with no warm season

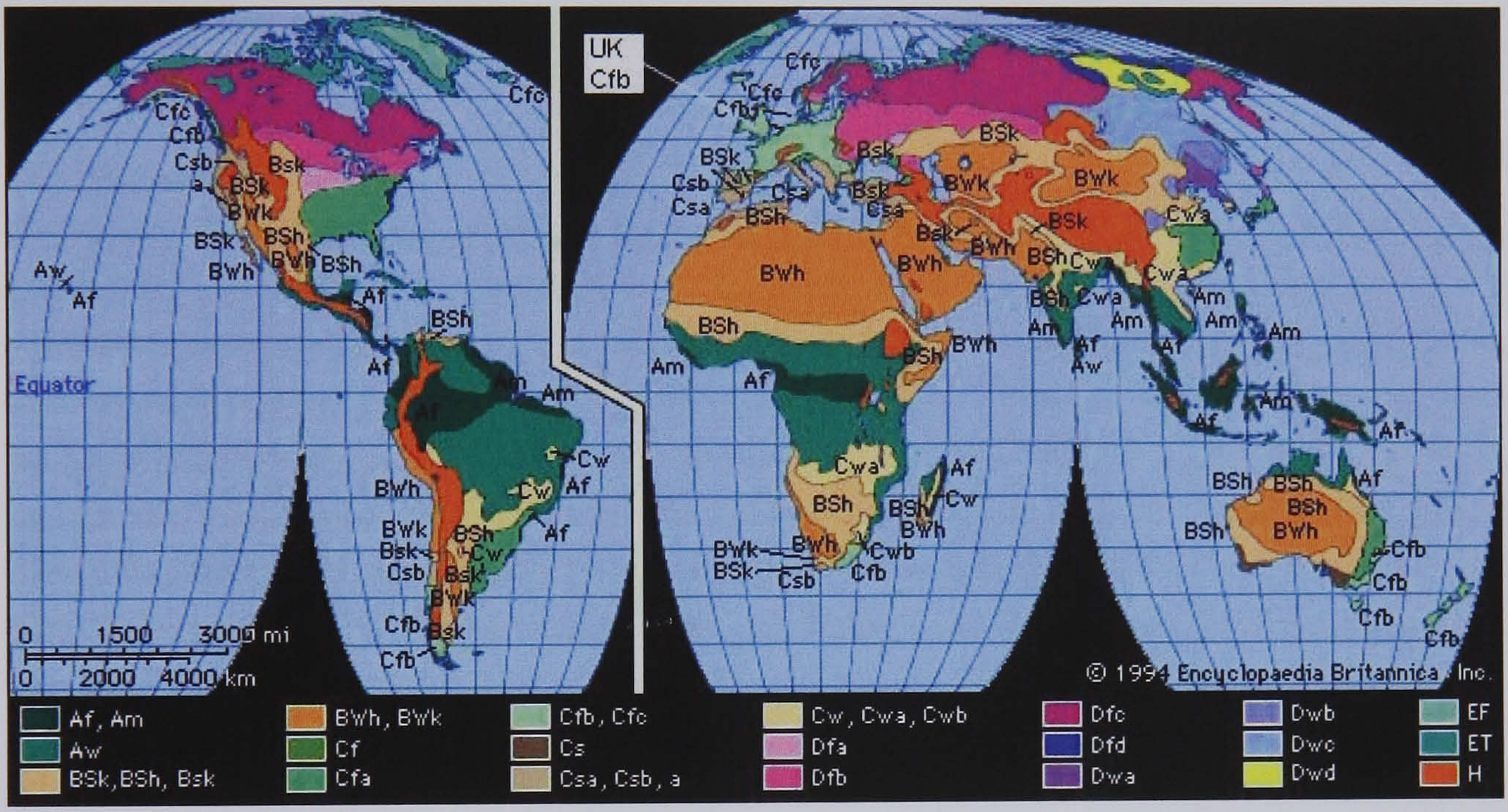

Figure 5.4 Map of climate zone

More specifically, the climate of the UK is classified as a 'Temperate Oceanic Climate' (Koppen climate classification Cfb), and this type is shown in Figure 5.4. According to Givoni [7] the main characteristics of the temperate oceanic climate regions are generally warm summers, cool winters and plentiful precipitation throughout the year, rather than seasonal extremes of hot and cold. The principle factors of influence on the climate include the UK's northerly latitude, its close proximity to the Atlantic Ocean and, especially, the warming of the waters around the British Isles by the Gulf Stream which is a powerful, warm, and swift Atlantic ocean current that originates in the Gulf of Mexico. However, its temperate climate also makes for a very unpredictable weather pattern. The UK is at the boundary of convergence between the warm tropical air to the south and the cold polar air to the north, and thus experiences instability in its weather due to the large temperature variation. This is a major factor that influences the changeable and often unsettled weather, which means many - or even all - types of weather can be experienced in a single day.

Regional climatic differences in the UK are dominated by the Atlantic Ocean. The western side, being closest to the Atlantic, is the mildest, wettest and windiest region of the UK. As its temperatures are most under the moderating effect of the Atlantic, temperature variations are seldom extreme. Eastern areas are by contrast drier, cooler, less windy and also experience great daily and seasonal temperature variations [8].

5.2.2.1 Climate Factors

There are many climatic factors that are used to represent the essential elements of climate and weather. However, air temperature, relative humidity, wind, total rainfall and sunshine hours are five major meteorological variables that have great influence on the built environment and of architecture [9]. Therefore, these elements are discussed in a more detailed way.

Air Temperature

Generally Sheffield has mild to cool winters and warm to very warm summers with moderate variation in temperature throughout the year. The average annual temperature varies from 8.5°C in Jan to 12°C in Aug. The small variation in temperature is to a large extent due to the moderating effect of the Atlantic Ocean since water has a much greater heat capacity than air and tends to release it slowly throughout the year. In winter the ocean is at its coldest in late February and early March, thus in Sheffield, it is often the coldest time. Temperature at night rarely drops below -10°C and in the day rarely rises above 15°C. On occasions, cold polar or continental air can be drawn in bringing with it very cold weather. A temperature of -26.1°C was recorded under such conditions on the 10th Jan/82, the coldest temperature ever recorded in Sheffield. The following day the coldest maximum temperature here, -11.3 °C, was recorded as well.

Spring is generally a calm, cool and dry season, principally since the Atlantic has lost much of its heat throughout the autumn and winter. Indeed, summer climatic differences are more influenced by latitude than any other factor. July is often the warmest month, but it is rare for summer temperatures to go much above 35°C. Nevertheless, temperatures of over 32°C have been recorded during particularly hot summers: it soared to 38.5°C on 3rdJul/83, the highest temperature ever recorded in Sheffield. Autumn is extremely unsettled: as cool polar air moves southwards following the Sun in the sky, it meets the warm air of the tropics and produces an area of great disturbance along which the UK lies.

In 2005, Sheffield began with a very mild month in January. It continued until the first half of February, but then turned cold. Feb/05 was recorded as the lowest average temperature (4.4°C) during the survey period. In March, mean temperatures were again well above average, despite a rather cold start to the month. The temperature then went up in April and May. In fact, temperatures in these two months were not too different from the normal average temperature of this 16 month period. However, it was in June that the hottest temperature recorded occurred - on the 19th (30.4°C). July was reasonably warm with the highest average temperature and a mini heat wave from the 9th lasting for 5 days. Temperature in August was not too far different from the previous month (16.4 vs. 16.9°C). From Sep to Dec, the temperatures fell lower and lower although they were still higher than the average level. The coldest day recorded (-5.1°C) occurred on the 23rd Dec/05, Jan and Feb/06 both have the most stable temperature differences with about 13°C from maximum to minimum. By contrast in March the temperature difference went up to 22.5°C and it had the coldest night (-5.8°C) throughout these 16 months.

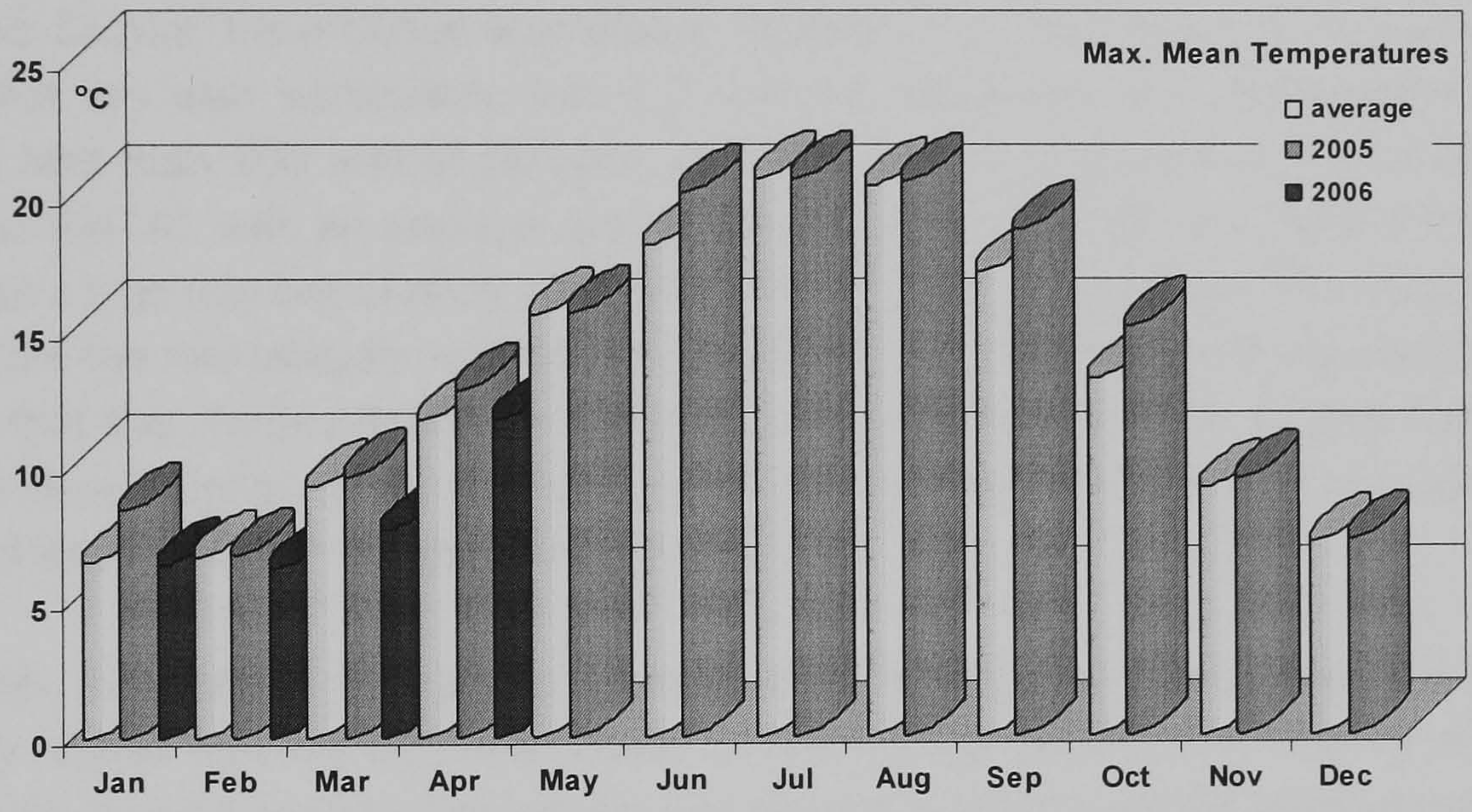

Figure 5.5 Monthly maximum temperature in Sheffield

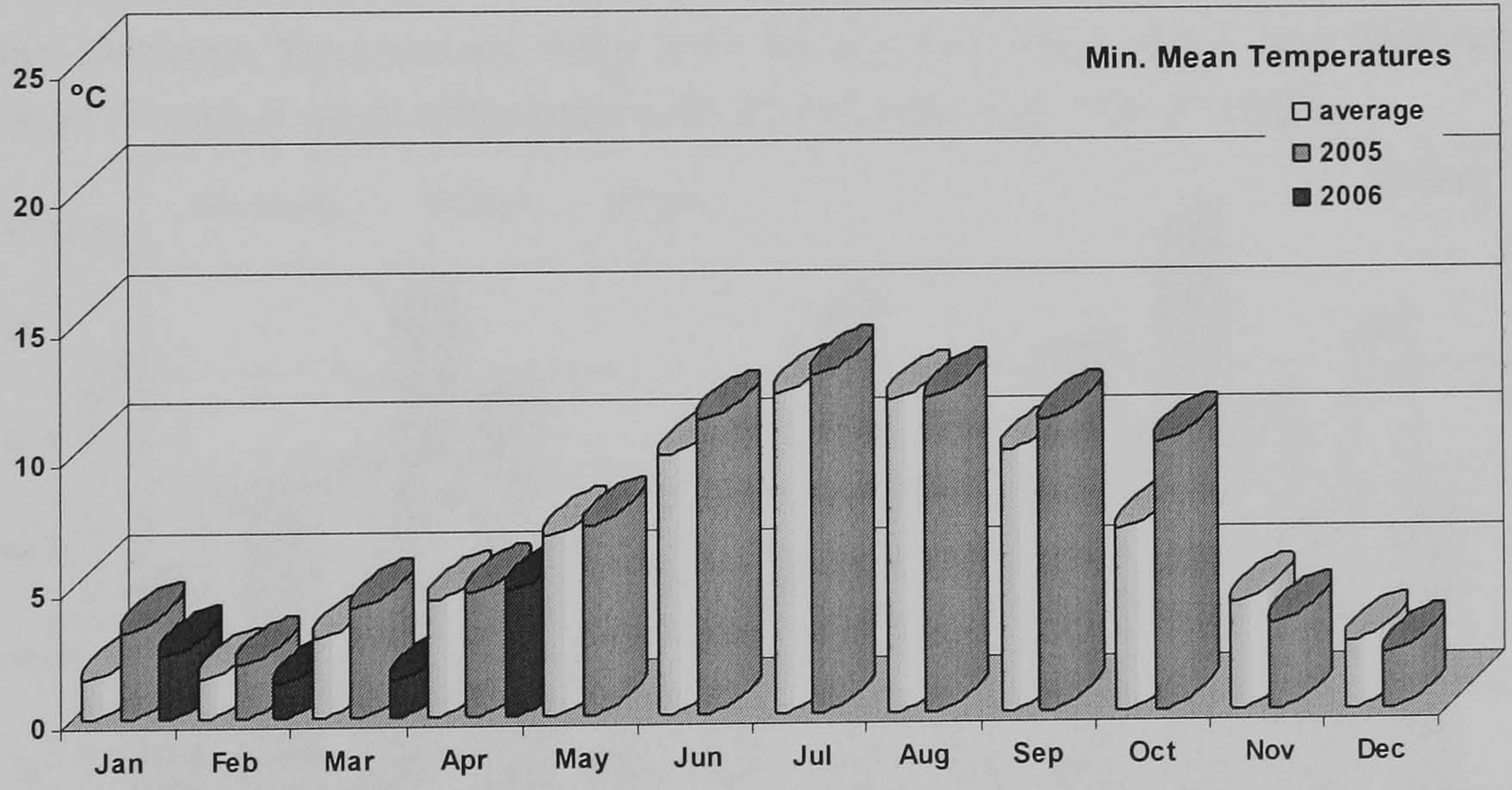

Figure 5.6 Monthly minimum temperature in Sheffield

For the convenience of analysis the records of the 16 months were sorted by season based on the average monthly temperature from 6am to 8pm. Therefore, there are six periods below (unit: °C) (Table 5.1). This is especially important when the study discusses the seasonal effect on occupant perception and behaviour in Chapter Six.

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
05	05	05	05	05	05	05	.05	05	05	05	05	06	06	06	06
6.9	5.1	8.1	10.1	13.1	17.5	18.3	18.2	16.3	13.6	7.8	6.1	5.4	4.9	8.1	9.5
Winter I		Spring I			Summer			Autumn			Winter II			Spring II	

Table 5.1 Season and air temperature

Rainfall

Rainfall amounts can vary greatly across the UK. Generally the further west and the higher the elevation is, the greater the rainfall is. The Scottish Highlands is one of the wettest places in the UK with an average annual rainfall total that exceeds 3,000 mm. The Lake District, the mountains of Wales, Scotland, the Pennines and the moors of the southwest are also particularly wet. By contrast, southern, and south-eastern areas receive less than 700 mm of rain per year. The county of Essex is one of the driest places in the UK, with an average annual rainfall of around 600 mm. Most of the British Isles has a high number of rainy days with around 100 days per year. The main reasons for this are the mid-latitude position, close proximity to the Atlantic Ocean and the warm waters that the North Atlantic Drift brings. Most rainfall in the UK comes from North Atlantic depressions, which roll into the UK throughout the year and are particularly frequent and intense in the autumn and winter.

Generally, in Sheffield precipitation occurs with a high degree of reliability: the average monthly rainfall reaches 68.7mm. When comparing the wettest and driest period time, there is no marked seasonal emphasis and there is adequate rainfall in all seasons. Dec and Jan are the wettest months with 91.9 and 86.5mm of total rainfall, roughly 29.8% more than average. By contrast, May and Jul are the driest (51.0 and 55.5mm). The value doesn't make a great difference with 22.5% less than the average.

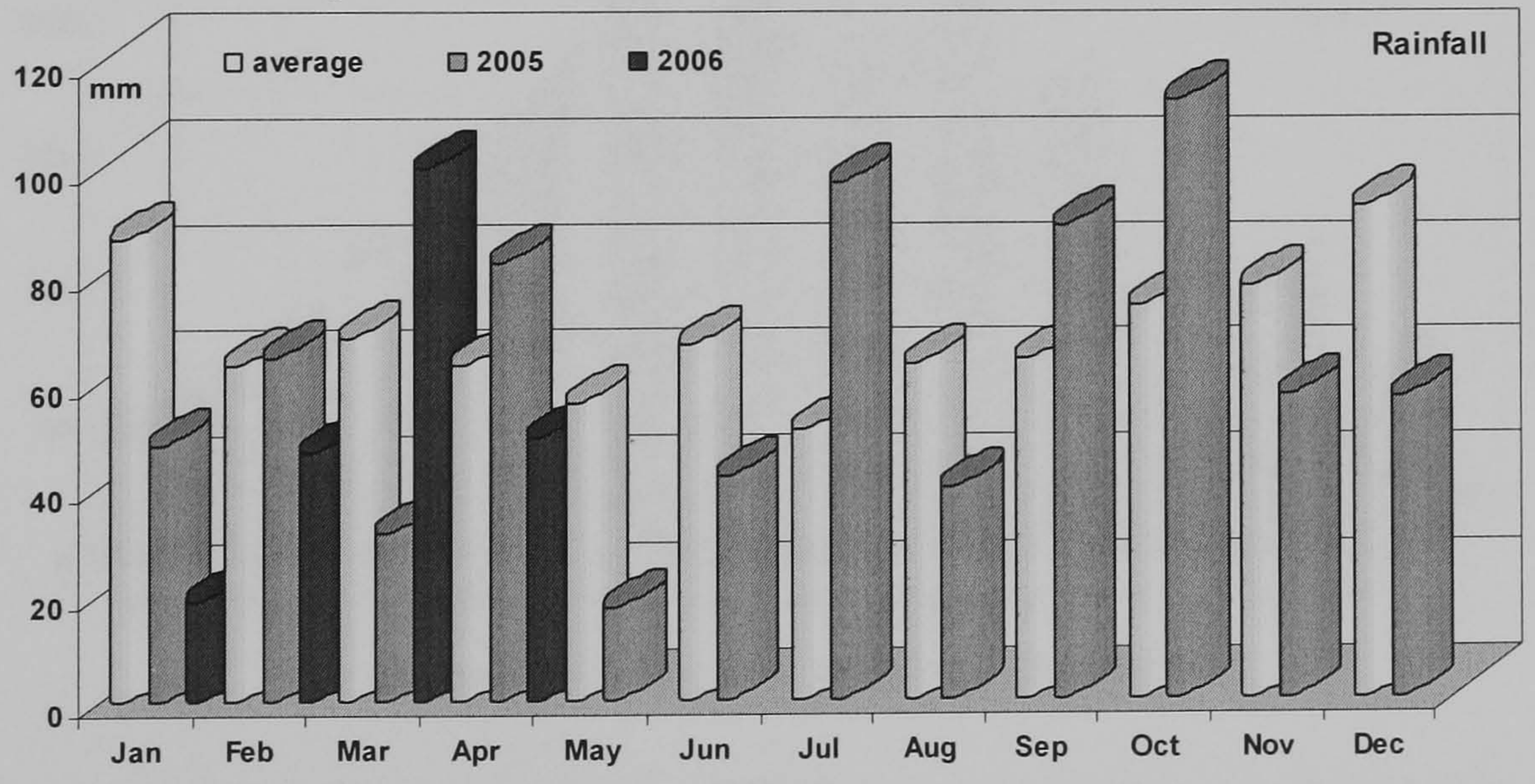

Figure 5.7 Monthly total rainfall in Sheffield

Compared with the statistical results from 1970-2000, the year 2005 had a little less rainfall with a total of 740.9mm (61.7mm monthly). The amount of rainfall fell dramatically in Jan (48.1mm) in 2005 - only 55.6% of the average record. And in 2006, it went down even further with only 18.7mm, which was less than a quarter (21.6%) of the normal rainfall. In Feb, however, it went up above the average while falling again in Mar with just half of the normal. However, in 2006, it became wetter, and there was twice as much rainfall in Mar as there was in Feb (100.0 vs. 46.8mm), although in Apr/06 it turned back again (49.4mm). May was the driest month with only 17.5mm of rainfall. Jun was dry as well as it was still lower than the average value, while in Jul it turned much wetter. In Aug there was a similar pattern to Jun. From Sep to Dec these four months all received more than the average amount of rainfall, especially Oct, which turned out to be the wettest of the 16 months (113.1mm). Broadly, though, monthly values show an irregular pattern and these monthly differences are much greater than displayed by the thirty years' average record.

Sunshine Hours

The average annual amount of sunshine for the UK is relatively low and around 2/3 of days experience partial over-clouding, occasionally with little sun at all. Indeed, the amount of sunshine that is usually recorded is only between 30% and 55% of the maximum that is theoretically possible annually. Southern coasts, however, often have the clearest skies because cumulus cloud formation generally takes place over land, so coastal areas are often cloud free. Dorset, Hampshire, Sussex and Kent have annual average totals of between 1,750 and 2100 hours of sunshine a year, while North-western and mountainous areas are generally the cloudiest areas of the UK, with some mountainous areas receiving less than 1,000 hours of sunshine a year.

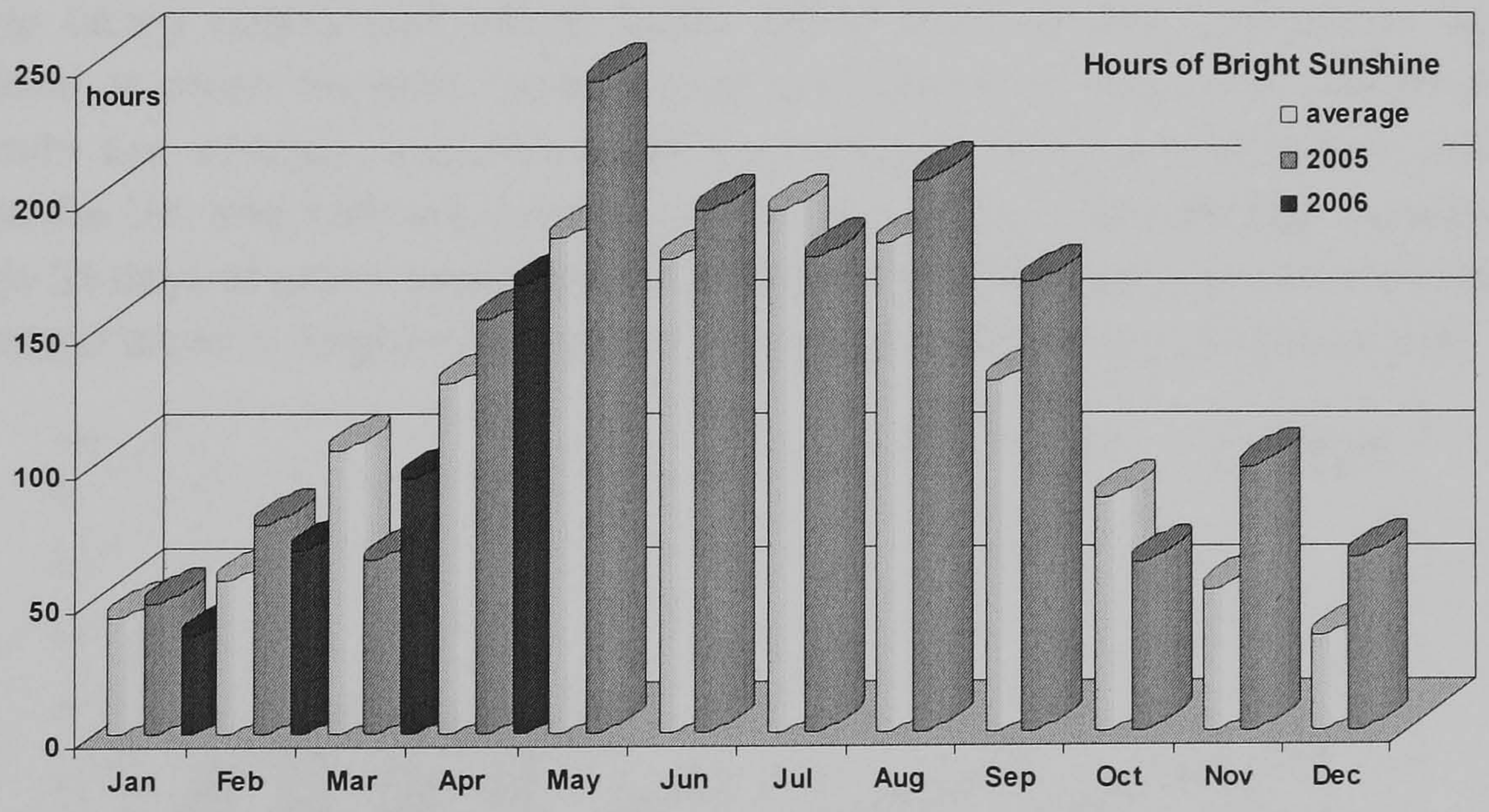

Figure 5.8 Monthly sunshine hours in Sheffield

Broadly, Sheffield receives an average 1600hours of sunshine over the course of the whole year. In midwinter it drops to its minimum with 1 hour per day or less in Jan and Feb while reaching its maximum, ranging from 4 to 8 hours in Aug and Sep. The year 2005 began with a dull Jan with only one third of the average hours of sunshine (48.1 vs.

120.5h) for the total 16 months, a situation that changed little over the next two months (Feb and Mar). From Apr, it turned much sunnier with more than twice the amount of sunshine hours received than in Mar (64.6 vs. 154.4h). A similar situation came about in Apr/06 as well (95.0 vs. 167.3h), whereas May was the sunniest among the 16 months of the period, enjoying 243.8 hours of sunshine. From Jun to Sep it was generally sunny too as all these months had above average levels of sunshine hours. In addition Aug was the only one apart from May to reach more than 200 hours. However, the situation changed from Sep, becoming dull and this lasted right into Jan/06, which became the cloudiest with only average 1.2 hours (of sunshine) per day in this month.

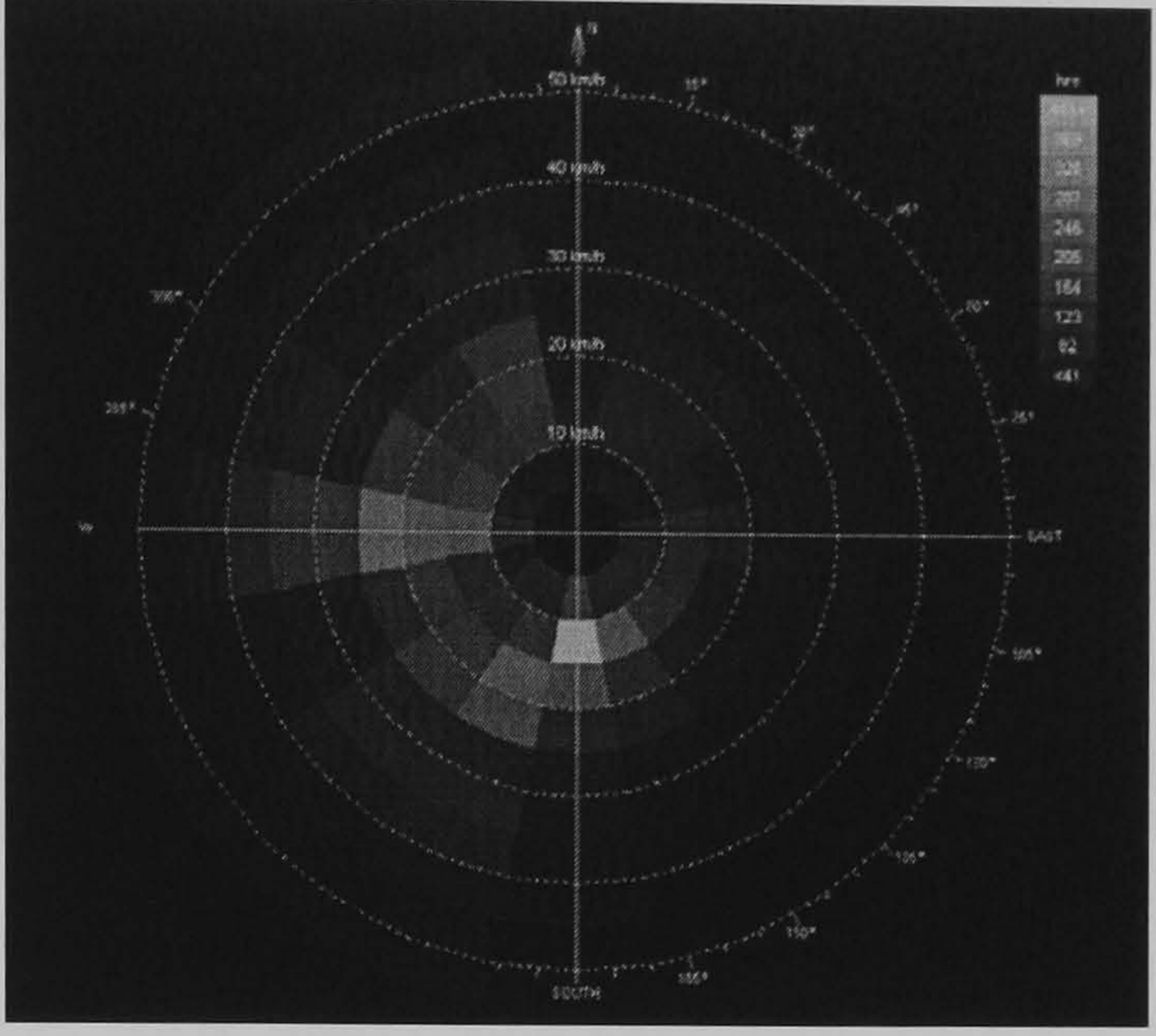

Figure 5.9 Wind rose diagram in Sheffield

Wind

The UK is a windy country, which is to a large extent due to a high temperate latitude and close proximity to a large ocean on its westerly side. The prevailing wind in the UK is from the southwest from the North Atlantic Current but in such a changeable climate it may blow from any direction for sustained periods of time. Winds are strongest near westerly facing coasts and inland areas where there is little topography, such as mountains, to divert the wind. Gales (which are defined as winds with speeds of 50 to 100 km/h) are strongly associated with the passage of deep depressions across or close to the UK, and both are most frequent in the winter. The Hebrides experience on average 35 days of gale a year (defined as days when there are gale force winds) while more inland areas in England and Wales receive less than 5 days of gale a year.

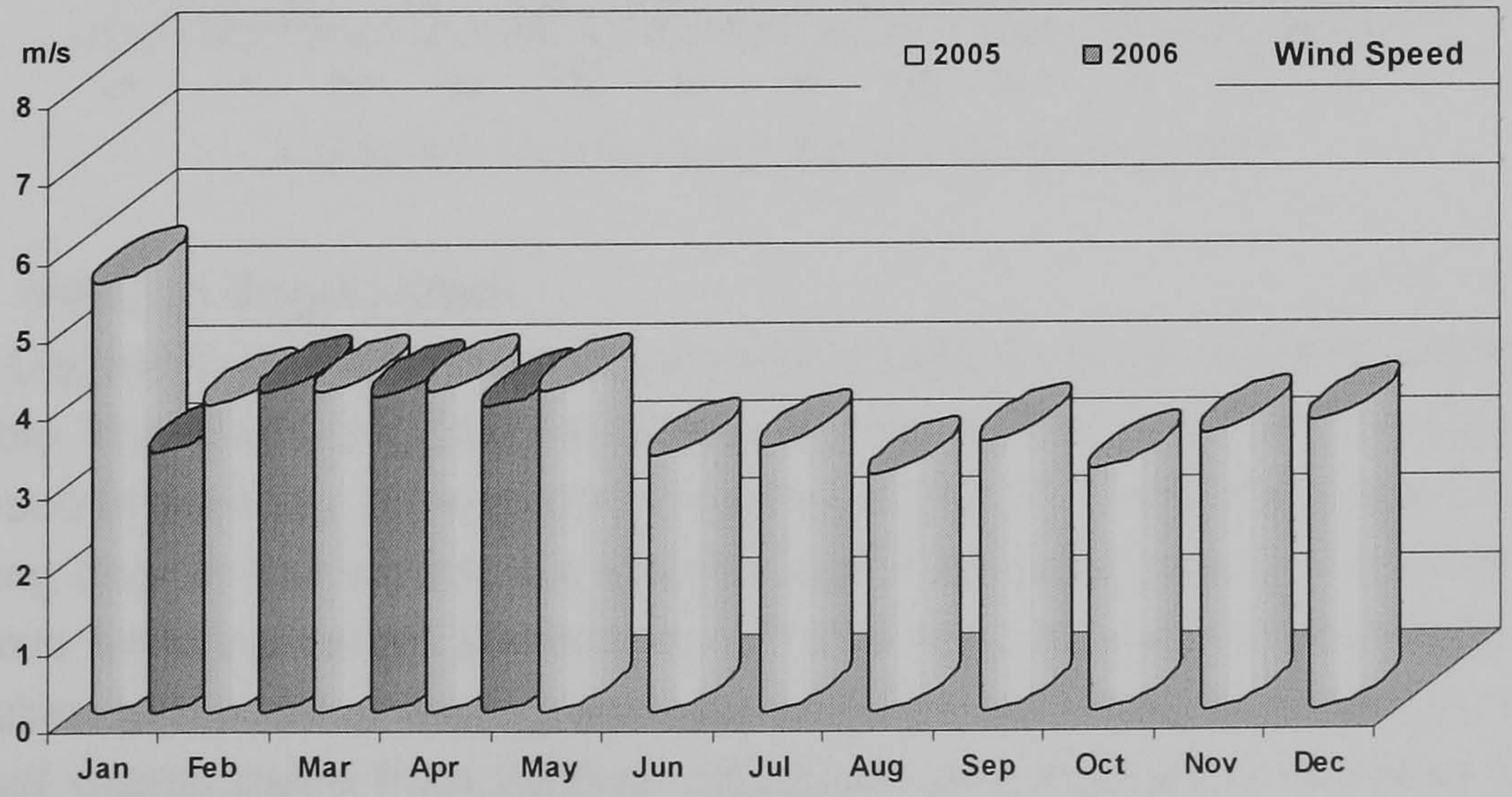

Figure 5.10 Monthly wind speed during survey time

Figure 5.9 is the wind rose diagram showing the relative frequency of directions from which the wind is coming, and the relative frequency of the wind speed generally in Sheffield. It shows that 50% of time the wind speed is within 4 m/s for a particular direction from the southwest. But winds with higher wind speeds come from the west. During the survey time, the monthly average wind speed, from Figure 5.10 has a high degree of reliability. Except Jan/05 which was windiest (5.5m/s) in Sheffield, the others were all maintained between 3.0 to 4.1 m/s.

Relative Humidity

One of the most important influences on the British climate is the Atlantic Ocean and especially the North Atlantic Current which brings warm waters from the Gulf of Mexico to the UK by means of the global conveyor. These warm ocean currents bring substantial amounts of humidity and contribute strongly to the wet climate that the UK experiences. Depressions are another major product of the Atlantic Ocean and roll in towards the UK throughout the year and are especially intense and frequent in autumn and winter. These depressions can be very severe and often bring in heavy rain and strong winds. For these reasons, the UK has a high level of relative humidity, sometimes hovering in the eighties and or nineties for weeks. Compared to the average records, RH in 2005 displayed a similar pattern and value, changing in the range from 70 to 88%.

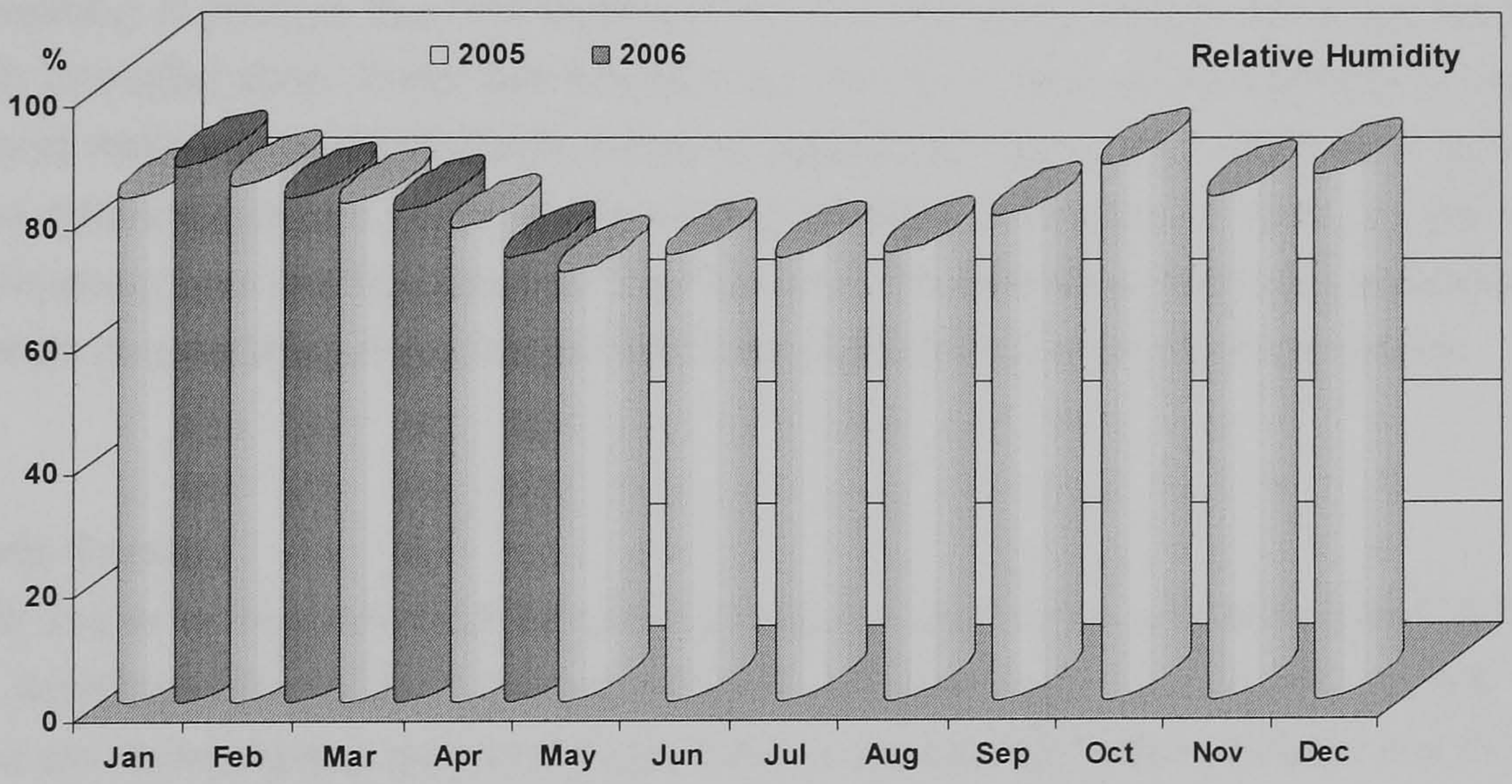

Figure 5.11 Monthly relative humidity during survey time

5.2.2.2 Heating Degree Days

Heating Degree Day (HDD) is an index used to determine the duration and intensity of winter cold. The index, originally developed in 1927 by the American Gas Association, is widely used to estimate home heating requirements [10]. There are various methods of calculating degree-day values, but all refer to a 'base temperature'. For heating, this is the outside air temperature at which no artificial heat is required to keep the building comfortable. In the UK a heating base temperature of 15.5°C is traditional, the theory being that casual gains from lighting, occupants and equipment will raise the indoor temperature a few degrees higher than is required for space heating to maintain a comfortable indoor temperature. But other base temperatures can be adopted when it comes to some modern buildings such as super-insulated or passive solar buildings, which normally have a 'lower balance point'.

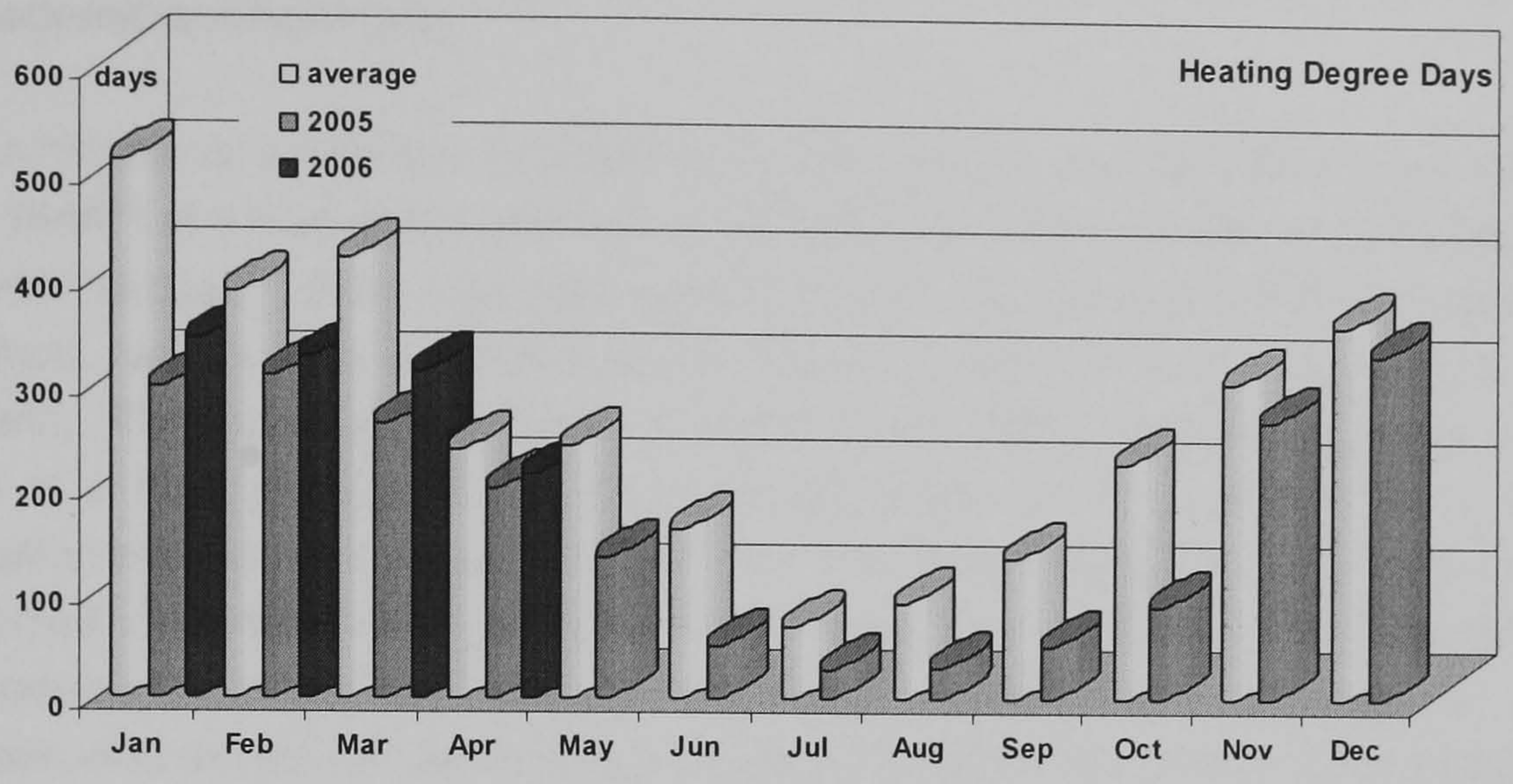

Figure 5.12 Monthly heating-degree days in Sheffield

Figure 5.12 shows the monthly heating-degree days both on average and during the survey period in Sheffield (with 15.5 °C as the baseline). It can be seen that in Sheffield space heating is always the first strategy and that building design needs to be taken as the main consideration. Over the whole year, more or less, extra heating is needed to create and maintain a comfortable interior, especially from Jan to Mar and from Nov to Dec; the heating-degree days of these five months occupied 71.5% of total value in 2005. However, comparing the 2005 value with the average level, the heating-degree days presented a clear drop from 3158.75 to 2058.85 with 34.8% decreasing.

5.3 Arts Tower

The Arts Tower is an institutional building with a mass block and also listed as being of special architectural, historical and cultural significance [10]. As this study focuses attention on its occupant environmental issues, description and analysis are concerned only with its architectural design and occupancy distribution.

5.3.1 Background to the Building

The city of Sheffield has been world famous since the nineteenth century for its production of steel. During the first and second wars, the steel factories were set to work making weapons and ammunition. As a result, once the wars were declared, the city became a main target for the bombing raids that were the cause of the most substantial damage to the city as well as great loss of life [11]. Following the war, the 1950s and 1960s saw large parts of the city centre cleared, new buildings erected and a new system of roads were laid out. This was also the period in time that saw the University of Sheffield began to expand rapidly. In the early fifties, the Gollins, Melvin and Ward

Partnership (now called GMW Architects) won an open competition to masterplan and design the central campus of the University of Sheffield. The Arts Tower was part of this scheme and also one of the first times in the UK that modernist language was made use of for academic buildings [12].

GMW Architects is a practice founded by Frank Gollins, James Melvin and Edmund Ward in 1948/9 at a time when post war social reforms dictated investment in education, health and housing. 1950s was also generally cited as the beginning of Postmodern Architecture, which was a response to the International Style that matured into Modernism. The International Style blossomed in 1920s Western Europe [13]. It features of a number of common characteristics that are easy to identify: a radical simplification of form, a rejection of ornament, the adoption of glass, steel and concrete as preferred materials, the transparency of buildings, acceptance of industrialized mass-production techniques and the machine aesthetic, the acceptance of the automobile, and design decisions that logically supported the function of the building etc. As with many cultural movements, some of the most pronounced and visual ideas of high-rise International Style can be seen very clearly:

- Square or rectangular footprint
- Simple cubic ‘extruded rectangle’ form
- Windows running in broken horizontal rows forming a grid
- All facade angles are 90 degrees

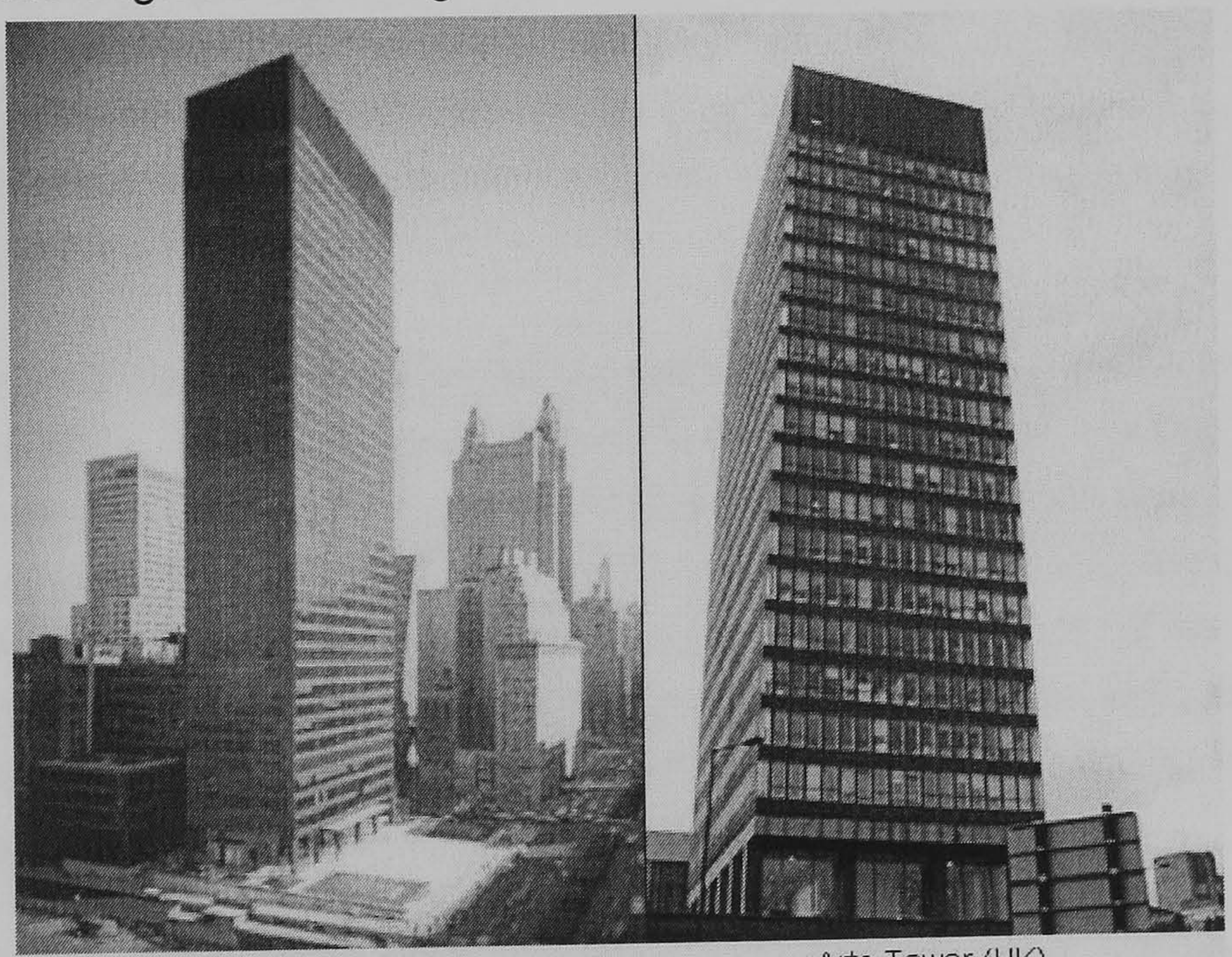
Seagram Building (US) Arts Tower (UK)

Figure 5.13 Seagram building and Arts Tower

One of the most famous manifestations of high-rise International Style is the Seagram Building in New York City which was designed by the German architect Ludwig Mies van der Rohe, in collaboration with the American Philip Johnson and completed in 1958. It is 156.9 meters tall with 38 stories. This building stands as one of the finest examples of the functionalist aesthetic and a masterpiece of corporate modernism. GMW Architects is an influential and innovative post-war practice that introduced the first fully-glazed curtain wall to the British building. Although the Arts Tower is always referred as having been inspired by the Seagram Building, it is only about half its size. After several years of design modification, construction of the tower began in 1961 and lasted four years. The building itself was officially opened by Her Majesty Queen Elizabeth, The Queen Mother, in 1965. Its completion made it the tallest educational building at the time and it became an icon for the University itself; even now the Arts Tower is the tallest building in the city and remains the tallest university building in the UK. It has been given protection and listed Grade II* [14].

5.3.2 Location of the Building

The University of Sheffield is not a campus university, though most of its buildings are close together. The centre of the University's presence lies one mile to the west of Sheffield city centre where there is a mile-long collection of buildings belonging almost entirely to the University (Figure 5.14). This area includes the students' union, the Octagon Centre, Firth Court, the Alfred Denny Building, and the Hicks Building etc. A concourse under the road of Western Bank allows students to easily move between these buildings. The Arts Tower is also located in this area.

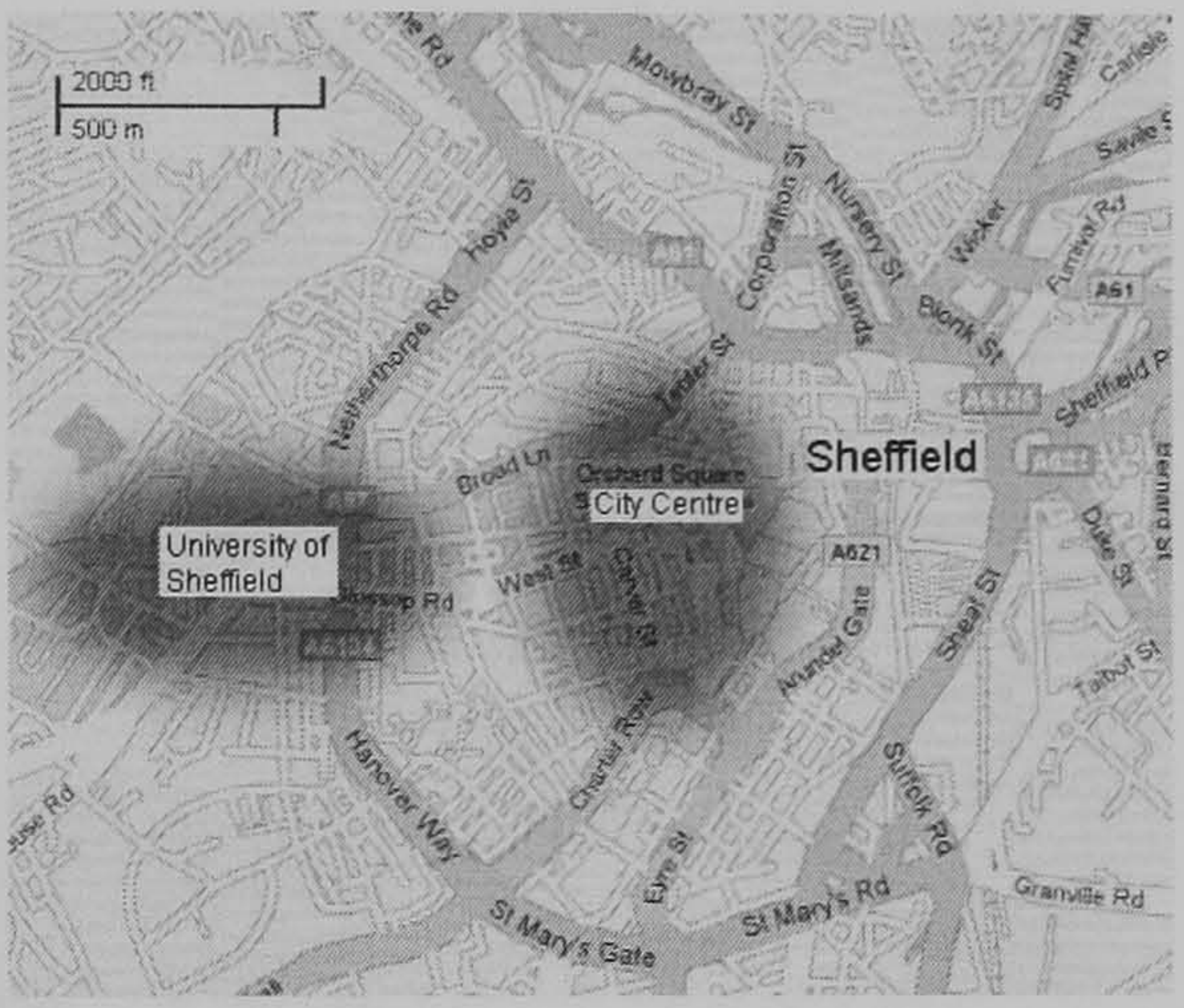

Figure 5.14 Position of the University of Sheffield

The building site is essentially a triangle formed on two sides by roads and one side by main library building. Western Bank (the A57) is a critical section of the S10 transport corridor. The eastern part of this road is roughly 27° anticlockwise due east and forms the southern edge of the triangle. Bolsover Street is one of the main roads into Sheffield city centre linking to the Brook Hill roundabout, and at an angle of 53° to Western Bank this north-western street forms the other boundary of the triangle, with the main library to the west becoming the third side. Between the roads and the existing buildings, there is an overall drop in elevation of nearly 500mm.

The Arts Tower is a small rectangular tower proportioned 5:3 with the longer side towards Western Bank set back about 110 metres to form an open plaza in front of the entrance to the building. Entry to the building was originally made by a wide 'bridge' between fountains over a shallow pool area in front of the building, a design similar to one incorporated in the Seagram Building. However, this pool was eventually drained and covered over when it was found that strong down drafts of wind hitting the building on gusty days caused the fountain to soak people entering and exiting the building. At present, this open plaza is mainly for parking, although trees and a paving of white bricks enliven the open space. Some other university buildings surround this plaza: the Department of Animal and Plant Sciences Building (26 meters high with 8 floors) is on the west side while the Printing Resource Building and Dainton Building are on the opposite side. Due to elevation differences, the ground floors of these two buildings are lower than the plaza and their main entrances are towards Bolsover Street. The Printing Resource Building is nearly 2m high above the plaza. As far as the Dainton Building is concerned, its highest part is roughly 15m above the plaza while other sections rise only 6m (Figure 5.15).

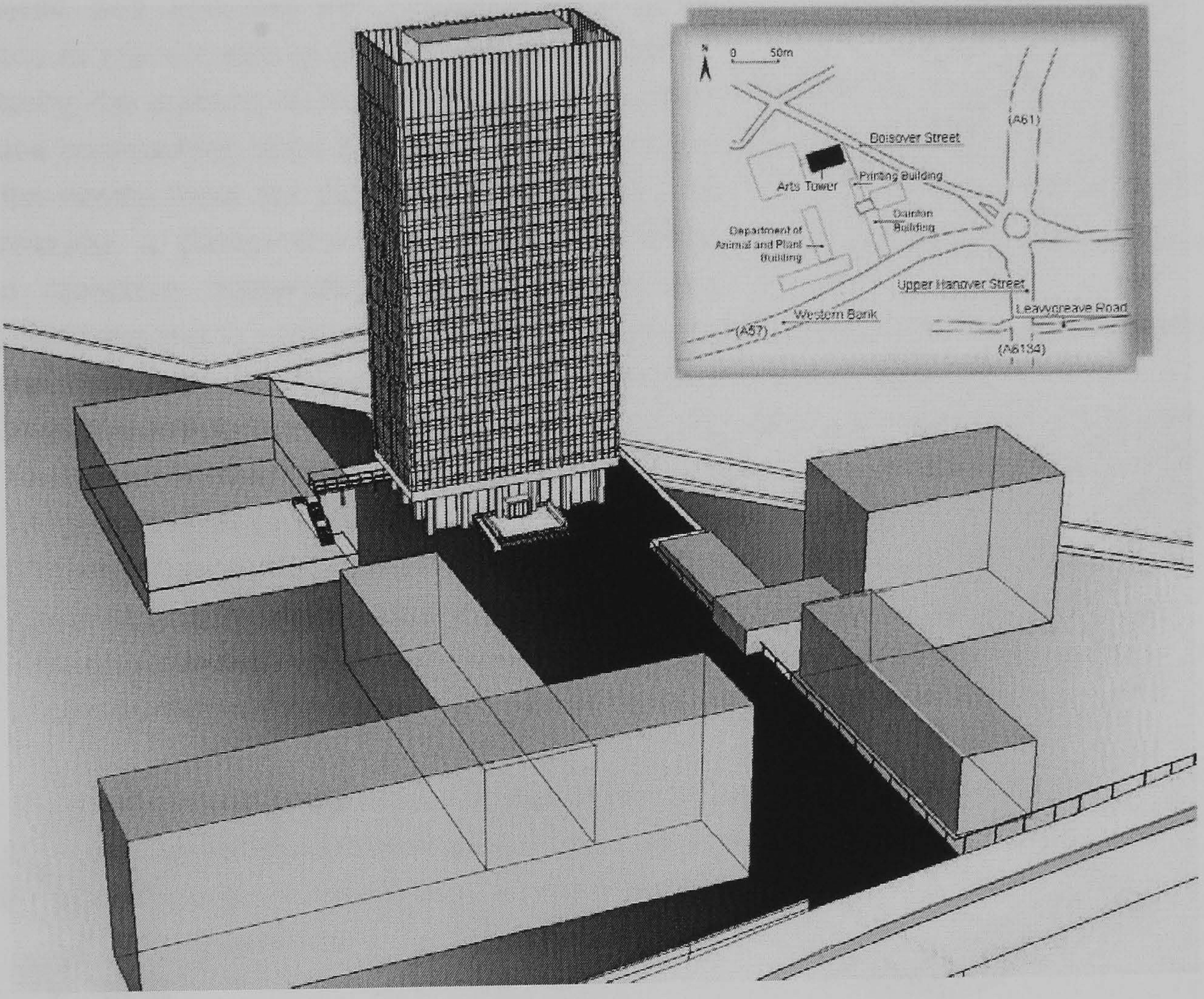

Figure 5.15 Position of the Arts Tower and its surrounding

5.3.3 Building Design

Arts Tower is a simple freestanding building. The main mass is nearly a perfect cube in form, five bays wide and three bays deep, with 20 floors plus a Mezzanine and 2 basement floors measuring 19m wide, 35m long and 78m height. The building has a tubular concrete structure having exterior perimeter columns spaced closely and a central core providing shear bracing and increasing the stiffness of the building by sharing the loads with the façade tube [15] (Figure 5.16).

The tower sits squarely on a series of 8520mm high concrete columns and is surrounded by fully transparent glazing with the main entrance towards Western Bank. The ground floor of this building is 900mm higher than plaza. A big platform outside is placed with two stone benches on each side for seating. In addition a wheelchair ramp is installed along the platform to permit easier access to the building. A small transition space measuring 3.3X3.9m^2 is attached to the entrance, thus making the door double layered and ensuring the existence of a buffer space to prevent strong winds, rainfall and cold air entering the building. In the lobby, there is no room space encroaching upon this flow of space; instead in the centre there are the necessary two lifts and staircases, a paternoster and mechanical shafts and reception. Separated broad staircases are provided leading to underground lecture theatres and a Mezzanine floor which is linked to the main library of University via a glazed corridor bridge (Figure 5.17).

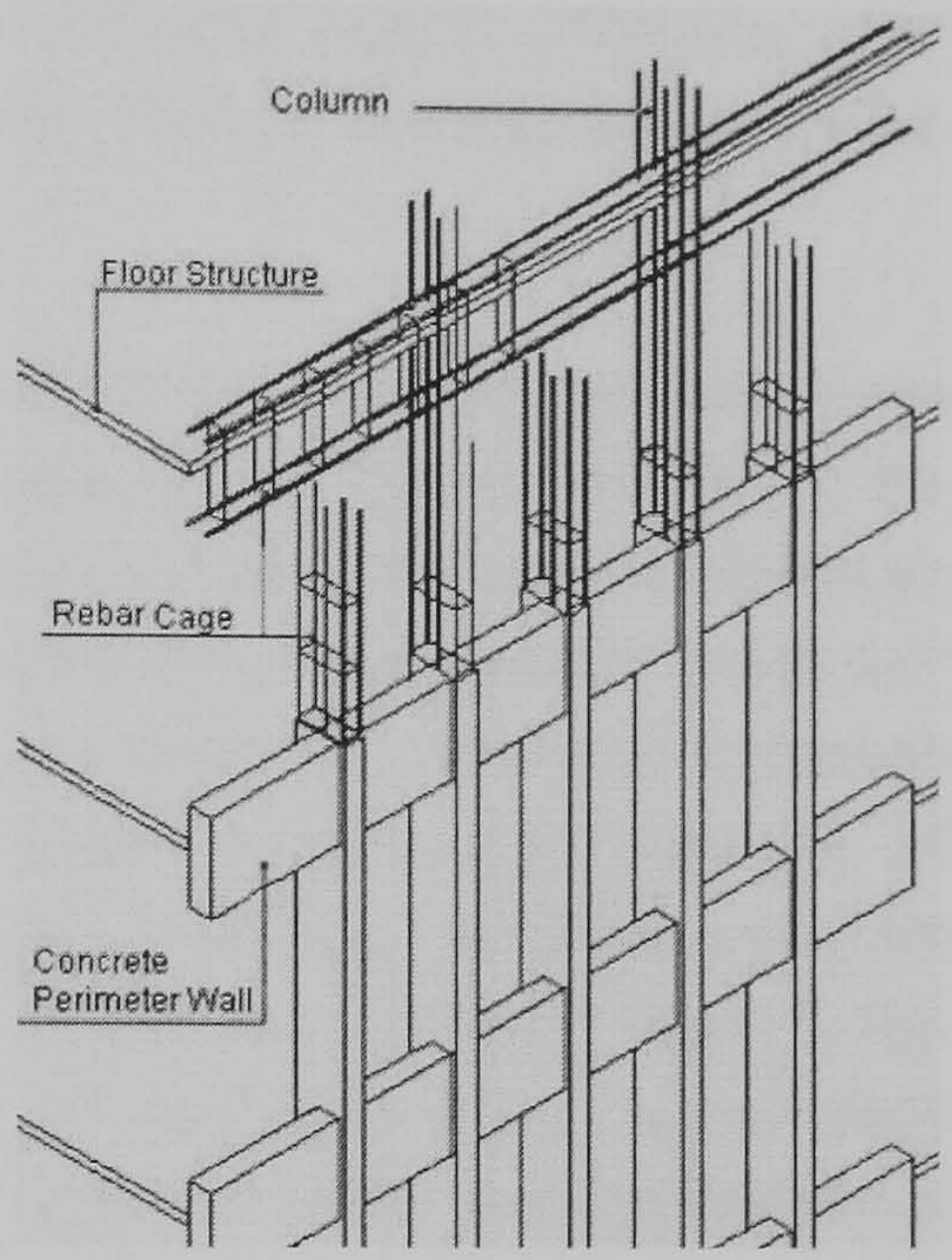

Figure 5.16 Structure of the Arts Tower

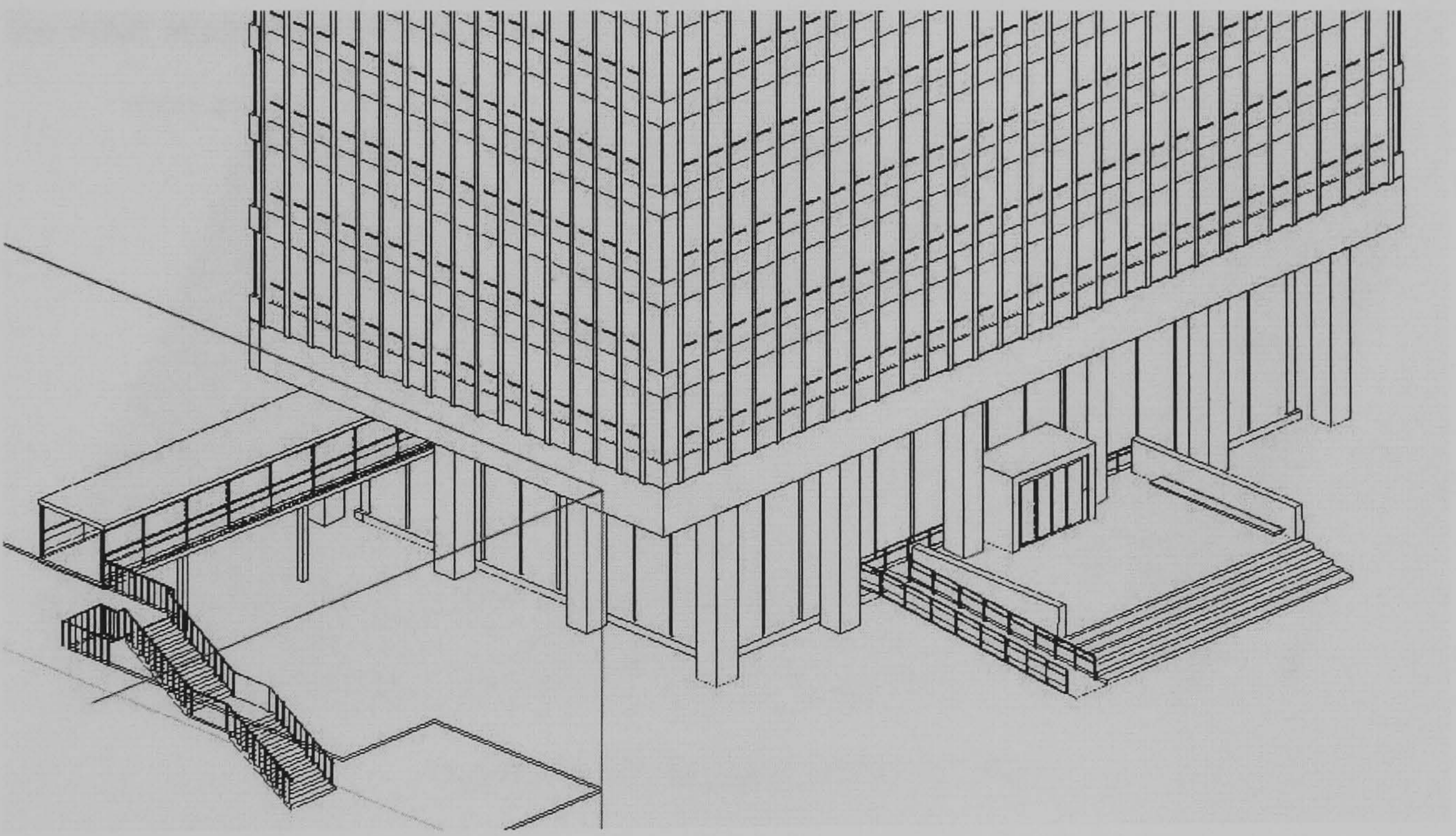

Figure 5.17 Entrance of the Arts Tower and the bridge to the main library

Above, supported on clad columns, rises 19 floors of academic space. Apart from the uppermost 19th floor, whose external wall is set back 1400mm (on average) to form an open corridor and protected by aluminium framed curtain walls, the others, from the 1st to the 18th floor are enclosed within the same curtain wall material that clads the whole building, and a skin of single glazing, set in white metal frames with mullions and spandrels. Statistically there are 522 and 288 openable windows on the south/north and the east/west façades respectively. The windows are all same height, 2450mm, while the widths vary a little: 970mm towards the south/north, 920mm towards the east/west and all the corner windows 600mm.

Each floor is 3350mm high with an area of around 665m^2 per floor. All these floors have a similar plan pattern of which can be divided into three layers. The centre part is the core with two conventional lifts, a paternoster, mechanical shafts and two staircases on opposing sides. This is the area mainly for vertical transport, measuring 7.8X5.4m^2 while the transition part is a 1500mm-width corridor mainly for horizontal transport connecting the centre core, each room on the floor and two rooms for toilet services. All the academic rooms including those for offices, seminars, meetings and studios etc. are located around the perimeter of the building, composing the external layer (Figure 5.18). These rooms are all naturally ventilated by means of vertically sliding upper sash windows at each bay between the columns. With the exception of the sealed windows at each corner, the size of opening aperture is variable, allowing for a maximum 500mm opening, while the head of the window is protected from the ingress of rainwater by a lintel. For this reason the centre and transition areas of the building are non-passive zones while the external layers can be looked at as passive zones, and thus constitute the main study area of this research.

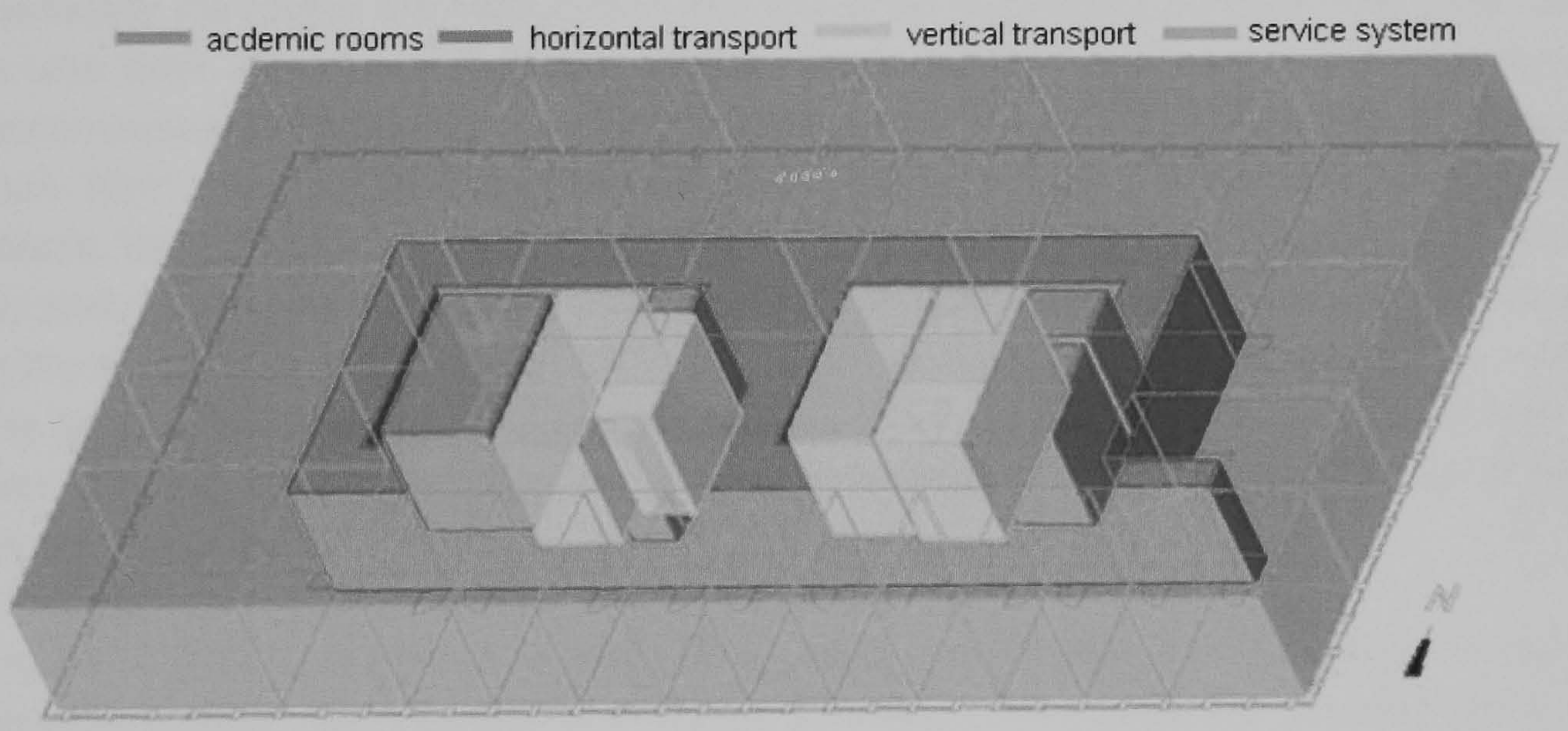

Figure 5.18 Internal design of the Arts Tower

The Arts Tower is a centrally heated building. All perimeter convective heaters are mounted at floor level on exterior walls under each window to provide an upward movement of air to counteract cold downdrafts and minimize condensation. A relatively inefficient oil-fired boiler plant, designed by the G.H.Buckle and Partners Consulting Engineers, was originally used to heat the building, which was then upgraded in the mid-1990s and connected to the Sheffield District Heating System which now supplies most of the City's heating, including the University buildings. Emergency Lighting and upgrading of the fire alarm system was also carried out in approximately the same period. Currently, the tower's electricity supply is provided via the University's high voltage electrical ring mains, serving over thirty buildings in the area. All artificial lightings in academic rooms are typical panel luminaires with fluorescent tubes providing upward and downward light with mirror louvers fitted beneath.

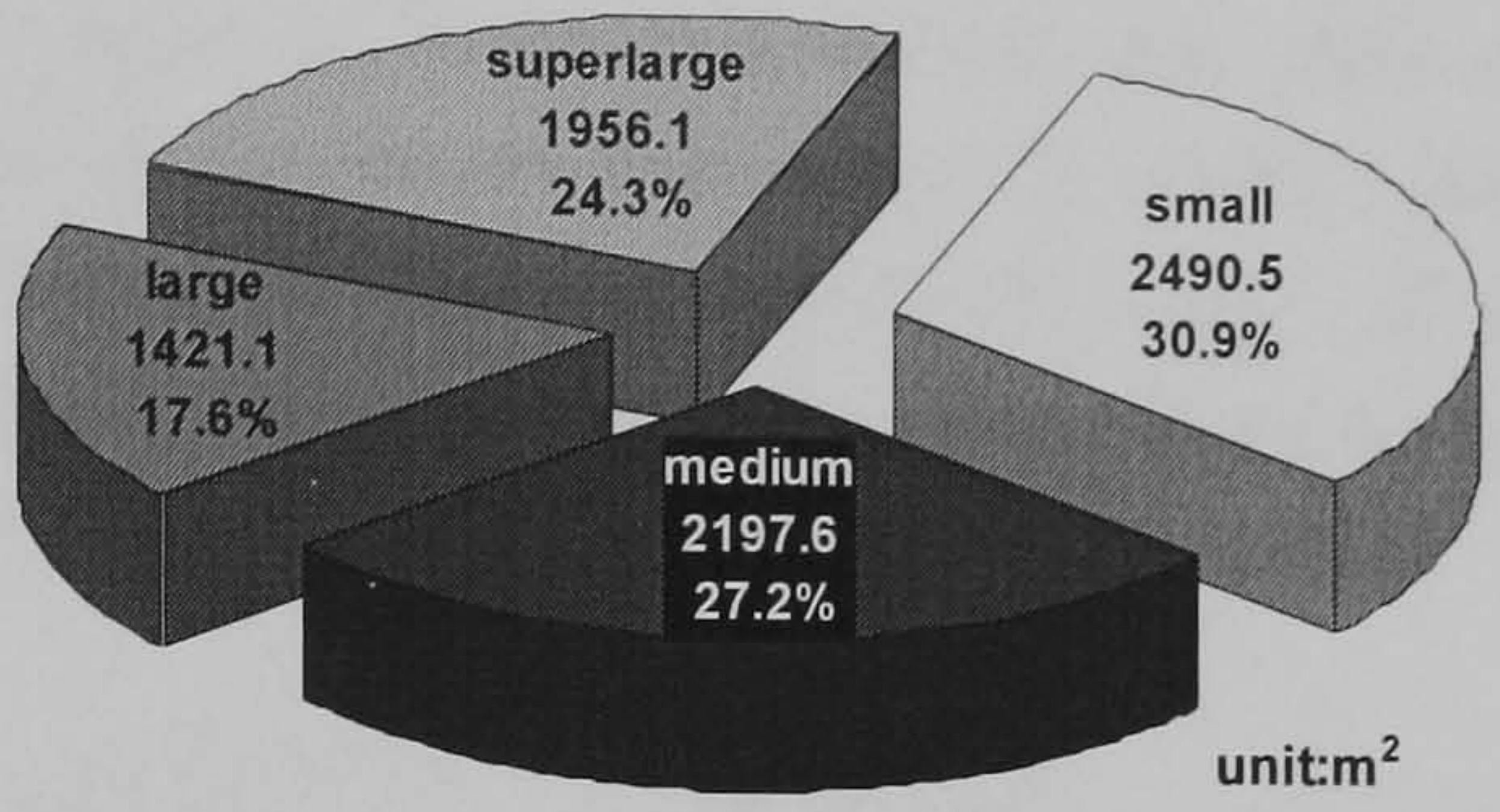

Figure 5.19 Breakdown of different size rooms

5.3.4 Room Distribution

The plan for each floor is different due to university development and the need for interior space to be flexible. The 333 rooms and 1764 windows in the passive zone from the 1st to the 18th floor are used for analysis. The gross indoor area is 8065.3m^2, 67.4% of the total floor area of the Arts Tower. Of these rooms, the biggest one is on the 16th floor (414.1m^2), which is a studio for architectural students, while the smallest, which is just for printing, is on the 12th floor with an area of 2.7m^2. In order to have a clear view of how these building rooms are distributed, they are all grouped into different size categories and further analysed from the orientation point of view.

Generally the rooms are categorized into four sizes depending on area. The *small* one is less than 20m^2 (inclusive); the *medium* is up to 40m^2 (inclusive); while the *large* encompasses the range up to 70m^2 (inclusive) and the *super large* those that are bigger than 70m^2. Figure 5.19 shows the breakdown of total area in terms of different sized rooms. Broadly they are distributed nearly evenly across all the different functions such as staff offices, seminar rooms, computer labs, student studios etc. The biggest of these is the *small room* category with 2490.5m^2, which occupies 30.9% of the total area while the *large room* category occupies the smallest area (17.6% of the total) with 1069.4m^2 less than the *small room*. *Medium* and *super-large* rooms are in the middle (27.2 and 24.3% distribution).

Figure 5.20 looks at room distribution from another point of view – orientation. To make analysis simple, the orientations of rooms involved in this study are grouped into four categories: *east*, *south*, *west* and *north*. The guiding principle of dividing them is determined by window orientation and is illustrated in Figure 5.21. If the windows of a room are toward more than one orientation, the room is labelled with the orientation prior to its peers, according the following sequence: south, west, east then north. The west is prior to east due to the whole building having roughly an 18°

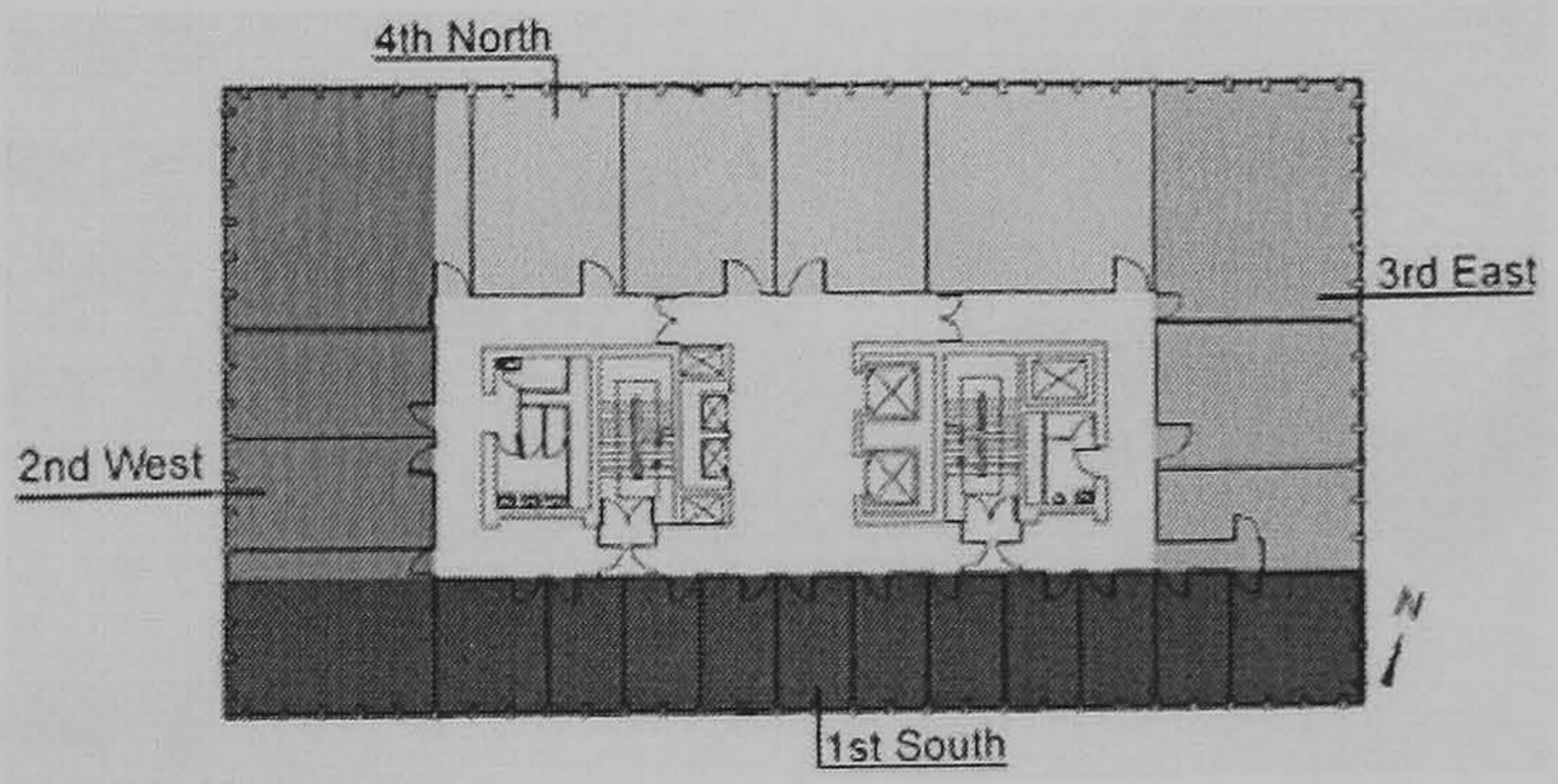

Figure 5.20 Orientation priors of room in the Arts Tower

anticlockwise bias due east. From the figure, most of the *small rooms* are placed towards the south with 56.4% of the total number of areas. The *medium rooms* are distributed quite evenly from 23.4% towards the east to 34.5% towards the south. The *large* ones are more centralized towards the west façade (34.6%) while the *super large* ones are generally towards the north (26.7%).

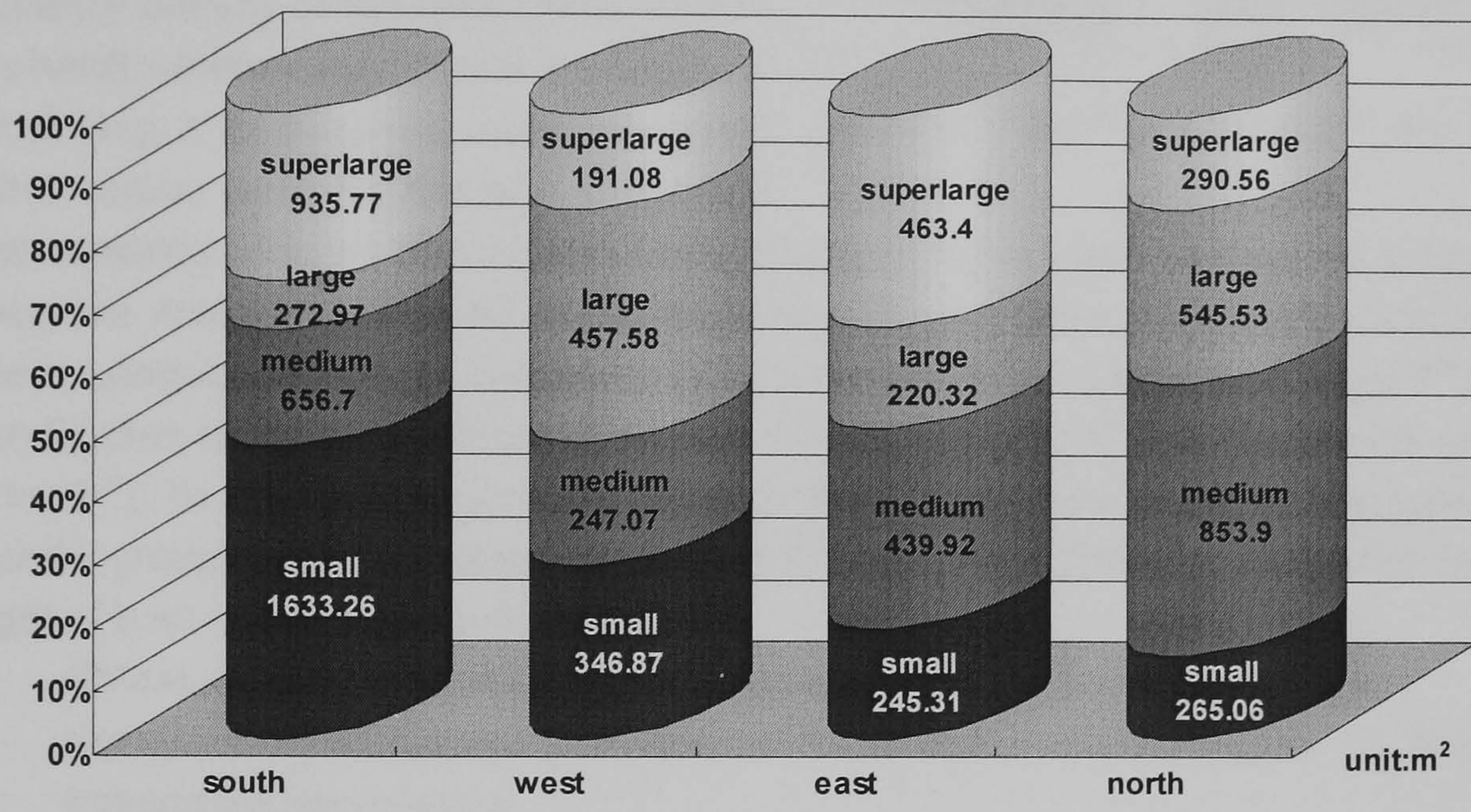

Figure 5.21 Breakdown of different orientation rooms

5.3.5 Occupancy Pattern

Different types of buildings are accounted for by their own expected patterns of use. For an institutional building like the Arts Tower, this pattern is quite fixed with standard starting and finishing times from 9am to 5pm, excluding the non-semester days such as weekends (Saturday, Sunday), holidays (Bank, Public) and vacations (Summer, Easter and Christmas). Figure 5.22 shows the breakdown of both periods in a year. From the University schedule claimed, the standard semester day is 65 days less than the non-semester ones in the year 2005. In terms of the whole building, the occupancy pattern of the Arts Tower is quite predictable and follows a set daily, weekly and annual schedule. Generally, on a typical day, before 6am, the occupancy density approaches 0. After 6am, however, it increases slowly, and from 9am, the occupancy density goes up dramatically with peaks from 11am to 4pm. After that, the occupancy density falls down gradually. After 8pm, it resumes closing to 0 again. Conversely on a non-semester day, the occupancy does not seem to change much, with only a slight increase between 11am to 4pm.

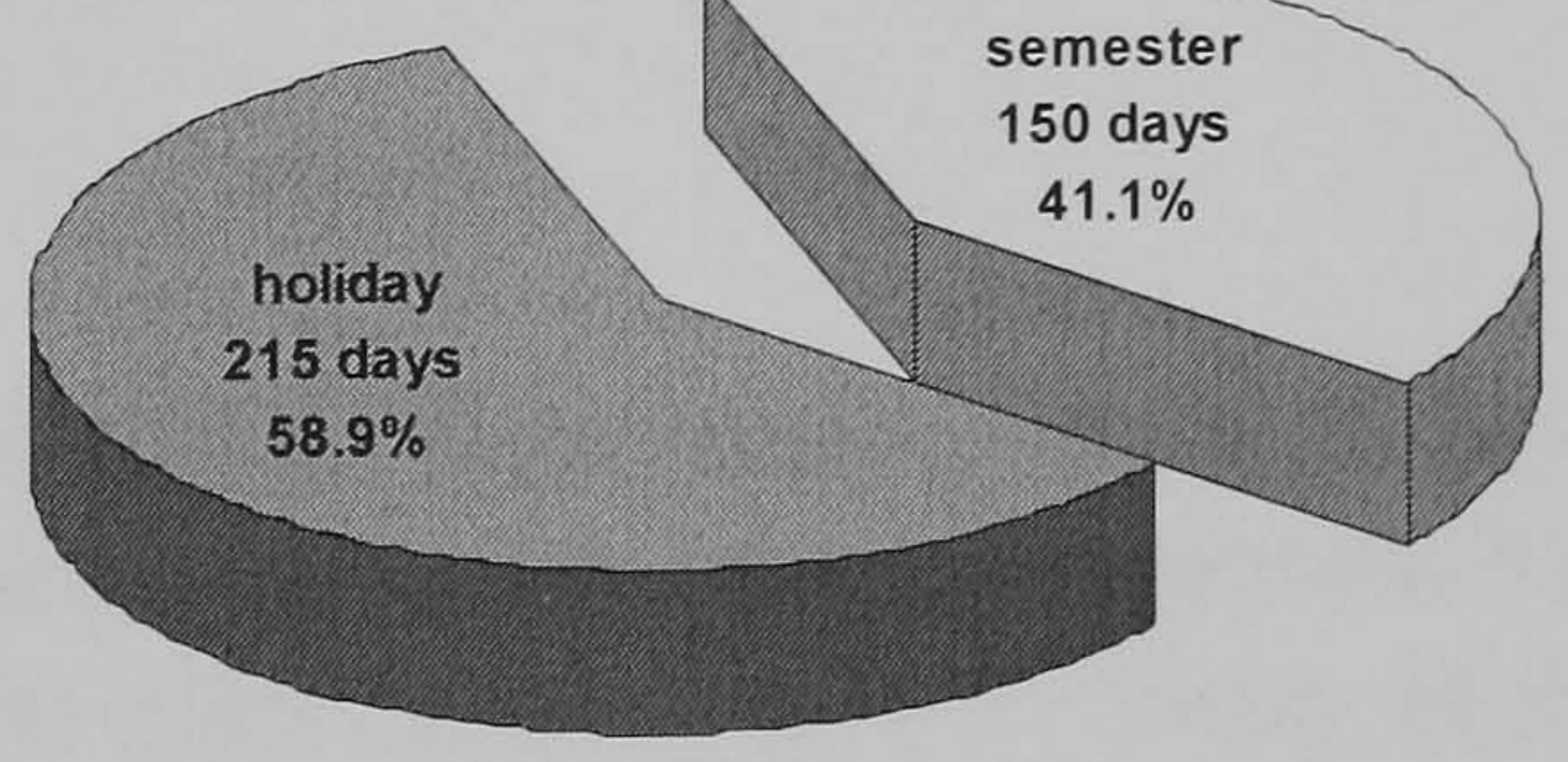

Figure 5.22 Semester and non-semester days in the University of Sheffield

However, when it comes to specific building rooms and occupants, the time spent in a room by each occupant varies greatly.

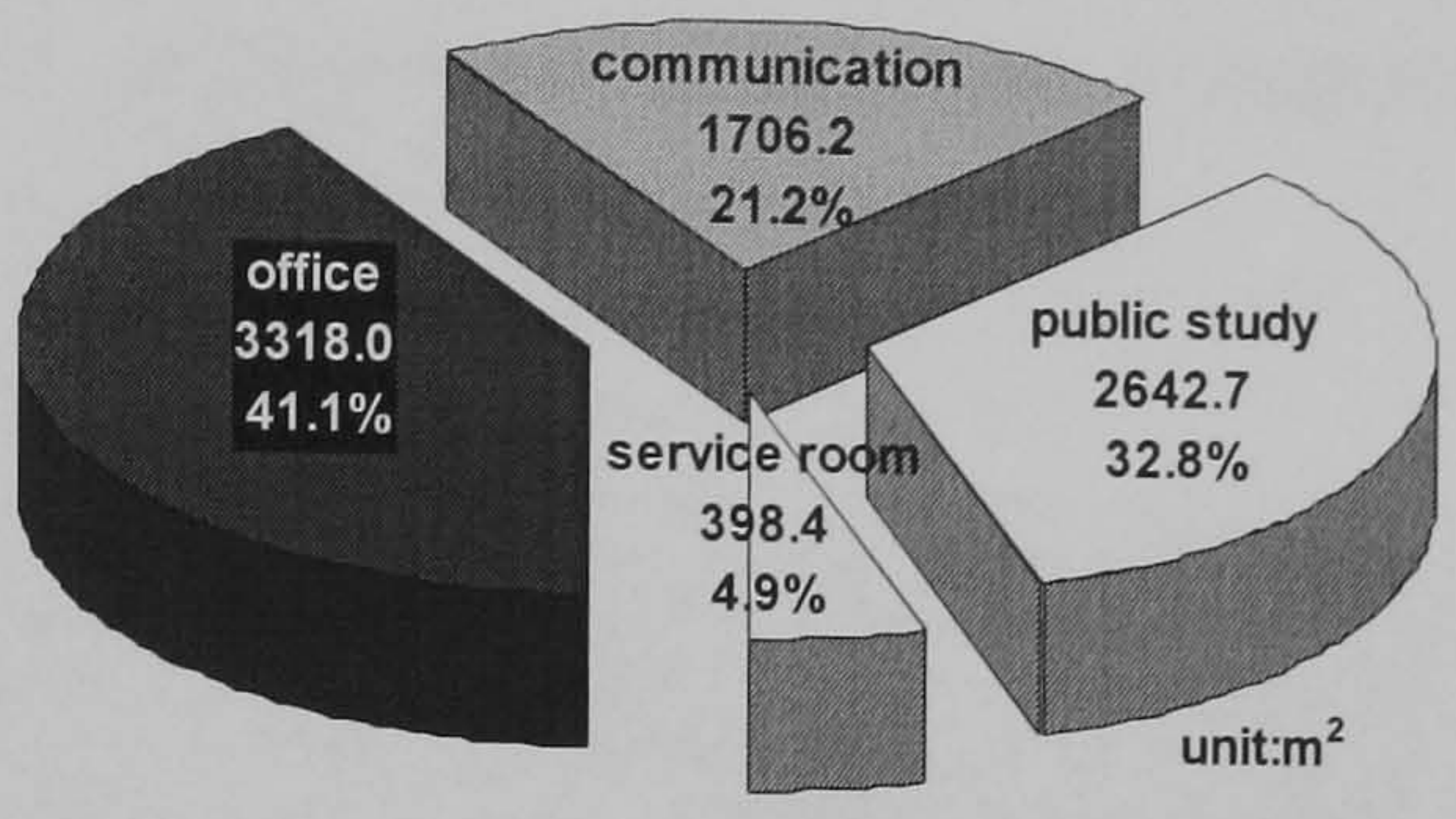

Figure 5.23 Breakdown of different occupation rooms

Occupants are in the building for different purposes such as working, studying, teaching, training, meeting etc. These reasons determine how long they spend in the building and thus ultimately influence the occupancy density of the Arts Tower. On the other hand, whether the room is full or empty or how long it is occupied mainly depends on the rooms specific function. The Arts Tower contains all kinds of function rooms due to its huge mass. During the time of the survey, the Arts Tower housed the main library office (1st floor) and the Department of Modern Languages and Linguistics (2nd, 7 to 10th floor), Landscape (3rd and 4th), East Asian Studies (5 and 6th), Biblical Studies (11th) Philosophy (12th), and Architecture (from 13th to 19th). To make the analysis easily controlled all the rooms under investigation are generally grouped into four types in terms of their occupancy features following the time budget of their established pattern:

- Offices for academic staff, clerk, technician and research student etc;
- Communication areas such as seminar rooms, lecture theatres for teaching, training and/or meeting;
- Public study areas such as computer rooms, libraries, studios and workspaces;
- And other service rooms for students and/or staff, such as rooms for resting, assembling, copying and printing, and storage etc.

Figure 5.23 shows the breakdown of total areas between these four kinds of rooms. It can be seen that service rooms are the smallest of the constituent parts in the Arts Tower (4.9%) considered in terms of function. These rooms are occupied according to a very intermittent and unpredictable pattern and occupancy in these rooms is normally just for a short period of time. Public study areas are, more or less, always occupied, especially during semester days. Communication areas are used intermittently and their occupancy and evacuation patterns change quickly and dramatically. Occupants are usually in these specialized rooms for no more than three hours. Offices make of the biggest part of the Arts Tower in terms of functional space, taking up 3318.0m^2 (41.1% of the total area). In these rooms, occupants normally have fixed study/working places and stay for more than 80% of the total semester time and day.

5.4 ICOSS Building

The Informatics Collaboratory of the Social Sciences (ICOSS) is based in the University of Sheffield and is the fist large scale dedicated facility for social science research in the UK. The building design represents a landmark development, both in terms of its sustainable performance and its physical presence. As in the case of the Arts Tower, this study focuses the attention on the occupant environmental issues of this building, and description and analysis are restricted to its architectural design and occupancy features [16].

5.4.1 Background to the Building

Figure 5.24 Northwest view of the ICOSS Building

The University of Sheffield is a large organisation which has over 20,000 students, 6,000 staff and several hundred buildings. Due to both its size and the nature of the activities undertaken, the University recognises it has a significant impact on the local and global environment, including the use of natural resources, the consumption of energy and water and the production of a variety of waste by products etc. In order to demonstrate its desire to improve its environmental performance, the university entered into a corporate commitment by signing up to an Environmental Policy in 1997. One of the main principles of this policy is *to promote energy conservation by efficient use, careful planning and design with due regard to improved energy utilisation and appropriate investment in energy efficient measures*. In the year 2004, a more specific 'Energy Policy' was established to highlight that highest standards of excellence and also to be developed in its energy and environmental management [17].

With this background in mind, when the decision to build the Informatics Collaboratory of the Social Sciences (ICOSS) Building was made by the University of Sheffield, the university was determined to develop a concept for a new inter-departmental research facility that aimed to offer a radically different approach to academic inquiry. The brief was to create an information technology based research facility, which would affirm itself both environmentally in terms of energy performance and visually as a landmark building. Later within that same year, the new ICOSS building was opened (Figure 5.24). It was the first large scale dedicated facility for social science research in the UK and was an initiative funded by the Science Research Infrastructure Fund (SRIF) together with a substantial investment by the University of Sheffield, which acknowledged the crucial importance of multidisciplinary research for the advancement of social science and public policy.

Issues of energy use and sustainability are fundamental to the architectural principal. It was designed by CPMG Architects and ARUP engineers both of whom were very experienced not only in producing a striking appearance but also designing for performance. They are constantly researching new technologies and materials to find ways of optimizing performance and sustainability in building designs [18]. In 2006, the ICOSS building was a national gold prize-winner at the International Green Apple Awards in the built environment and architectural heritage category for the ability of its designers to combine a low level of energy use with a striking appearance [19].

5.4.2 Location of the Building

The building site is not far from the Arts Tower, which is essentially a peninsula formed on three sides by streets and one side by another building. Portobello Street forms the north edge of the site, which is roughly 6° anti-clockwise due east. The street is around 50m away from the nearly parallel Broad Lane (A57), which is one of the main roads into Sheffield city centre linking to the Brook Hill roundabout. Victoria Street (4.5m wide) and Regent Terrace (5.2m wide) become the boundary of the east and west sides. The west side is parallel for a distance of 40m with Upper Hanover Street (A6134), which is also a south exit of the same roundabout. Between the streets and the existing buildings, there is a drop in elevation of nearly 500mm from north to south.

These boundaries form a rectangular site, measuring 39m long and 25m wide. The ICOSS building occupies 72.3% of the site area with the main entrance towards the north. Some medium-sized buildings are surrounded the ICOSS building. The nearest one is the Innovation Centre, which is a 15m high building. It is east of the ICOSS Building, opposite Regent Terrace. Another one is a 7-storey building 20m high towards Leavygreave Road. Its main entrance is set back about 30 metres to form an open space in front of the entrance to the building. There are mainly single storey buildings no more than 3 metres high to the south side (Figure 5.25).

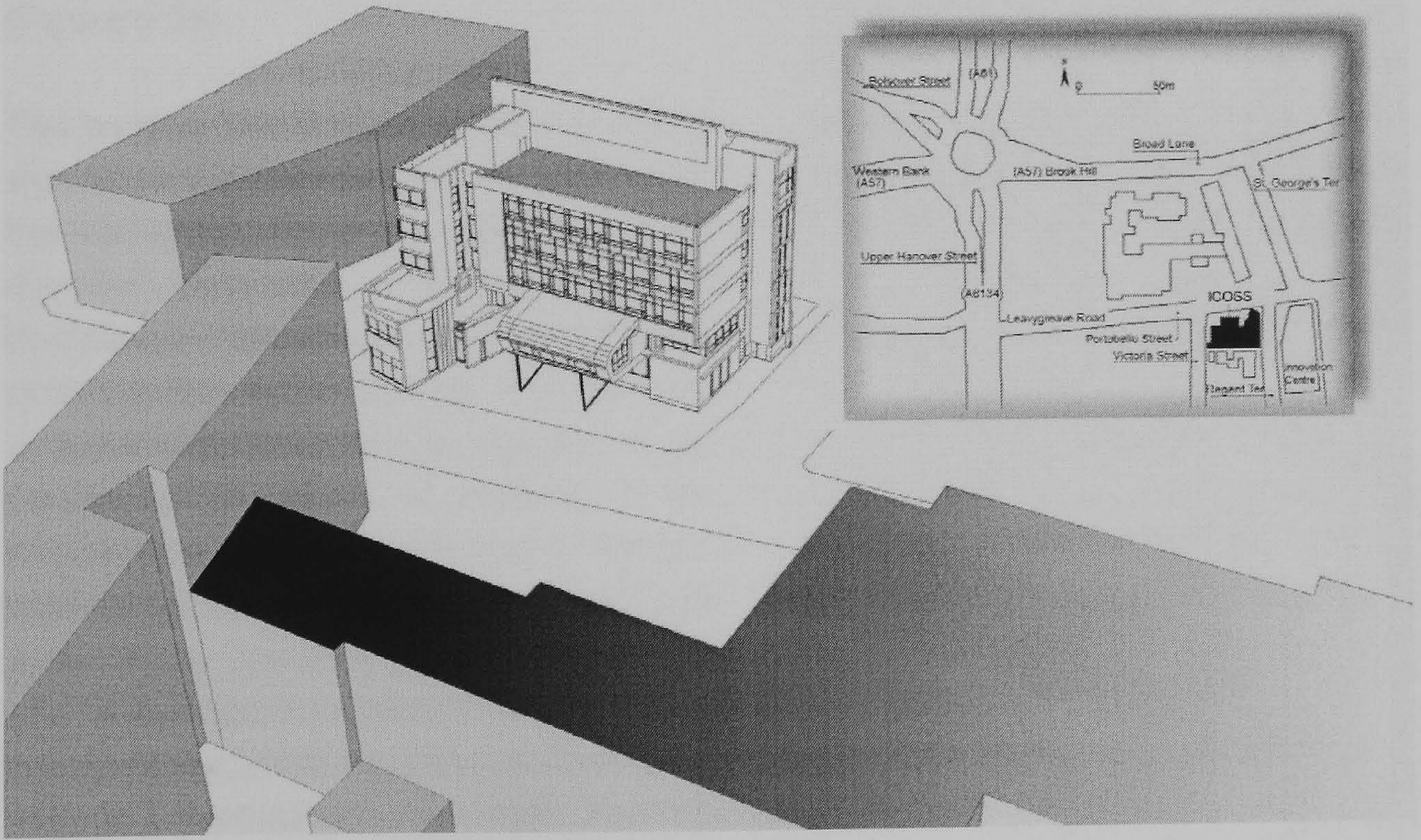

Figure 5.25 Position of the ICOSS Building and its surrounding

5.4.3 Building Design

ICOSS is a free-standing building with 5 floors and an area of approximately 1850m^2. Its longer side is towards the north. The north façade is designed to be set back about 10m in order to provide for a small public space (25X10m^2) in which the main entrance is located. This open space is animated by an elevated, sculptural conference room with attractive green coverings and red columns, which opens up new views across the site and forms a dramatic marker for the new building's entrance.

The north façade has a large glazed area which occupies of the 56.4% area from 2nd to 4th floor. The windows are designed in an irregular pattern with many different sizes. Statistically, there are 138 fixed windows and 72 operable ones, with the operable area only occupying 25.1% of the total glazed area. Although the south façade is also fully glazed, the windows are all the same size (1500X1700mm^2) and completely sealed except those on the top floor with different height. The upper ones are 500mm high while the lower ones are 1000mm high and top-tinged, allowing them to swing open towards the outside. Both sides of the glazing are transparent and set in dark metal frames with mullions and spandrels. Roller blinds are installed in order to cover every window. Most of the façade areas are covered by metal curtain walls with silver and blue colour while dark blue bricks are also used in some places on the ground floor. Additionally, as an expression of the environmental aims of the development, the roof level will be used as a roof garden, with benefits to building insulation and rainwater run-off control, as well as establishing a dramatic external space (Figure 5.26).

The building is a concrete structure with a significant proportion of the surface of high thermal mass, and thus used to absorb daytime heat gains which are then dissipated via night-time ventilation resulting in passive cooling. This building is specifically designed to use the south façade as a means of drawing in air through the building. Each floor is aligned against a south-facing atrium 1200mm wide, which contains the primary vertical and horizontal circulation, and act as a thermal collector to drive the passive stack natural ventilation. A high-reaching projection above the roof is exploited so as to have sufficient magnitude and enhance

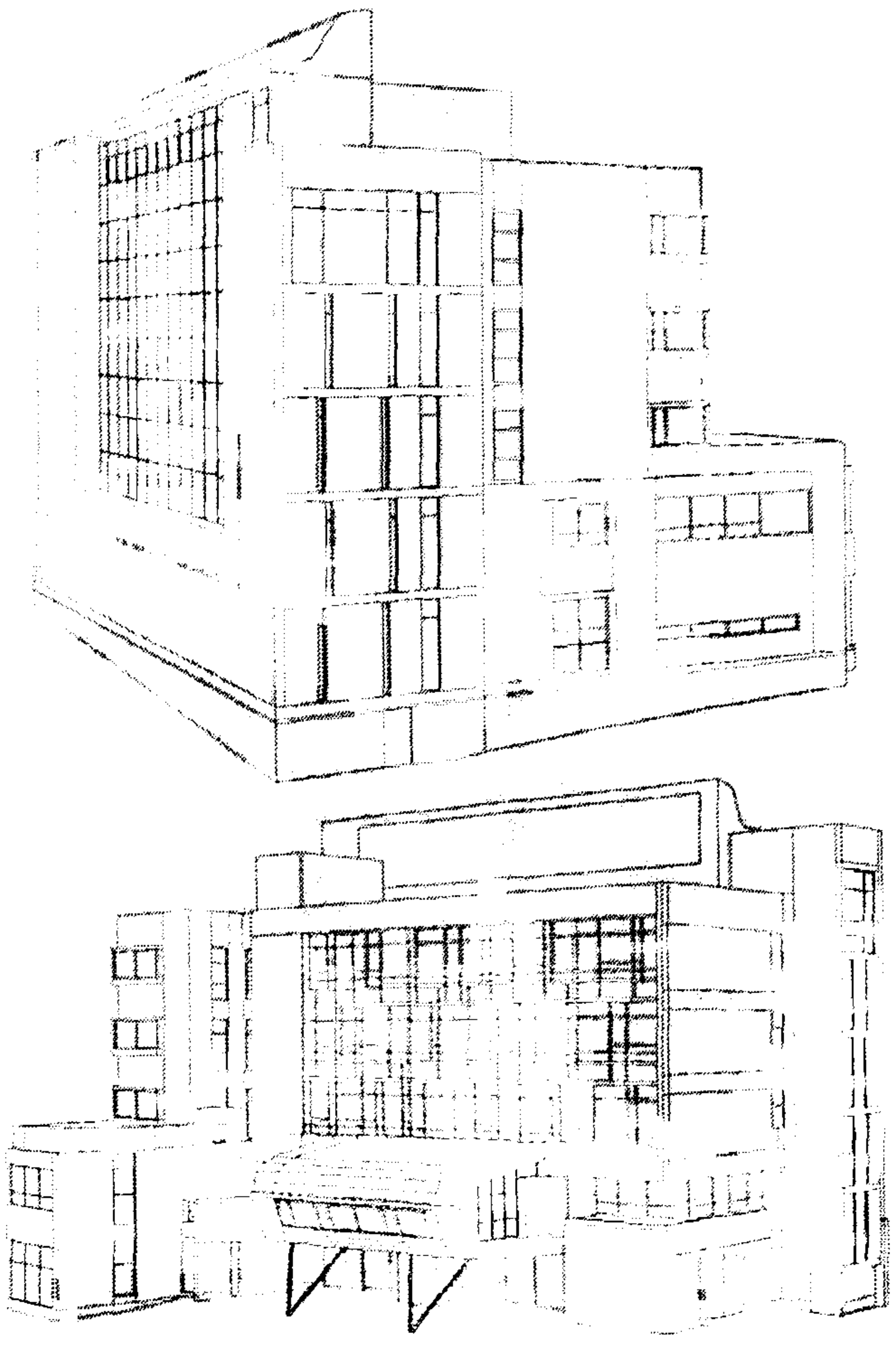

Figure 5.26 3D model of the ICOSS Building

the performance of the stack effect for natural ventilation. It serves as a suction zone to exhaust the air through the top. An extractor fan is installed to ensure the rate is controlled and air movement can be introduced more uniformly across the space.

Large glazing areas also encourage the flow of air through the building effectively because solar energy is transferred across into the building, heating the air which then rises and is vented out at the top. The replacement air is supplied via openings on the north façade. In warm or sunny periods, all of the glazing is equipped with full length roller blinds which enables solar strength to be moderated for different weather conditions and internal patterns of use, e.g. to avoid glare and overheating.

The service systems are basically located on the southeast side of the building, including staircases, toilets, storage and a Café, except for another staircase at the corner of the southwest side. A lift is installed here as well which runs between the ground floor and 5th floor. The whole building is centrally heated with emitters mounted on walls. This uses the necessary radiator to release heat mainly by means of radiation and convection. The emitters consist of fin-tubes to maximize the heat transfer by natural convection. The roof lights are all energy efficient bulbs, while a table lamp is provided in every work station for maximum flexibility to suit personal requirements.

5.4.4 Room Distribution

The ICOSS Building is a purpose-built centre that offers a spacious modern work environment to enhance internal communication through the use of space with IT and telecommunications facilities (Figure 5.27). On the ground floor, an entrance hall of 2-storey height, measuring 16X7m^2 was designed in order to accommodate walkway, resting and communication functions.

It is surrounded by the necessary plant room, service space and reception area. A formal meeting room of around 90m^2 is located at the northeast which has its own entry door. On the second floor, a Geographical Information Systems (GIS) Laboratory is located covering the east part of the building.

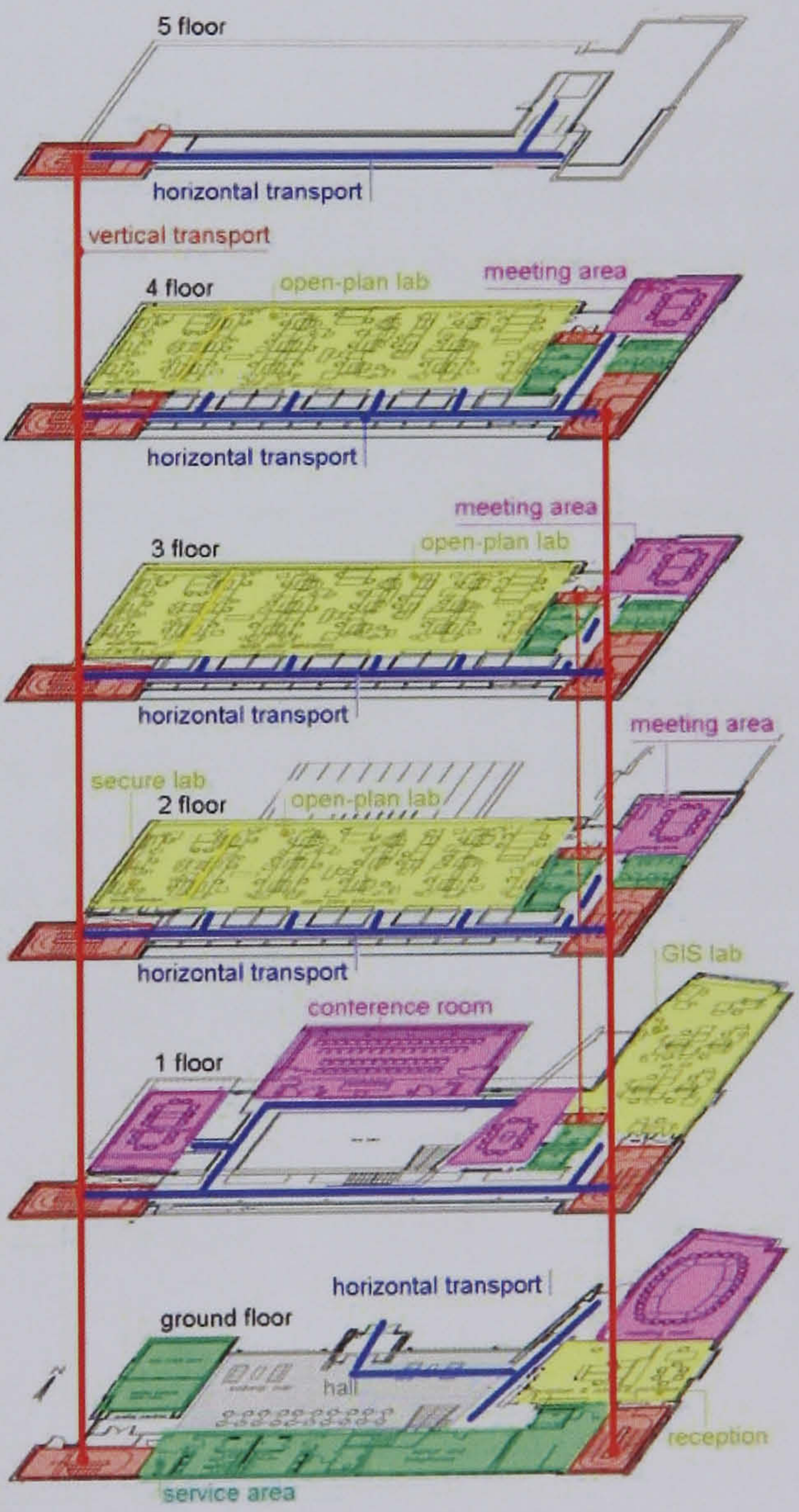

Figure 5.27 Room distribution of the ICOSS Building

A directorate, central conference room (10X7m^2) with a narrow row of skylights is attached above the entrance to the north. Another small meeting room (25m^2) with a modern flatscreen monitor installed is at the west side. These spaces are connected by a feature walkway.

From the 2nd to the 4th floor, each plan is similar with a big open laboratory 19m long and 9.5m wide in the centre. There is no partition wall between the spaces from the north to the south façade. Beside the open-plan lab, there is a secure laboratory towards the northwest and a meeting room at the corner of the northeast. The 5th floor is only the part of a high-reaching projection above the roof with 4.8m width. Due to the atrium and the feature walkway, the work station in each open plan laboratory is 5m from the south façade. Furthermore, the work station units can be repositioned to allow users to design their own work-space. The desks are free to perform a variety of roles: they can be used as individual units, wheeled together to create informal meeting areas or delineated 'office' space or can be stowed under shelves to provide a clear floor area for conference use.

5.4.5 Occupancy Pattern

The ICOSS building is a research centre which is designed to accommodate up to 100 researchers. The interdisciplinary focus across the social sciences recognises the importance of collaborative work and physical proximity in addressing problem focussed and policy relevant research. A number of research groups from across these disciplines are already located within it. The scope of research will extend as ICOSS grows. Before the survey finished in Apr/06, there were roughly 45 occupants working in it. These were comprised mainly of management and technical staff and research students.

For the people who work in this building, the basic workweek is Monday through Friday from 9:00am to 5:00pm. However, work schedule alternatives allow the occupants to customize their work arrangements to fit their personal needs and goals. Basically the occupants can choose their starting and stopping times within certain limits. Thus the alternative consists of two components: flexible bands and core hours. No matter whether working a standard or alternative work schedule, the lab is always occupied during core hours. The flexible time bands are the times during which occupants may vary their workday starting and ending times. The core hours and flexible time bands are outlined in Table 5.2.

Band/core hours	**Begins**	**Ends**
Flexible Band	7:00am	9:30am
Core Hours	9:30am	11:30am
Flexible Band	11:30am	1:30pm
Core Hours	1:30pm	3:30pm
Flexible Band	3:30pm	7:00pm

Table 5.2 Band / core hours

5.5 Summary

This chapter explores the background to the investigated buildings. Although the information given in this chapter is general in nature, it touches on the characteristics of the UK and Sheffield climate and illustrates the topography and weather variation of Sheffield in particular. Through the comparison of the main climatic factors such as temperature, relative humidity etc. between the average statistical values of a 30 years period and those of the monitored period when the survey was undertaken in Sheffield, a general degree of precision in the estimates about the actual situation prevailing at other times can be obtained because the comparison provides a clear view of irregularities of weather that are still within the general pattern of climate conditions.

After this, the detailed backgrounds of the two cases were described and analysed separately, highlighting the issues in terms of five aspects: background to the building, location, architectural features, room distribution and occupancy patterns. Thus, a thorough understanding of the context of the investigated buildings was obtained.

In the next chapter, the results from the survey and site observation will be analysed to examine occupant comfort sensations and responses to environmental control in these buildings. Various issues of concern are pursued, particularly those regarding weather conditions, room features and user identities, in order to find out at what levels these different issues will influence the motivating forces for manual operation behaviour.

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Chapter Six

Results and Analysis of Investigated Buildings

Still, an intuitive assumption about behaviour is only the starting point of systematic analysis, for alone they do not yield many interesting implications.

- Gary Stanley Becker
(1992 Nobel Prize in Economic)

Chapter Six
Results and Analysis of Investigated Buildings

6.1 Introduction

The preceding chapter provides the background information about the two investigated buildings. Also in Chapter Four, it was shown how the data was collected and processed for further analysis. This chapter presents the result and analyses of the whole research study so that the hypothesis generated in Chapter One can be tested. Based on the proposed hypotheses, the analysis is divided into two parts (Figure 6.1). Analysis I concerns occupant comfort perception and responses to the built environment, and it requires a computer simulation in order to illustrate the results and establish the likely ranges in the thermal and visual environment over the working space. The results present in this part, apart from the simulation models, all come from the questionnaire survey and physical measurement. Analysis II, on the other hand, deals with the occupant's actual control of the window and internal shading device (venetian blinds in the Arts Tower and shading rolls in the ICOSS Building). The factual evidence from field observation in the form of photographic records is gathered in order to further understanding of the significance of certain key concepts regarding the occupant's environmental control behaviour.

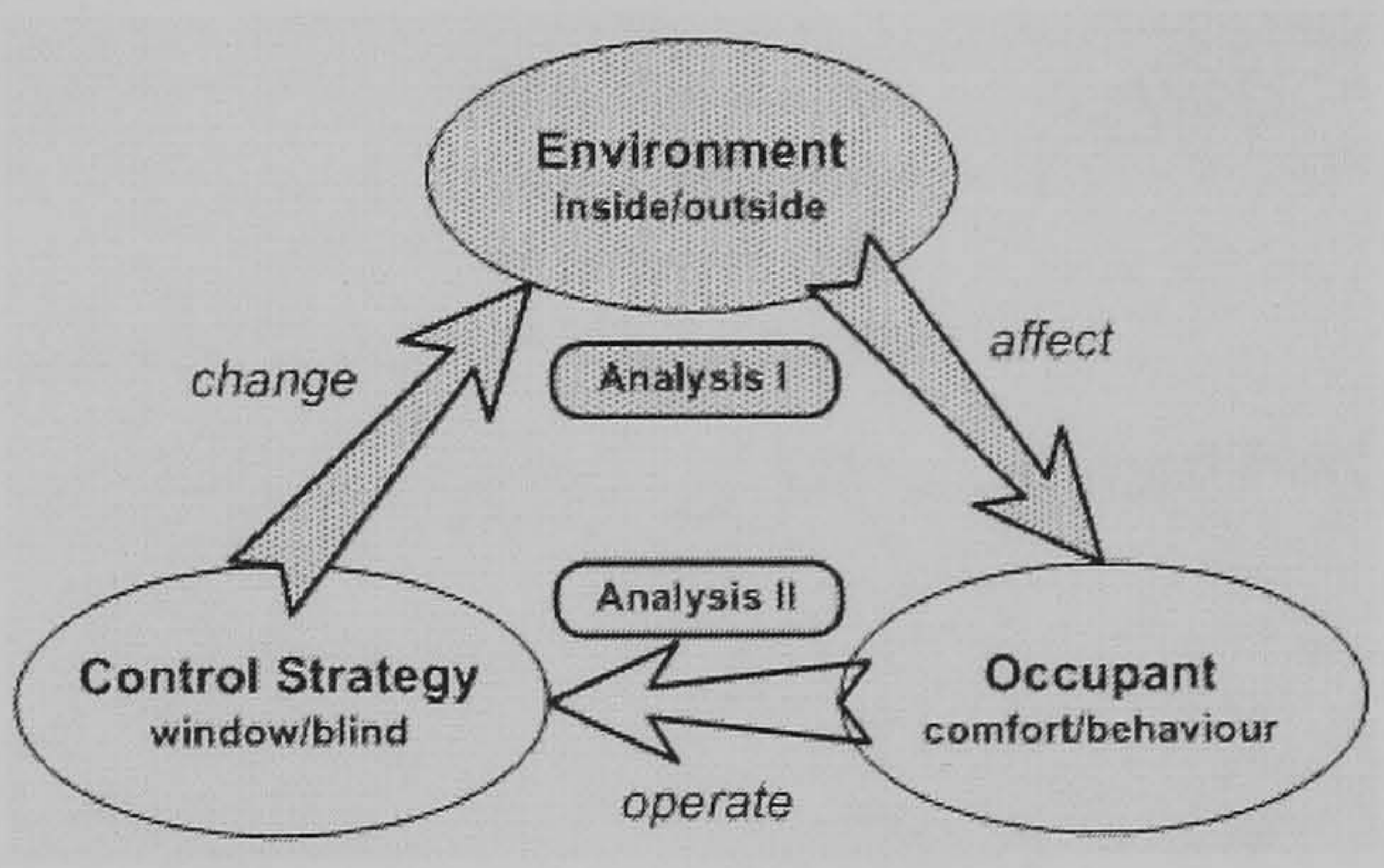


Figure 6.1 Step of analysis in Chapter Six

Data Analysis I

6.2 Occupant Comfort and Response to the Built Environment

It is widely accepted that in a naturally ventilated building, the occupant's perception of the built environment, whether partial or complete, can significantly affect the occupant's control over the built environment and vice versa [1]. In this part, the occupant's comfort and experience over the indoor environment are examined and analysed with attention given to the thermal, visual, acoustic environment, window seat preference, view appreciation, glare and noise disturbance and their responses to those simple easy-to-use and robust control strategies. The impact of these control strategies on the built environment are also tested by the computer simulation.

6.2.1 Arts Tower

In this part, room orientation is selected as the primary physical variable affecting the occupant's opinion on the questions since the sun path and solar heat determine the room environment in a very critical way from both thermal and visual points of view. In this particular case, it affects the noise level as well. The other variables such as respondent gender difference (i.e. whether they are male or female), clothing grading, age etc. are also included. Although these matters also have potential influences on the results, discussion is avoided here; they are to be reserved for future studies (Detailed information about the final version of the questionnaire is attached in Appendix A).

6.2.1.1 At the Point of Survey

When the questionnaire was carried out, the occupants were asked about their sensations and satisfaction levels with regard to their working environments. Simultaneous measurements of the internal physical environmental parameters were also made, e.g. temperature, relative humidity, sound level and illuminance (see below).

1. Please evaluate the overall environment in this room *at this moment* by ticking a score in each row?

	←Very	Fairly	Little	Neutral	Little	Fairly	Very→	
Cold	-3	-2	-1	0	1	2	3	**Hot**
Dark	-3	-2	-1	0	1	2	3	**Bright**
Quiet	-3	-2	-1	0	1	2	3	**Noisy**

2. Do you feel comfortable toward the overall environment in this room *at this moment*?

Very dissatisfied←	Fairly	Little	Neutral	Little	Fairly	→Very satisfied
Thermal -3	-2	-1	0	1	2	3
Visual -3	-2	-1	0	1	2	3
Acoustic -3	-2	-1	0	1	2	3

Measurement: Air temperature_____C RH____% Sound level ______dB Illuminance _______Lux

Thermal perception and comfort level

In total 188 responses were received. Results from 180 were regarded as valid - 95.7% of the total number. Generally, the outside environment was cold and humid with an air temperature of 10.8°C and RH 71.1% (average) when the survey was carried out from Dec/05 to Apr/06. However, because the central heating was always switched on, there was no strong correlation between the outside and the inside air temperatures (the coefficient value between these two variables is less than -0.032). The average inside temperature was 23.5°C with an RH of 45.7%, which was a positive combination of figures with respect to the thermal comfort criteria.

Figure 6.2 shows a clearly increasing trend when it comes to the relation between air temperature and human perception. It is noticed that the regression line goes through the point (22.0) which may be looked as a benchmark of thermal neutral in the Arts Tower. In total 91.9% can be described as 'comfortable' if the Building Bioclimatic Chart is used to define the comfort zone i.e. one ranging from 18 to 25°C with a humidity between 20% and 60% [2, P75].

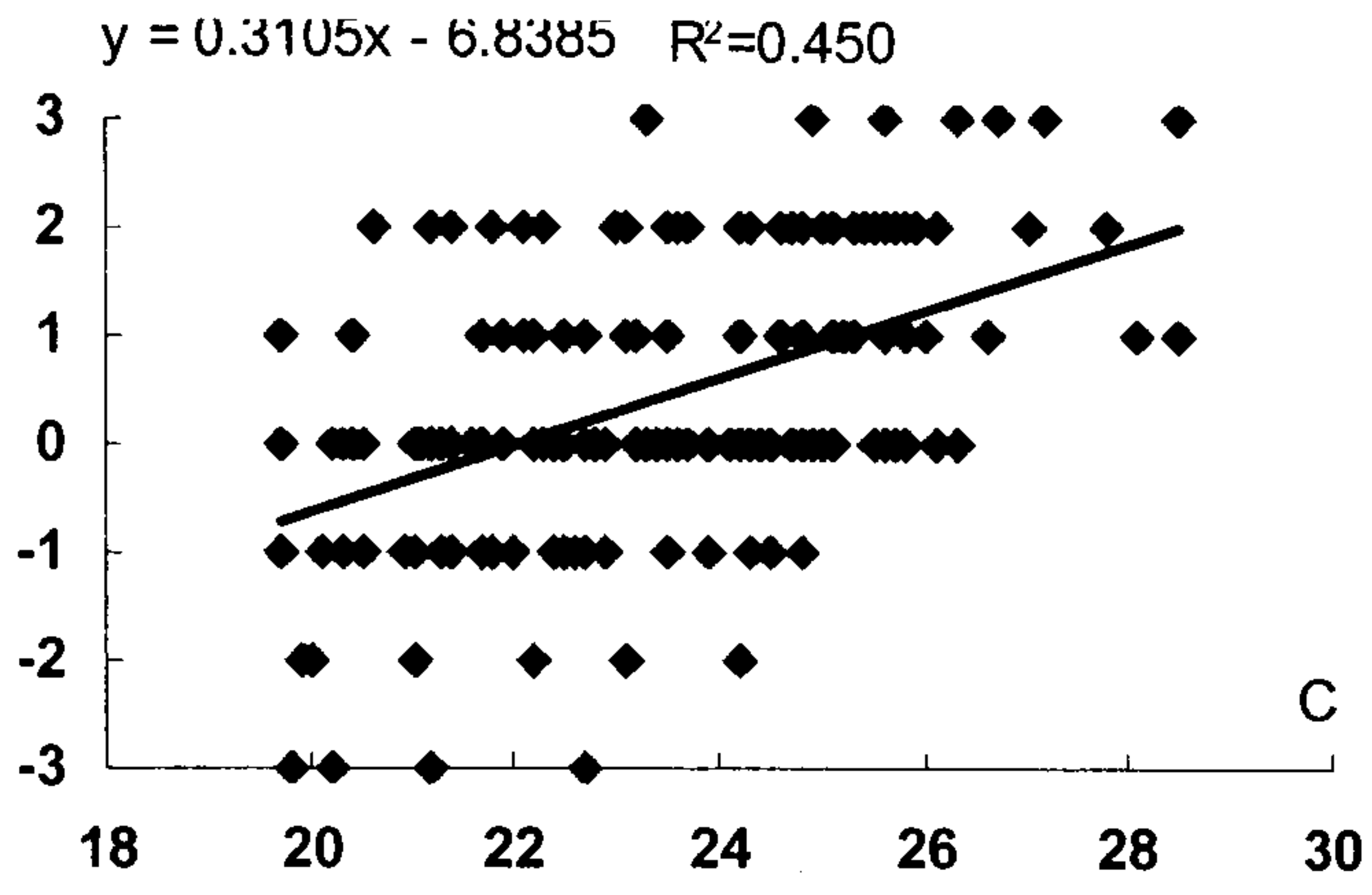


Figure 6.2 Relationship of perception and air temperature

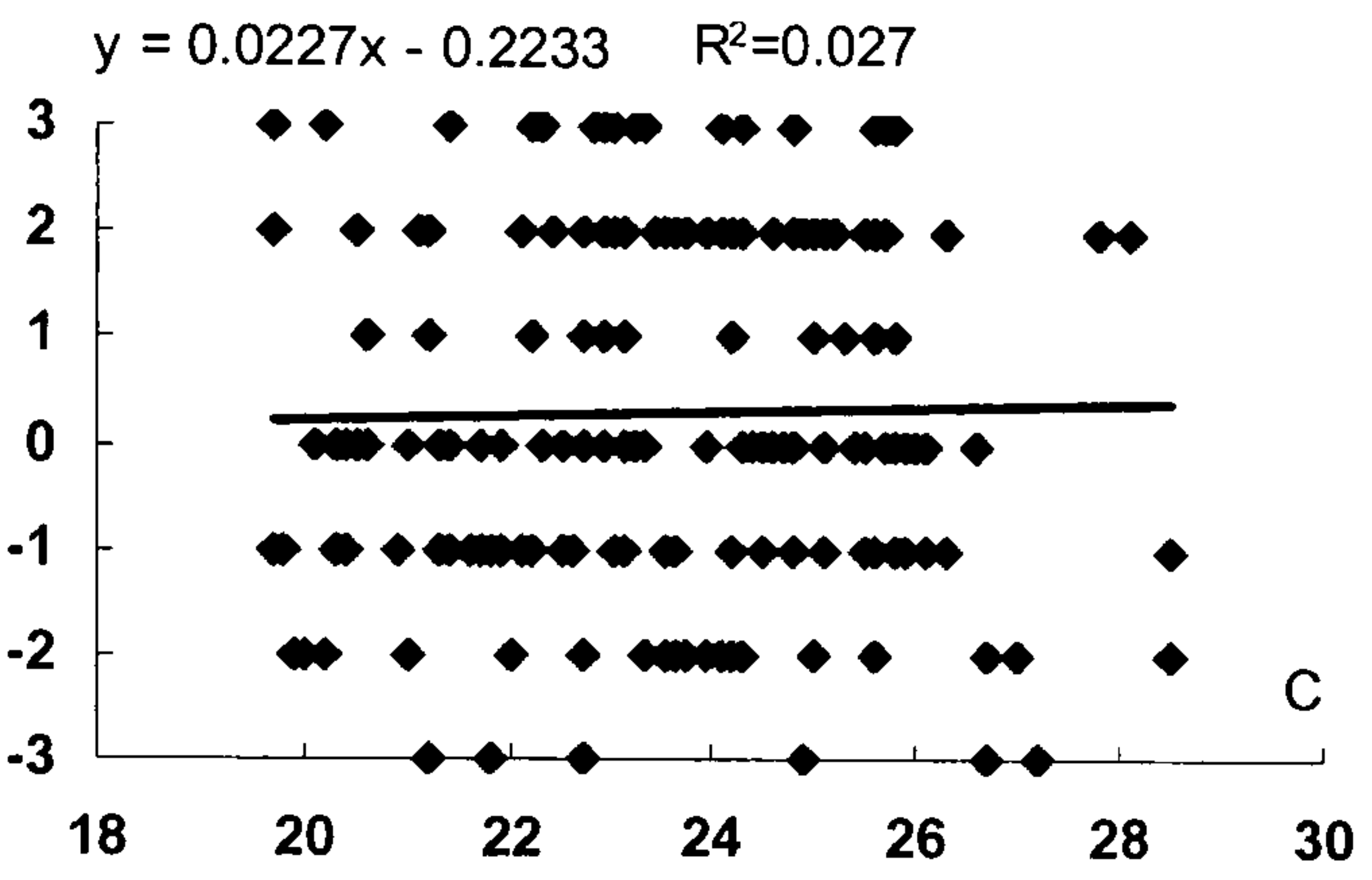


Figure 6.3 Relationship of satisfaction level and air temperature

Therefore, when it comes to the relation between temperature and satisfaction level (Figure 6.3), the regression line is very flat and close to 0 (neutral). However, there are 33.3% respondents not satisfied with their thermal environment at the survey moment, which indicates that in this particular case, there are other issues that affect the occupant perception of the thermal environment apart from air temperature and humidity. As discussed in Chapter Two, the parameters that affect the occupant's thermal perception in a conventional built environment are mainly air temperature, mean radiant temperature, air movement and relative humidity [3]. The influences of these parameters are not equal. When the air temperature and humidity are moderate, as happens to be the case here the effects of other factors may become more evident.

From the feedback of respondents, the dissatisfaction is increased in magnitude due to an increased sensitivity to the air movement under warm conditions and radiation temperature under cold conditions. The fact that extreme situations with both maximum and minimum temperature took place in the rooms towards the south and the west also confirm that they are the main issues that cause dissatisfaction in this case. In detail the local thermal discomfort can be grouped in terms of two conditions:

- Stuffy air caused by poor ventilation due to the nature of the high-rise building, such as the compact plan and the single-sided window;
- Cooling or heating parts of the body by radiation. Large areas of glazing intensify the asymmetry of thermal radiation both solar and cooling radiation.

Visual perception and comfort level

In total 188 responses were received. Results from 179 of these were regarded as valid and occupied 95.2% of the total number. It is interesting to see more than half of the responses leaving the artificial lighting on but there is no clear evidence showing that the combination of sky and artificial lighting can lead to higher illuminance. For example, of the records showing illuminance between 300 and 600lux, 45.8% were measured without artificial lighting; from 600 to 900lux, the records went up to 50.5%; and for more than 900lux, a further 8.0% more. Even when it came to over 1200lux, there were still 45.5% of records that show only the use of the skylight as a lighting source (Figure 6.4).

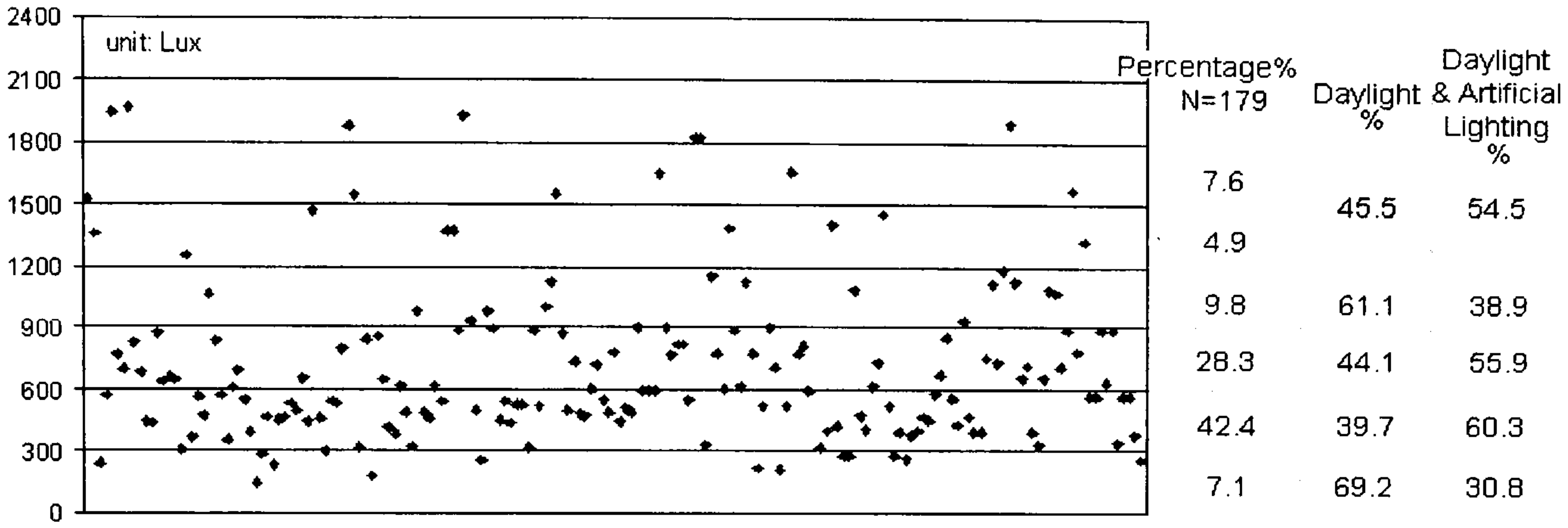


Figure 6.4 Distribution of the illuminance at the time of survey (Arts Tower)

The visual environment among these rooms were quite varied of which the highest was roughly 13.5 times the lowest due to the fact that there were many variables affecting indoor illuminance e.g. the position of the blinds, the effect of artificial lighting, room orientation, the condition of the sky etc. From Figure 6.5, the impact of illuminance is closely related to the respondent's visual perception of dark and/or bright environment.

Most of records measured at the time of survey were in the range between 300 and 900lux, thus occupying 70.7% in total. A figure of around 500lux is usually recommended for lighting in the office environment in most agreed standards and codes of practice [4, P180]. If this criterion is applied, only 65.6% of records suggest that this requirement for visual comfort has been attained. However, the regression line in Figure 6.6 presents that the satisfaction level is generally above the 0 point (neutral). It indicates that adequate illuminance is not the only requirement for visual comfort. The

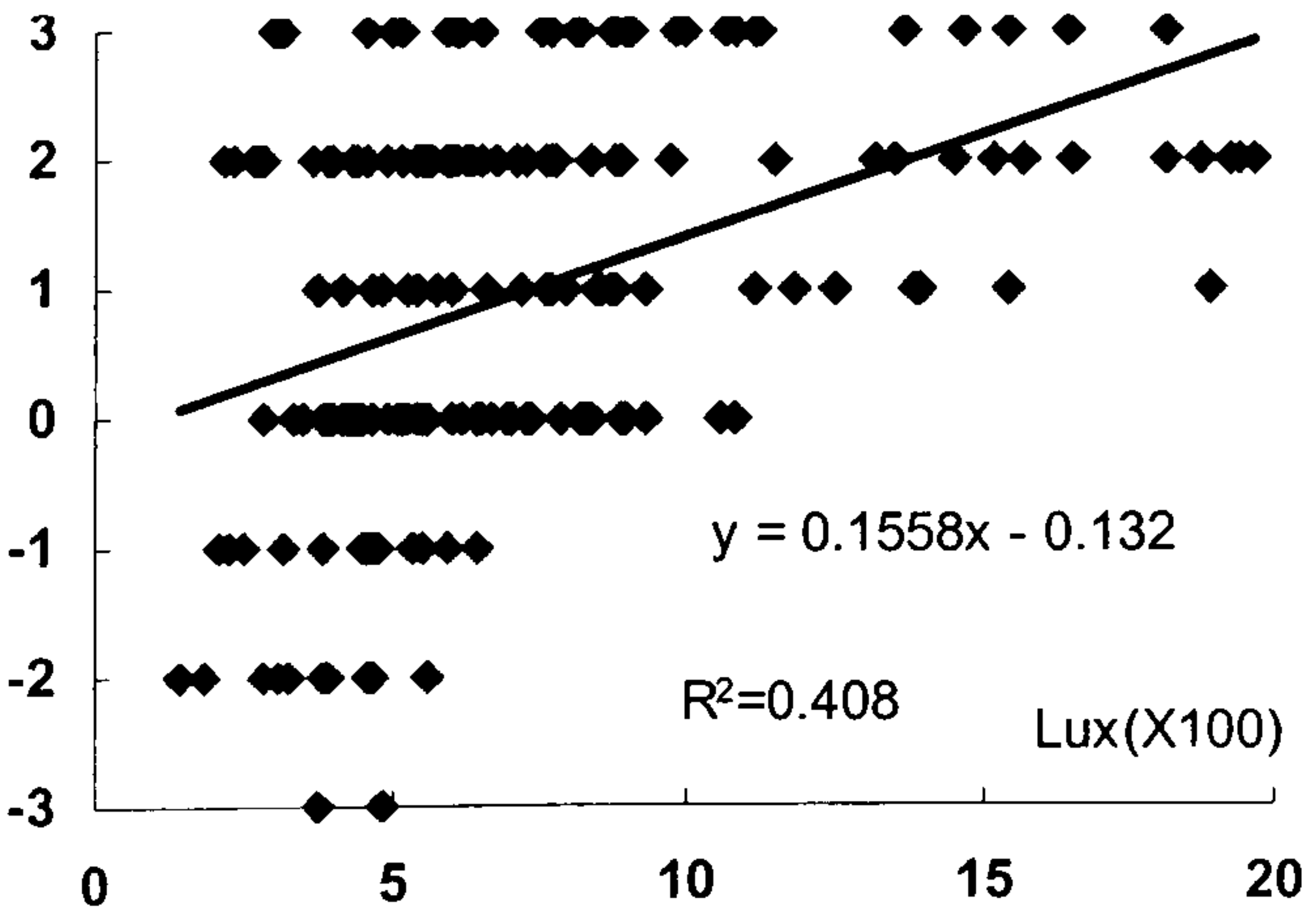


Figure 6.5 Relationship of visual perception and illuminance

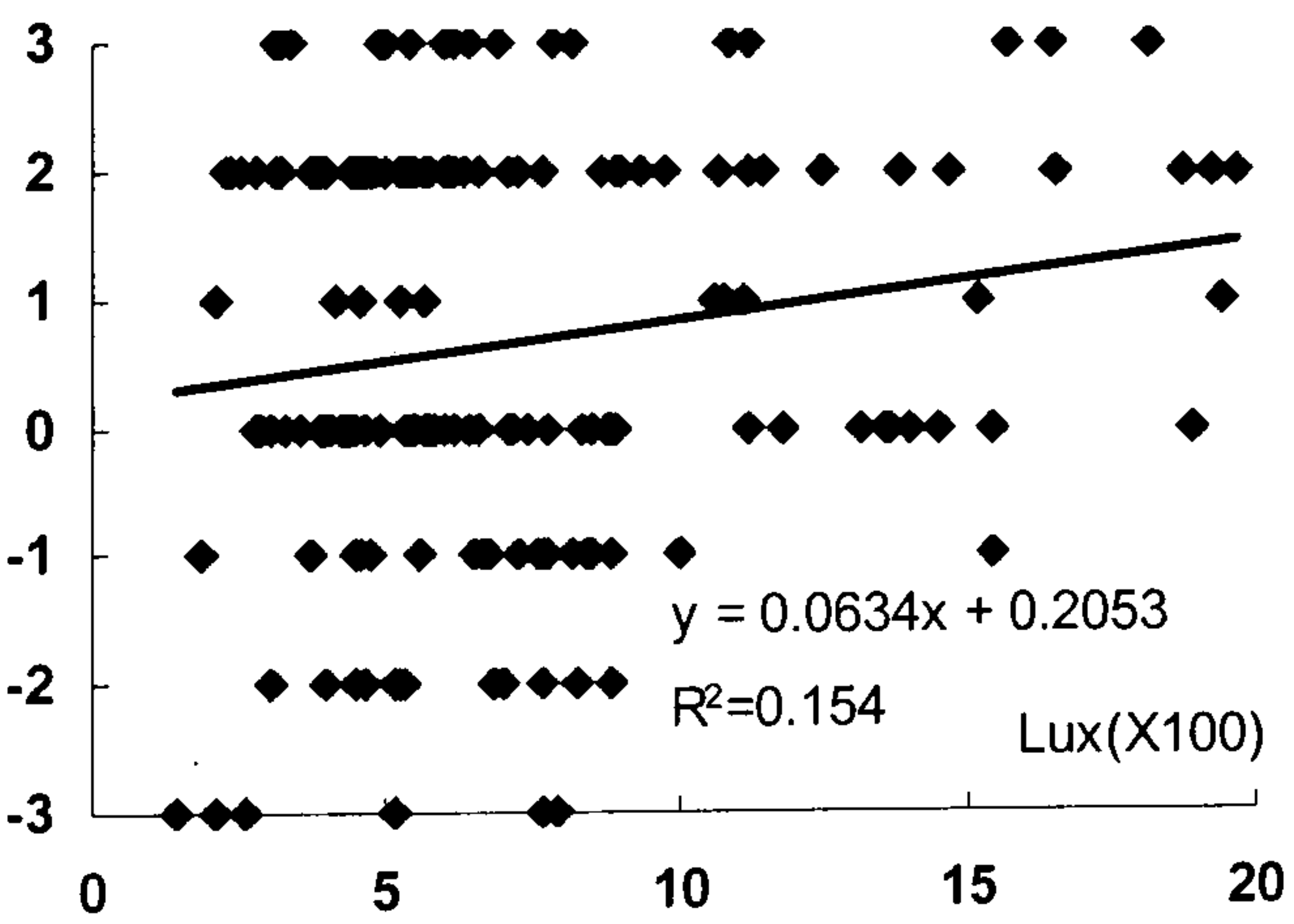


Figure 6.6 Relationship of satisfaction level and illuminance

occupant's perception of the 'bright' and the 'dark' depends upon the illuminance they are accustomed to [5]. Thus when it comes to the lighting levels, especially those slightly lower than the standard criteria, responders naturally do not feel dissatisfied.

In addition, the increasing trend may infer that the high-illuminance visual environment is preferred by the respondents of this building. Roughly, the higher the illumiance, the higher the satisfaction level indicated in the responses.

Acoustic perception and comfort level

In total 188 responses were received. Results from 177 were regarded as valid and accounted for 94.1% of the total number. It is found that records measured in the rooms towards the south generally were higher than the ones towards the west, perhaps because there are two busy roads surrounding the south façade, whereas the west side of the building is a city park. (see Chapter Five.)

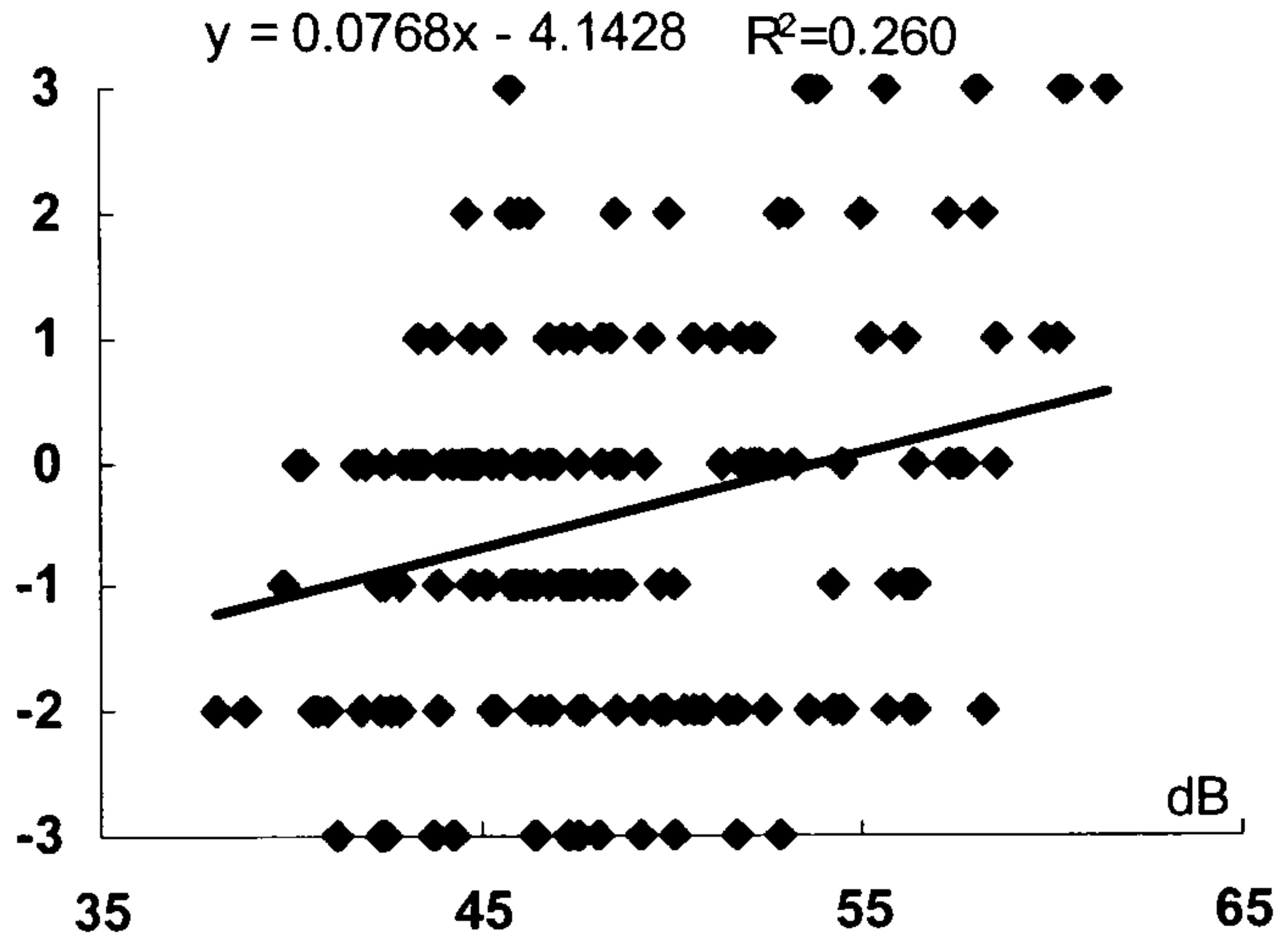


Figure 6.7 Relationship of acoustic perception and sound level

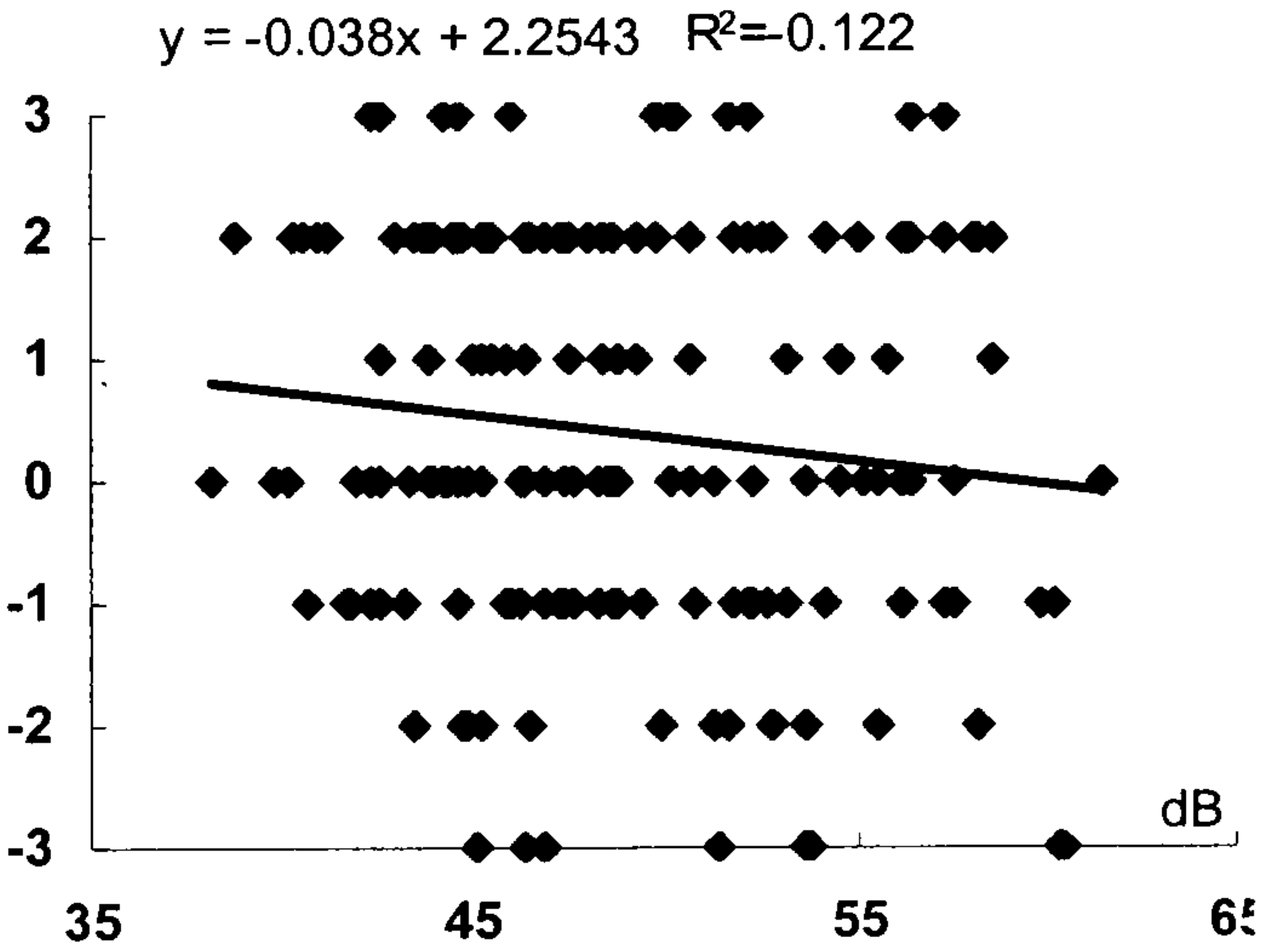


Figure 6.8 Relationship of satisfaction level and sound level

From the distribution of noise levels in Figure 6.7, it can be seen that most are between 40 to 50dB, thus occupying of 63.3% of the total records. The recommended criteria and suggested values for private offices and libraries is 40dB. When it comes to general office space, 45dB is applied [6,P173]. Under such standards, most records (72.2%) are higher than 45dB. 34.7% are even higher than 50dB, which means these rooms can be regarded as somewhat like a busy restaurant with respect to the noise level [6, P162]. Compared with the value of R square, the sound level presents a relatively loose relation with the respondents' acoustic perception: higher sound level results in noisier feeling. However, Figure 6.8 doesn't indicate a serious problem with noise disturbance.

Firstly, this figure is confirmed that the quieter the space, the more satisfied the response: it decreases steadily as the noise perception of the environment increases. Secondly, the regression line is still positively near the '0' point (neutral) with only 29.0% feels 'dissatisfied'. The result does not happen to apply the recommended criteria and suggested values: there should have been more responses for noisy. It indicates that direct adoption of the absolute criteria is not very practical. In a normal working environment, the occupants are quite free to use any criteria as a reference to decide the acceptable noise level. These references which occupants carry around with them can influence any *prima facie* judgment of the investigation. However, the human assessments are relative, not absolute, especially so when it comes to levels of noise disturbance that are deemed to distract from concentration on office-work activities. Given no agreed subjective standards, it is quite difficult to obtain an agreed barely acceptable level of noise: once again their answers depend upon what they themselves are used to [7].

Built environment	Average physical parameter	Average perception level	Average comfort level
Thermal	23.5°C	0.4	0.3
Visual	725.0 Lux	0.8	0.5
Acoustic	48.7 dB	0.5	0.4

Table 6.1 Comparison of average physical parameter, respondent perception and satisfaction level between thermal, visual and acoustic environment (Arts Tower)

The physical parameters, occupant perceptions and satisfaction levels with regard to these three aspects are summarized in Table 6.1 for comparison purposes. In general, it can be seen that the average temperature (23.5°C) and illumiance (725.0lux) during the survey period are both within the comfort criteria. However, the noise level (48.7dB) is a little high and is the only one that is outside of the comfort criteria. But the responses averagely give all these three aspects positive perceptions. Among them, the visual one has the highest value (0.8) which is approaching to 'a little bright' (1), followed by the acoustic (0.5), which is between 'neutral' (0) and 'a little quiet' (1). The lowest one is for the thermal aspect, which is just above the 'neutral' (0) with a 0.4 value. Accordingly, their comfort levels are shown positive in an average view as well with visual aspect highest (0.5) then acoustic (0.4) and thermal (0.3) which are all between 'neutral' (0) and 'a little satisfied' (1).

6.2.1.2 Monthly Satisfaction Level over a Year

4. Overall, are you satisfied with the environment in your office? (Please ignore the time that you are not here.)

January ☐ very dissatisfied (-2) ☐ fairly dissatisfied (-1) ☐ neutral (0) ☐ fairly satisfied (1) ☐ very satisfied (2)

February...

In this case, the occupants were asked to evaluate the overall satisfaction level with their working/studying environment for each month over a whole year (see above). Due to the different working/studying schedules of the occupants, the total numbers of the answers received in each month were not same. Figure 6.9 shows the distribution of all responses obtained. Averagely 205.3 responses were received. Oct, the middle of the autumn semester was the month in which most records were obtained (223), while the lowest number (192) was in Jul, which was in the middle of the summer vacation.

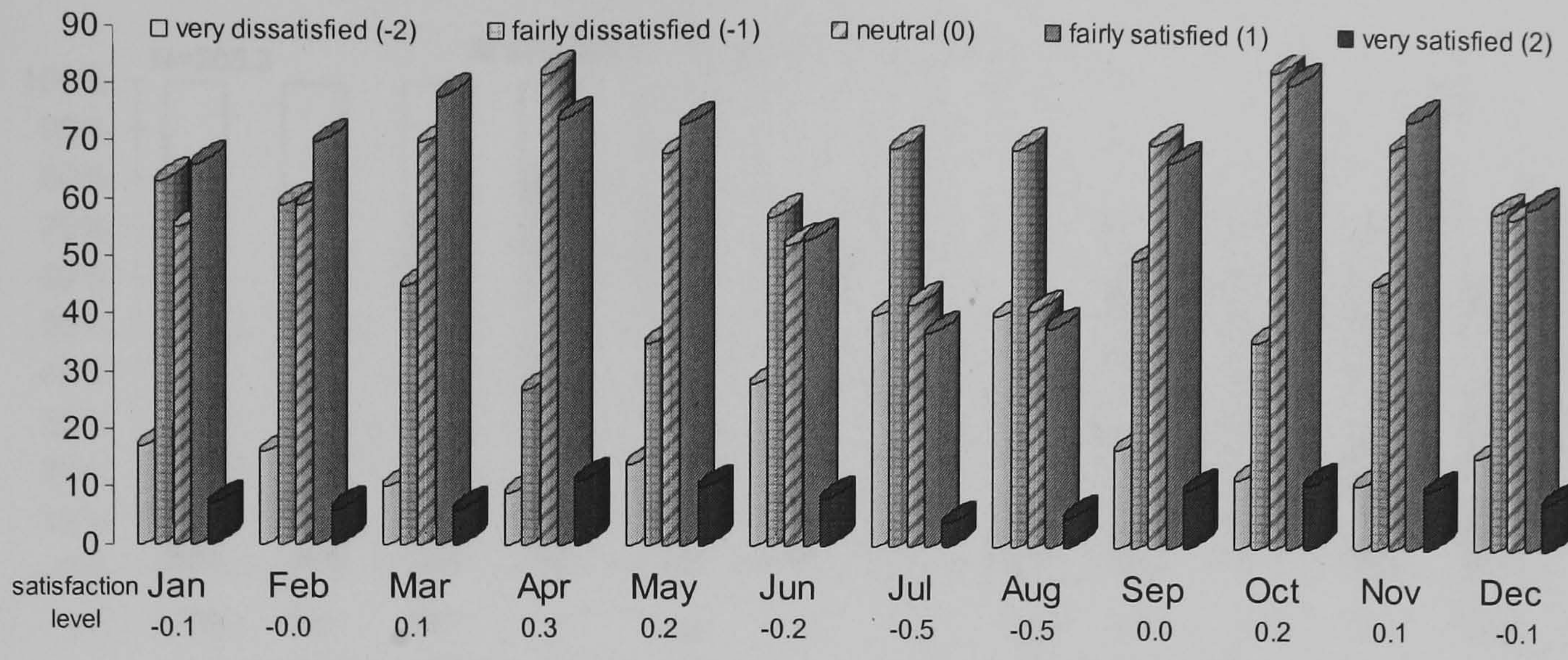


Figure 6.9 Distribution of the total responses obtained from the survey (Arts Tower)

Generally from the original data provided, the responses normally indicated avoidance of the extreme level. This was especially true with respect to the 'very satisfied' part of the spectrum of expressed opinion, and always represented the smallest component in each month with the total numbers kept relatively stable from 4 to 11. The 'very dissatisfied' segment was similar, except from months Jun to Aug, where it demonstrated a sharp increase thereafter dropping. On the other hand, the responses for 'neutral' and 'fairly satisfied' represented the largest fraction, except in Jun, Jul and Aug. On average, the responses from the building as a whole presented a 'negative neutral' attitude towards the comfort level (-0.0). Apr had the highest satisfaction level of all the months surveyed (0.3) while Jul and Aug got the lowest scores (-0.5), perhaps because Apr was a transition month in spring, and, as such, experienced a gradual increase in temperature and sunshine hours. However, in summer, especially Jul and Aug, high temperatures and solar radiation strengths could lead to serious overheating and glare problems. Besides this, the other three months Dec, Jan and Feb also received negative comfort results (-0.1). In this instance, the occupants complained that the heating levels and times were not properly controlled and that this allowed the rooms to remain cold during the winter time. Also with the large glazing areas involved, the low altitude sunlight was easily able to penetrate into rooms, which occasionally led to unusually high temperatures and uncomfortable glares in the work place.

Broadly speaking, more than one third (34.3%) of responses expressed dissatisfaction with the working/studying environment. Figure 6.10 indicates the percentage of responses received. It shows clearly the approximate level of the dissatisfaction that existed in each month (18.1 - 57.5%). Especially in June, July and Aug, the proportion of dissatisfaction even exceeded half of the total (57.3%). Apart from that, the satisfaction level in other months was relatively stable: the proportion rised from 35.1 to 41.9%. There are many reasons for dissatisfaction from occupants: high levels of wind outside, large areas of glazing, a lack of air conditioning and central heating etc, are all potential issues that may lead to thermal, visual and acoustic problems to a certain extent.

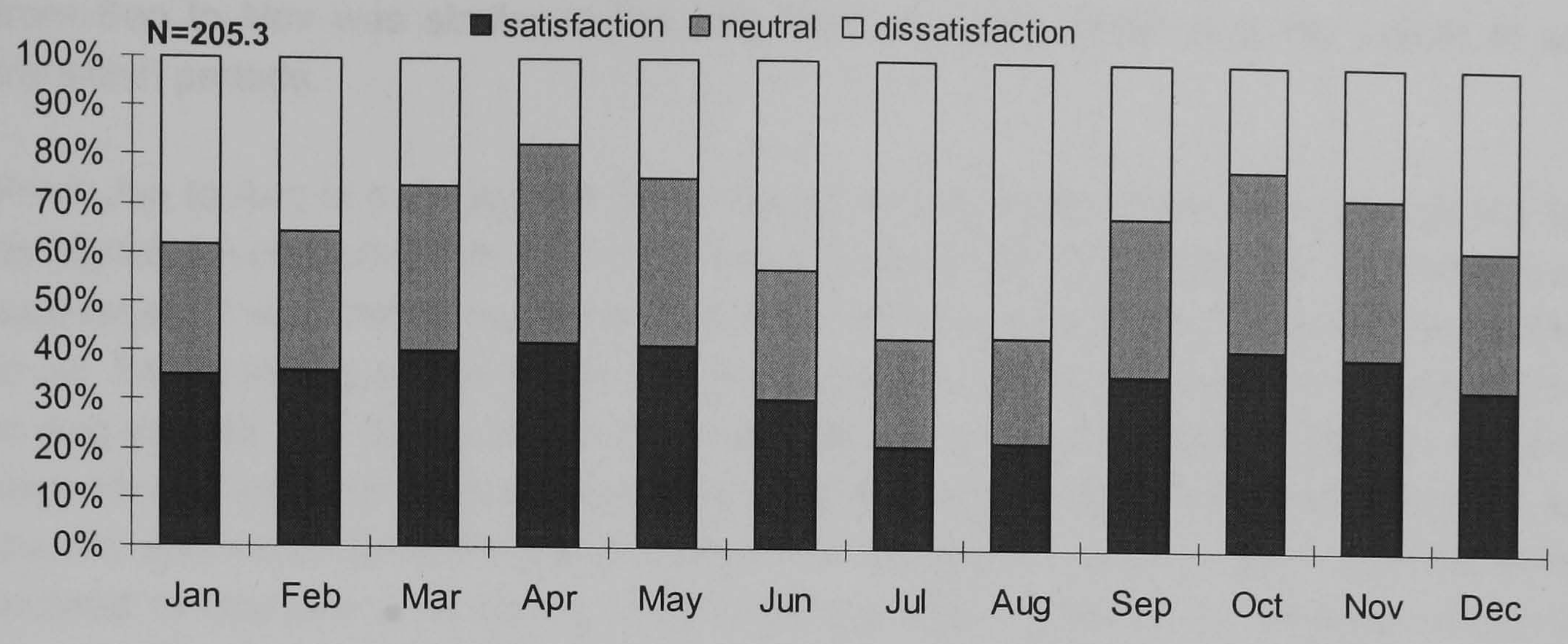


Figure 6.10 Breakdown of the satisfaction level in each month (Arts Tower)

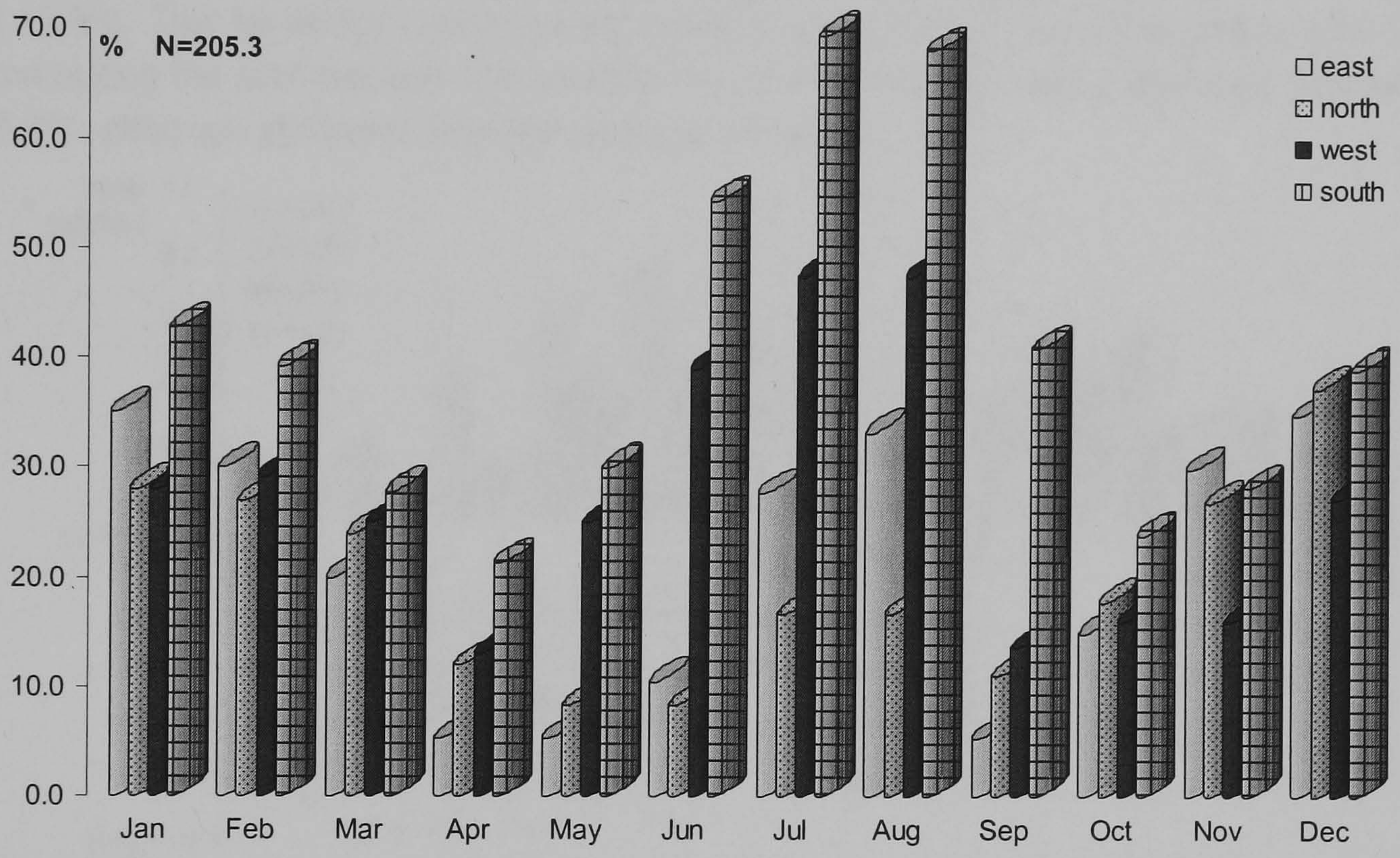


Figure 6.11 Breakdown of the dissatisfaction in each month based on room orientation (Arts Tower)

Figure 6.11 shows the distribution of dissatisfaction proportion based on the different room orientations. To make the analysis brief and short, the use of the word 'east' in the following refers to responses for the rooms toward the eastward direction. Likewise the words 'west' 'south' and 'north', refer to responses received for those respective orientations. As can be seen, spring (Mar, Apr and May) was the most comfortable time of the whole year. The weather at this time was moderate and the temperature was mild. Therefore, it was not surprising to find that the levels of dissatisfaction were relatively low for each of those months. The 'east' had the lowest dissatisfaction level with only 5.3% in Apr, and an average of 10.2% in the spring as a whole, followed by the 'north', which experienced 14.8% dissatisfaction. The 'west' and 'south' were a little higher with 21.0% and 26.4% dissatisfaction but it must be stressed that these levels were still lower than the average level (34.3%) for the building as a whole. The pattern in autumn from Sep to Nov was similar to the one seen in spring: both could be looked at as transition periods.

From Jun to Aug in summer, the proportion of dissatisfaction increased dramatically to its highest level. During this period of time it occupied 35.9% of the total dissatisfaction expressed. It was also to be noticed that most of these were from the south with 69.8% in Jul, 68.5% in Aug and 54.5% in Jun. This was followed by the west, which had 47.6% in Aug and Jul, and 39.1% in Jun. From the feedback it could be seen that both of them experienced poor ventilation, overheating and sunlight glare problems which led to thermal and visual discomfort, especially in the afternoon. Indeed, most occupants were inclined to describe it as having a 'greenhouse effect' because of the large areas of glazing. By contrast, the 'north' retained the lowest dissatisfaction level with an average of 13.9%. This tendency continued into early autumn (Sep). The dissatisfaction for the east during the summer was low as well: only in Aug was the ratio a little high, reaching 33.3%, although still lower than the average of 34.3%.

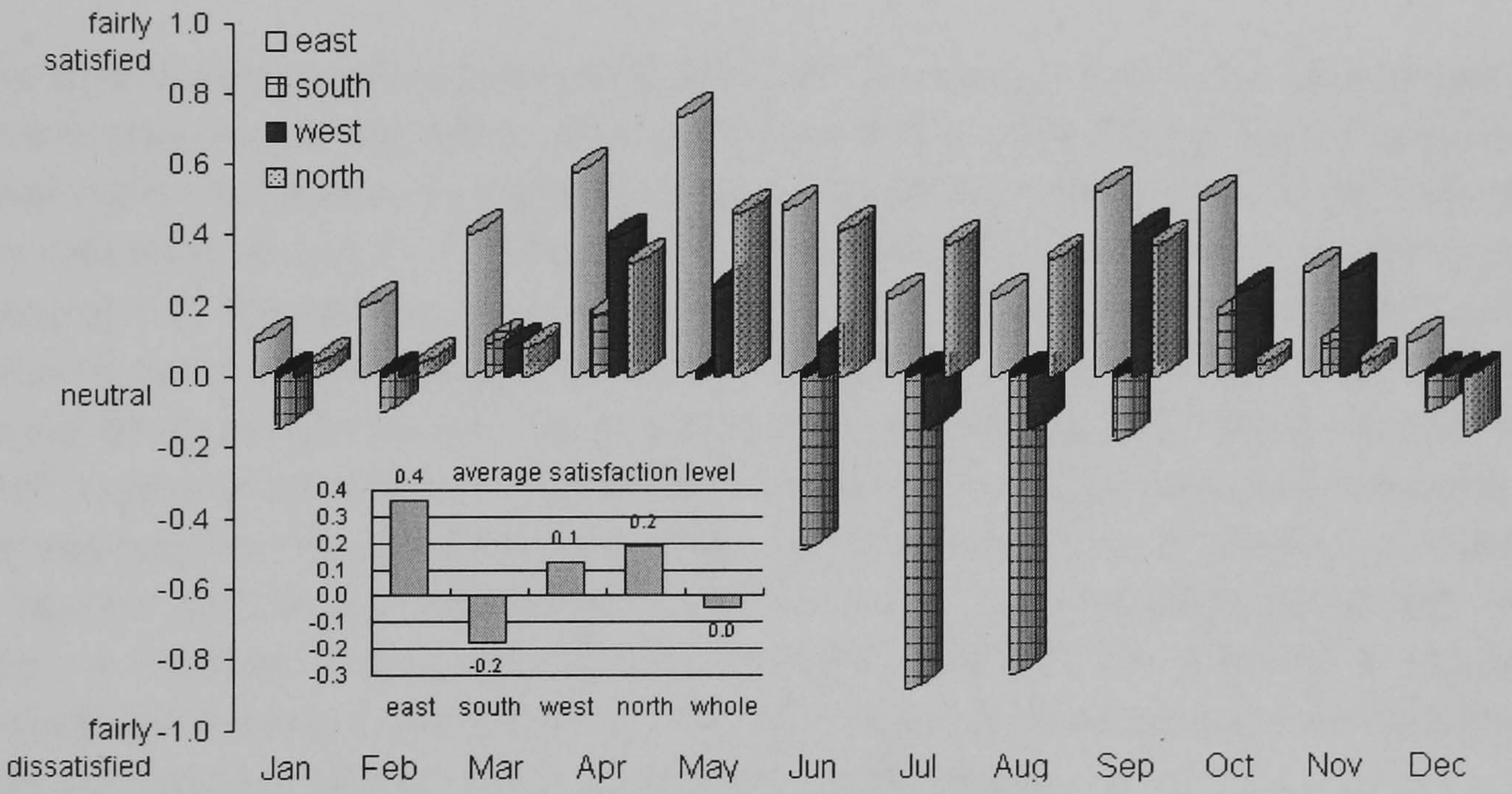


Figure 6.12 Distribution of the satisfaction level in each month based on room orientation (Arts Tower)

From late autumn (Nov.) to winter (Dec. Jan, and Feb), the temperature decreased to its lowest level. Therefore, in these months heating became the main issue for the indoor environment. In this case, central heating implies that heating levels and times are the same for every room in the building: no regard is paid to the natural variation that existent in those rooms with respect to how these rooms are heated; the issue of the 'passive' thermal environment is entirely ignored. As a result of this, rooms with less direct solar radiation are thus often colder than those that receive more. Therefore, it is to be expected that during this period of time, the north and the east will experience a higher dissatisfaction level than during the other months. In Nov, the dissatisfaction percentage from the north even became the highest among the rooms with other orientations. This was also the only month in which the south didn't have the largest portion of the dissatisfaction ratio. Broadly, because the temperature and solar altitude were both low, which could lead to thermal and visual discomfort, the feature and distribution of dissatisfaction levels distributed to the rooms with different façades were not as clear as in the summer time. The 'west' and 'north' had the lowest level of dissatisfaction, with an average of 25.1% and 29.8% of responses respectively. On the other hand, the highest level of dissatisfaction to the 'south' with an average of 37.4% and the east at 32.5%.

In general, rooms towards the east only seem affected by direct sunlight and solar heat in the morning. Although the altitude is low, power of the sun is not strong at sunrise. Therefore the temperature difference from low to high doesn't make for serious indoor environmental discomfort. Over the whole year there are 10 months in which the east experiences the highest satisfaction level, with the other two months in second place. Thus it has the highest average satisfaction value (0.4) of alternatively oriented rooms (Figure 6.12).

The north always receives diffused daylight over the course of the whole year except for several days in Jun: the indoor environment is therefore relatively stable compared with other room orientations. Its satisfaction level remains positive for most of the year with the exception of Dec (-0.2). Generally its average satisfaction value is in the second place at 0.2, followed by the west. Although it is subject to similar solar distribution patterns, some differences do exist, which are especially clear in the summer. This can be explained by the fact that the southern edge of the building is slightly towards the east: it receives sunshine for a longer time and there is stronger solar radiation going to the westward rooms, and thus the average satisfaction level for the west over 5 months is 'neutral' (0.0)' or near 'neutral' (0.1). For two months in the transition period (Apr. and Sep.) a relatively high level (0.4) is reported; while for the summer a negative 'dissatisfied' value is presented in Jul. and Aug. On average the west is in the third place with a 0.1 positive neutral among the other four orientations.

The south is the only orientation that has been given the average negative satisfaction level of -0.2. Except in spring from Mar. to May and late autumn from Oct. to Nov. the other 7 months are all below 0 (neutral). In winter, the problem mainly seems to be one of direct sunlight, since the low altitude allows the room a large penetration area that in turn leads to potentially uncomfortable glare on the working plane. On the other hand, the strong solar radiation in the summer intensifies the overheating problem. Compared with both situations, the later one is even more severe. In Jul. and Aug. it reaches its lowest level (-0.9 and -0.8), which is near the 'fairly dissatisfied' level (-1).

6.2.1.3 View Appreciation and Window Seat Preference

Among all the window's functional potentialities, the provision of sufficient quantities of light and pleasant views are the most fundamental and important aspects, especially the latter one, which is unique and cannot be substituted [8]. The Arts Tower is a free standing high-rise building with only a small part of the west rooms from 1st to 3rd floor sheltered by the main library. The available view through the perimeter windows is plentiful providing a wide-field vision to occupants with sky, distant urban and rural areas and landscape on all sides. The effect of view appreciation in the investigated rooms is considered to be one of the potential issues that influence an occupant's decision to choose a seat towards the window.

5a. Do you prefer a window seat in your office/classroom or not?

A. Not at all B. hardly C A little D. Somewhat E. Very much

5b. Does the view outside affect your appreciation of this room??

A. Not at all B. hardly C A little D. Somewhat E. Very much

Figure 6.13 indicates a broad and high consistency of appreciative feeling. Almost half the responses (43.8%) presented an opinion that the view is 'very much' appreciated, compared to 30.4% for 'somewhat'. An overwhelming majority have a positive attitude with an average of 3.9 preferences, while only 15.1% of the remainders show a negative towards it (7.1% with 'hardly' and 8.0% with 'not at all'). Based on the orientation of rooms, there is a marked and uniform trend with the distribution (Figure 6.14). The average effect of 'view appreciation' all tends towards the level of 'somewhat' (4) and the south façade even exceeds it (4.0) while for the north, although the lowest average, it still reaches the value at 3.6.

However, when it comes to 'window seat' preference, the average value of the total responses drops a little. Normally, occupants in this building can select their working plane relative to the window quite flexibly. Regarding the advantages of seats near the window, 'bright', 'warm', 'wide visual range' can be all on the top list. Conversely, the perceived disadvantages, although varying room by room, include 'heat', 'exposure to radiation', 'glare', 'air infiltration' and so on. Due to the complex factors for occupants by the feeling of real view intimacy and by thermal or lighting influences: one is toward window; the other is away from or toward window, the present result shows a little difference especially

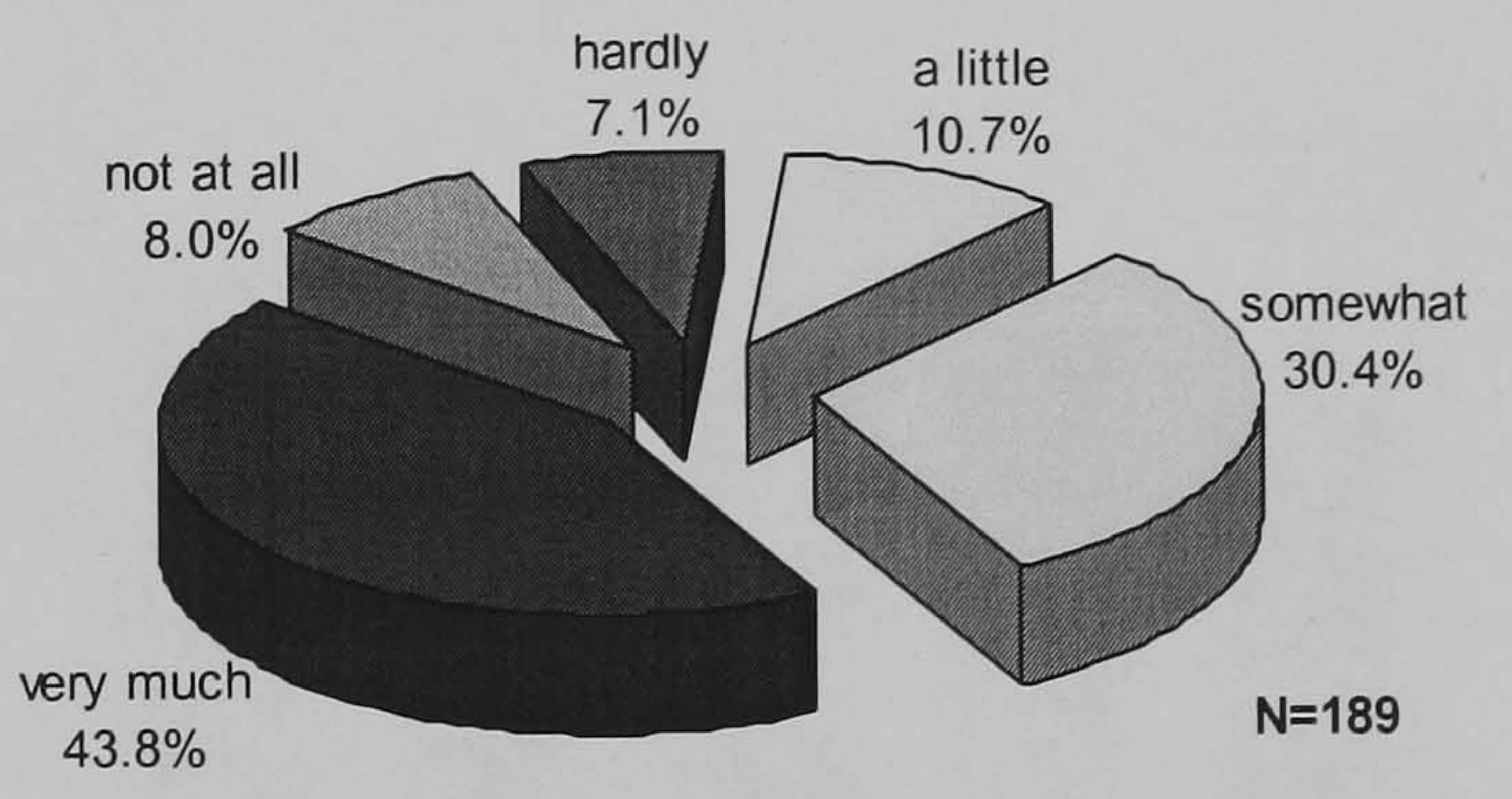


Figure 6.13 Breakdown of the view appreciation (Arts Tower)

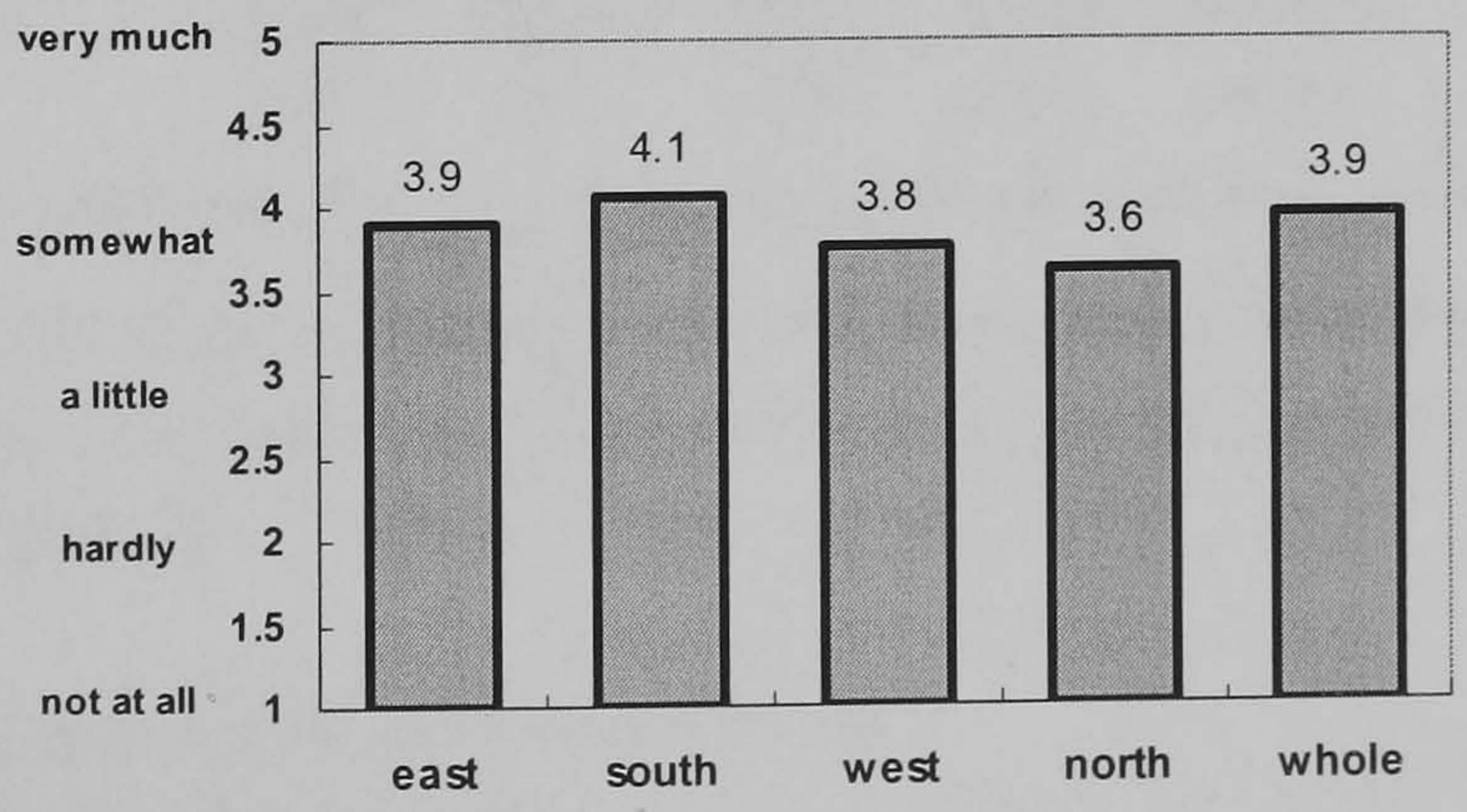


Figure 6.14 Distribution of the view appreciation (Arts Tower)

with the distribution based on the orientation of the rooms.

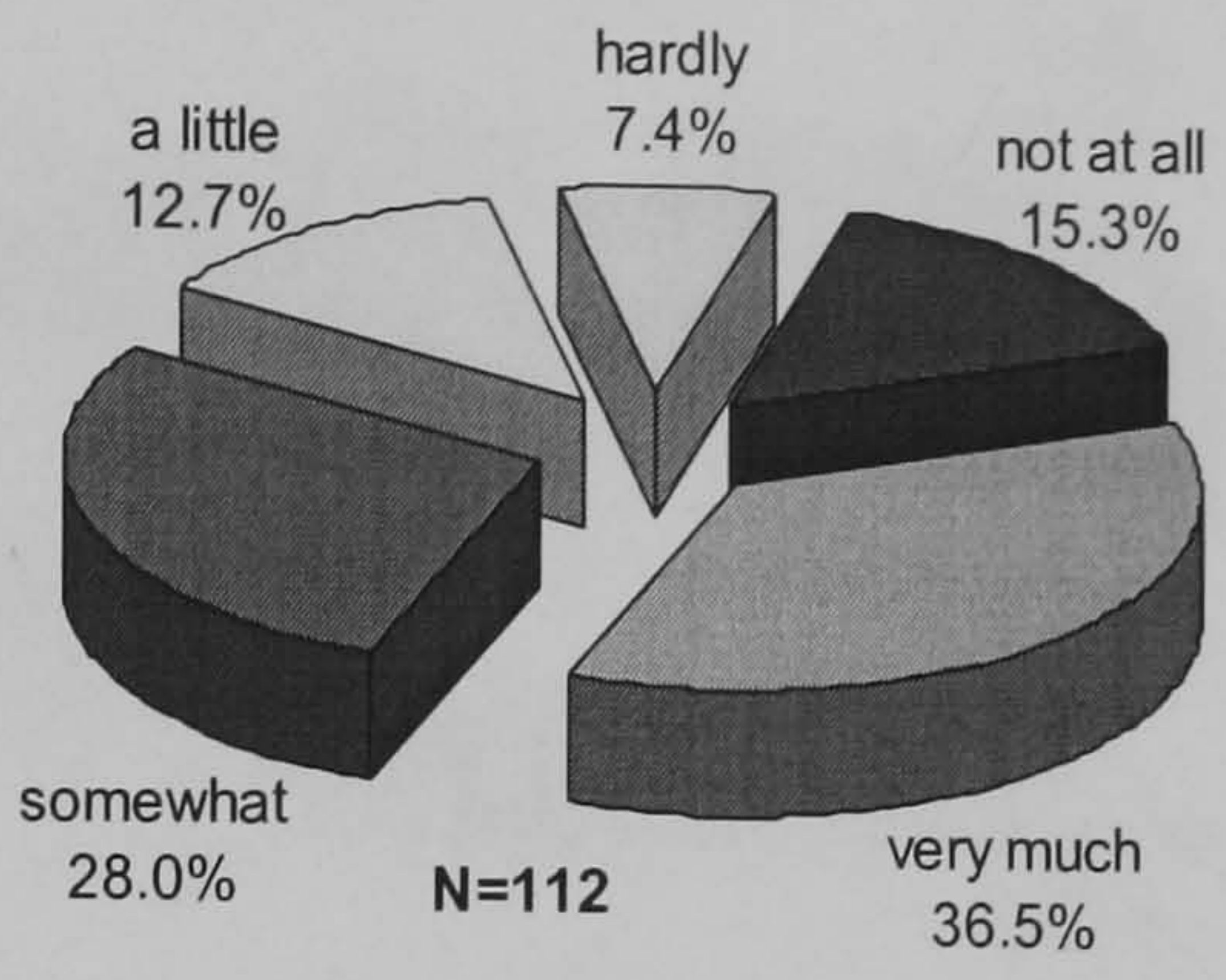


Figure 6.15 Breakdown of the window seat preference (Arts Tower)

Figure 6.15 displays a similar pattern in terms of 'view appreciation' but its positive perception part drops a little based on this issue. Accordingly, the 'negative attitude' rises to 22.7% in respect to this factor. The distribution of opinion from different orientation rooms in Figure 6.16 indicates that the east one reaches the highest value (4.3) followed by the north and west, while the south has the lowest (3.4). This order confirms the fact the occupant window seat preference depends on the orientation characterises take into account the hours of sunshine received and the non-symmetry of the working day.

The warm solar radiation from sunrise usually is welcomed by the occupant who works in the east room. Although the winter discomfort of air infiltration and cold radiation are normally associated with sitting near the window, with perimeter induction heating units, these disadvantages are greatly relieved. Therefore, the responses for east and north rooms display a higher preference for the 'window seat': 4.3 and 4.0, i.e. both at the level of 'somewhat'. However, in summer and even in winter on a sunny day, a seat near the window may suffer from overheating, intense direct solar radiation and discomfort glare. This is especially true when it comes to the rooms towards the south and the west. Therefore these reasons ensure that responders prefer a seat at a little distance from the window, which lowers their average value to under 4 (somewhat).

Generally, although there are some differences between 'view appreciation' and 'window seat preference', the averages of perceptions expressed in responses are still relatively high at 3.9 and 3.6 respectively. This confirms the fact that the function of the window - maintenance of a visual link between the internal, artificial environment and the exterior world of nature - still ranks very highly compared with other environmental factors no matter whether they are negative or positive.

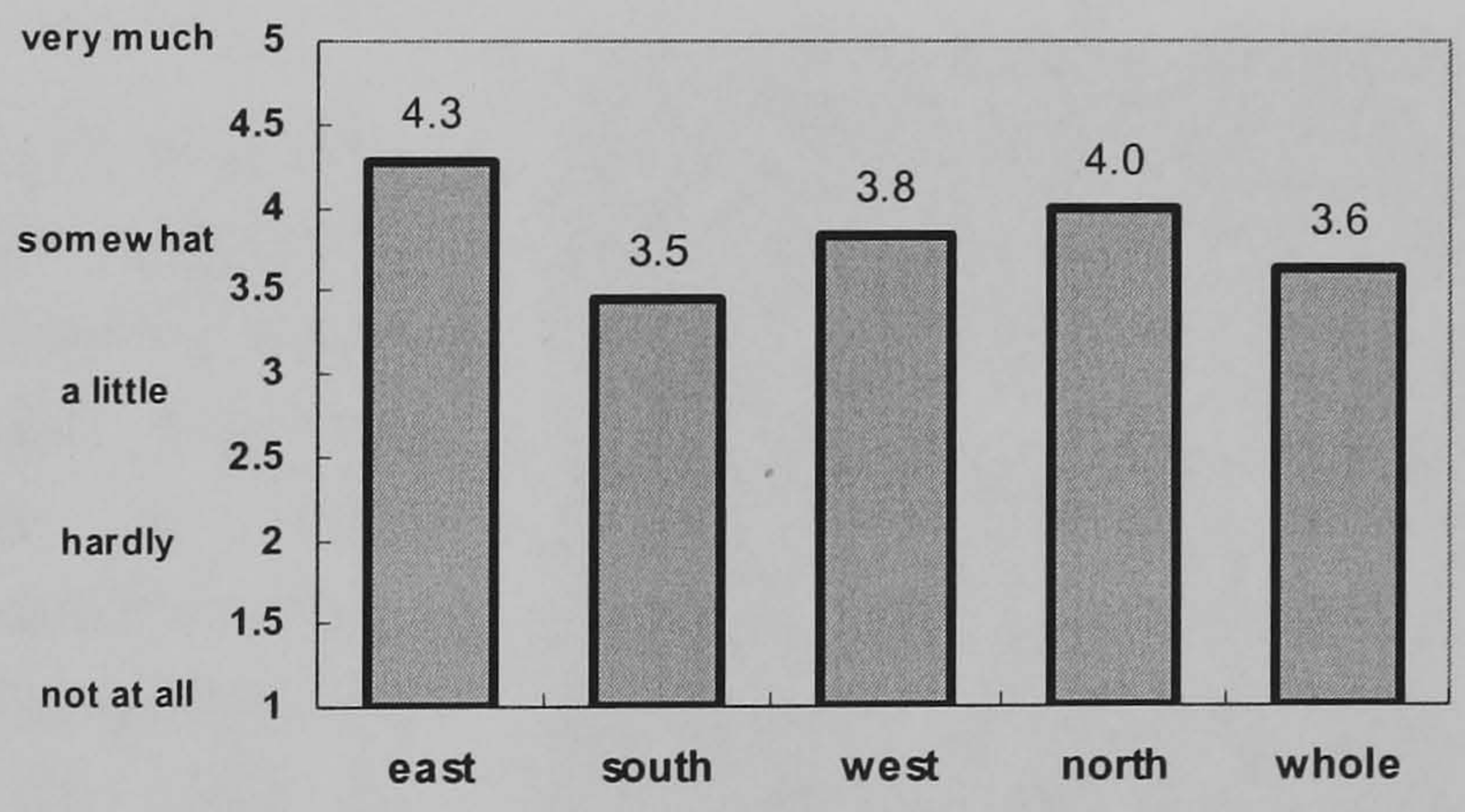


Figure 6.16 Distribution of the window seat preference (Arts Tower)

6.2.1.4 Effect of Glare Disturbance on the Built Environment

5b. Does the reflection on the computer screen affect your work due to discomfort glare?

A. Not at all B. hardly C A little D. Somewhat E. Very much

There is no surrounding building except the main library that can affect the Arts Tower by way of shadowing and reflecting light. With a significant transparent glazing area, the sunlight can easily penetrate into rooms and working plane without obstruction. Therefore in this case glare can be a direct disturbance and cause immediate discomfort and potential fatigue. Of all the categories [9], discomfort and disability glares occur most frequently and are the causes of many complaints from occupants.

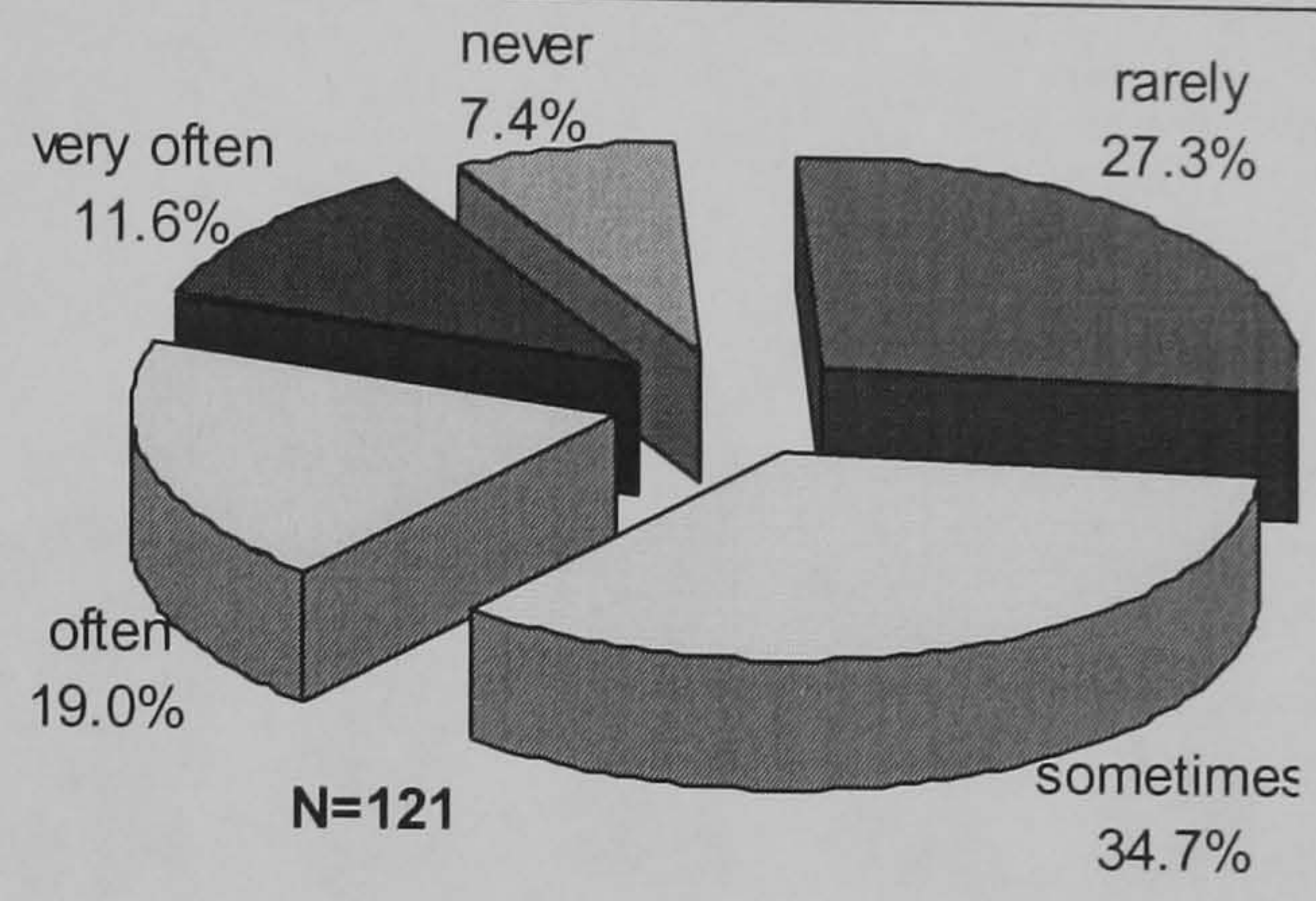


Figure 6.17 Breakdown of the glare distribution (Arts Tower)

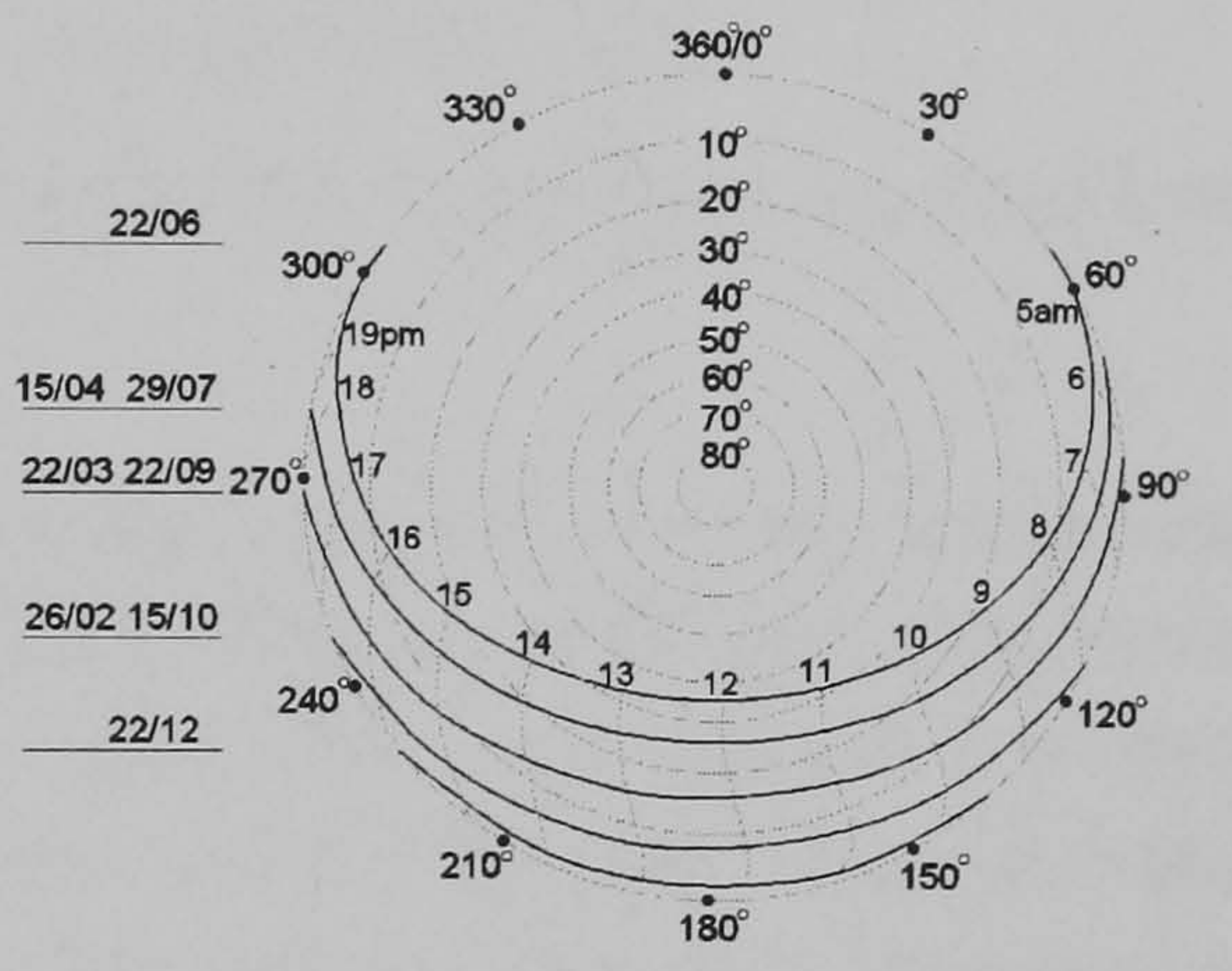


Figure 6.18 Sun path diagram for Sheffield

Discomfort glare does not typically cause a dangerous situation in itself but when concentrating on a task there is a bright source elsewhere in the field of view, this may be unaware for a short period of time or simply avoid looking; but in the long term, task performance is affected. On the other hand, after the computer became widely used in office buildings, disability glare started to occur frequently. When sunlight is reflected from the computer screen, with reduction in sight capabilities, and there is a bright luminaries area in the immediate field of view, the total amount of light falling on the eye can make screen reading impossible, thus leading to annoyance and irritation.

Figure 6.17 confirms that glare does affect the working environment. 11.6% of responses have this problem 'very often' while 19.0% feel that it is 'often'. The biggest segment 'sometimes' occupies 34.7% of total responses. The other 34.7%, around one third, are not affected by it, with 27.3% 'rarely' and 7.4% 'never'. Sunlight, in this case is considered to be the main cause of glare and occupants' visual comfort.

Figure 6.18 shows the sun path diagram for Sheffield, varied in intensity, angle and direction over time. It can be seen that if 5^{o} is applied as the minimum angle of solar altitude that the sunlight enters the room, more or less

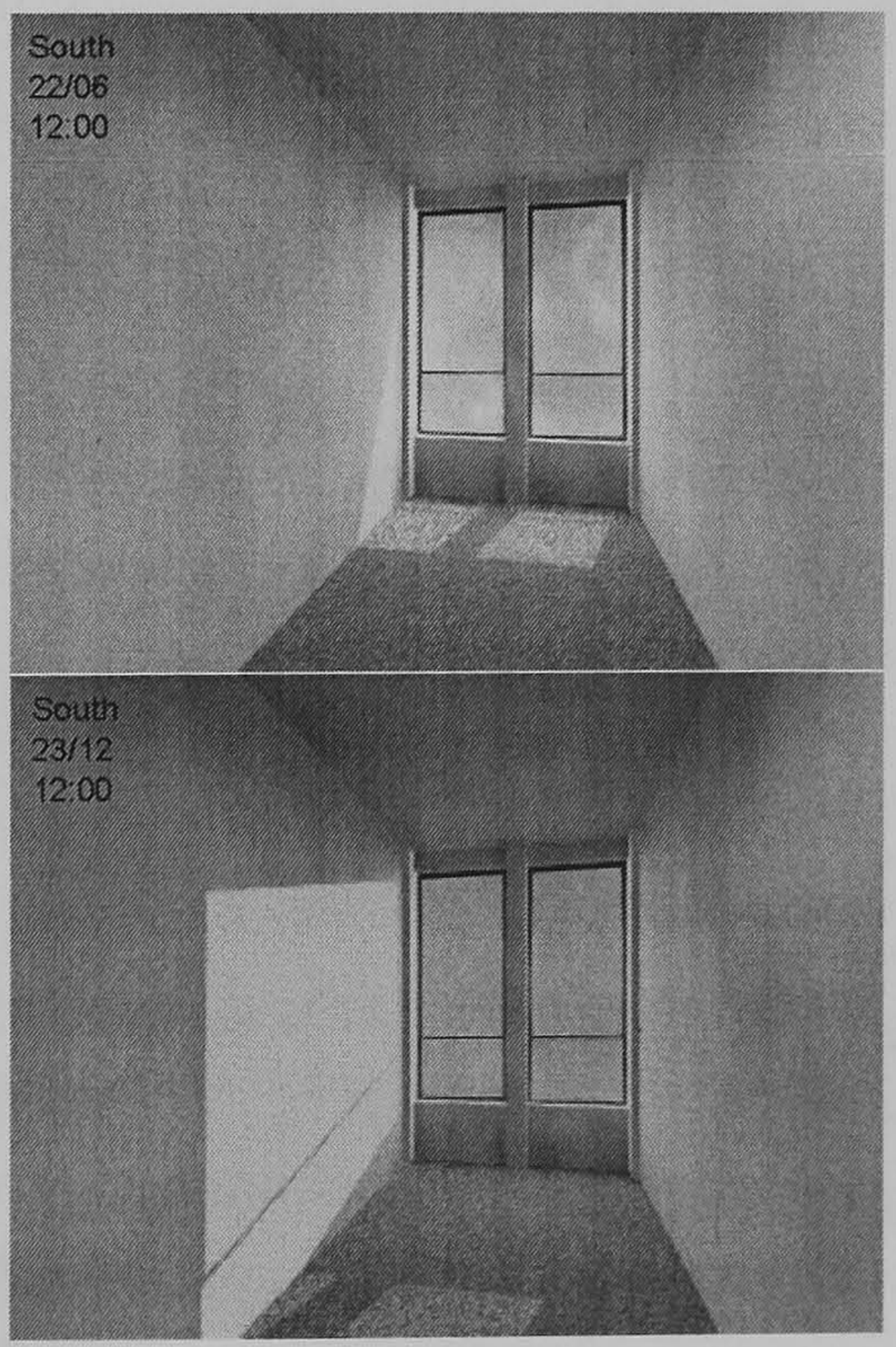


Figure 6.19 Sun penetration in a summer and winter day

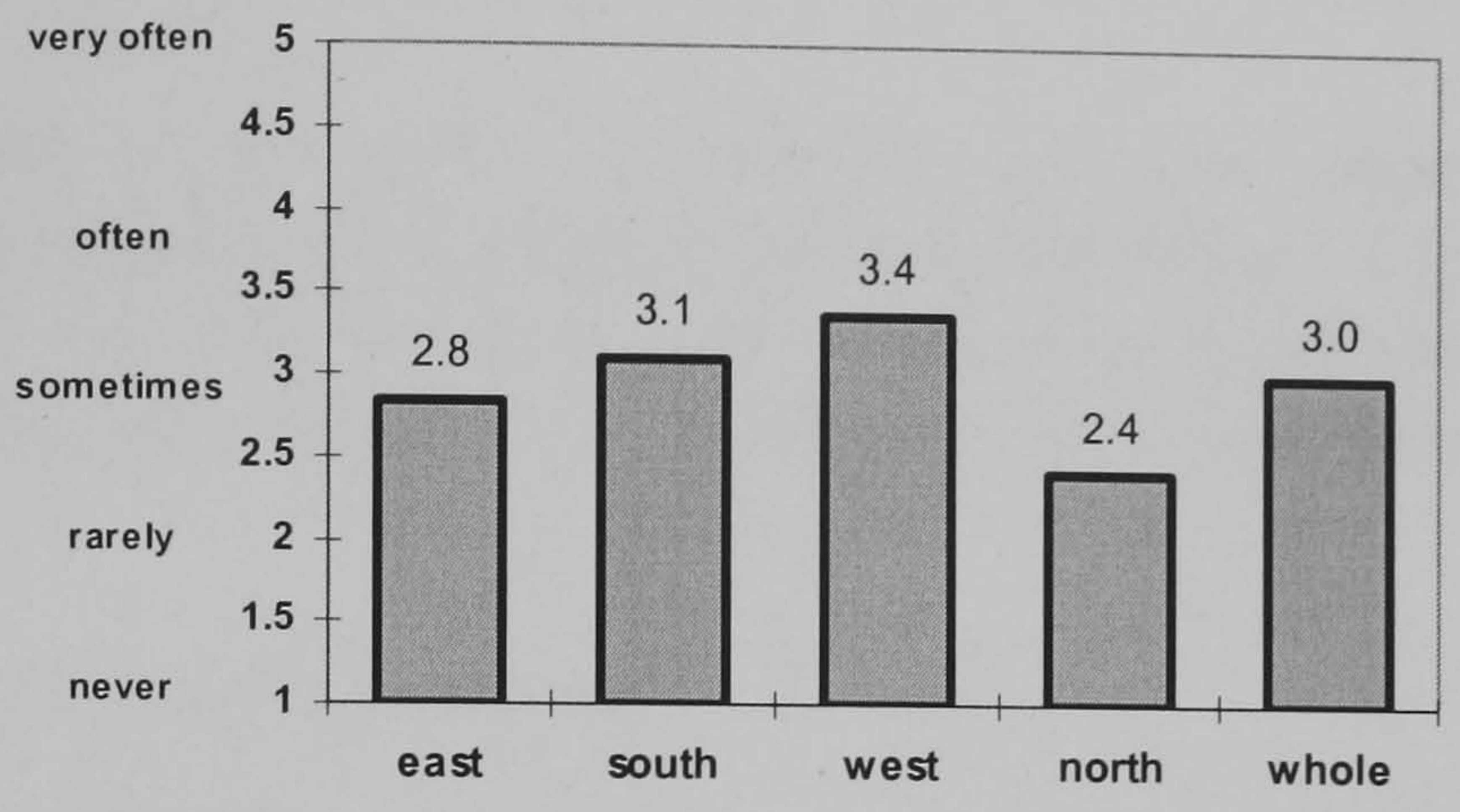


Figure 6.20 Distribution of the glare distribution based on orientation (Arts Tower)

every façade can receive direct solar radiation leading to glare discomfort due to the building's site and location at high latitude. In summer, the building's rooms receive the longest period of solar radiation. Although this period is at its shortest in winter, because of the low altitude, there is a greater penetration and larger area of interior illumination. An example is illustrated in Figure 6.19 which compares sun penetration of a room over two seasons.

When it comes to different orientations, a large difference due to the very predictable manner of sun path is to be expected. In Figure 6.20, the result reflects the relationship between room orientation and solar heat and sun path. The room towards the north façade has the lowest frequency of glare disturbance (2.4), between 'rarely' (2) and 'sometimes' (3). Normally, these rooms receive sunlight only in the late afternoon in June, thus for most of the time during the whole year direct sunlight has little effect. The second lowest is the east with an average value 2.8, approaching to 'sometimes'. These rooms always receive low altitude and warm solar radiation in the morning; sometimes glare happens but it doesn't usually create problems in a serious way.

The average value for rooms towards the south and west are both higher than 3 with the south at 3.1. The west in this case has the highest level at 3.4. Comparing the character of the sunlight going to the south façade on a daily basis, although the south receives longer periods of solar radiation, the solar altitude is always lower when the sunlight penetrates into the west rooms than the south ones. Figure 6.21 illustrates an example of two differently oriented rooms of the same size on a typical day. It can be seen that in terms of glare control, the west presents a more difficult case than the south. Besides, there is another fact to take into account, which is the intensity of glare discomfort for occupants in the westward orientation. The equipment and finish on the roof of the main library also become a sunlight reflection source and cast surplus light into the building. From the feedback responses, sometimes it is so intense and strong they cannot even look at the window.

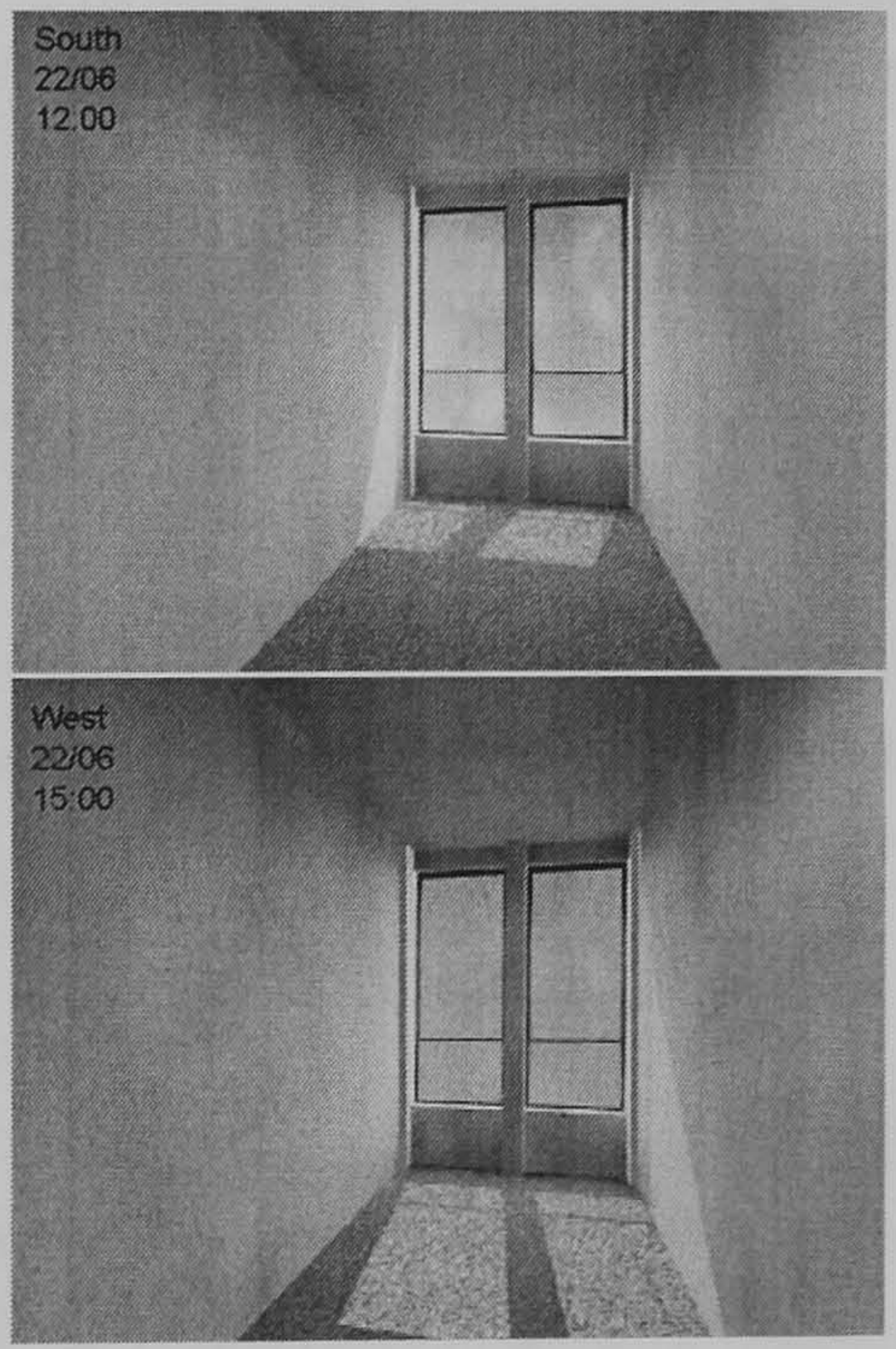


Figure 6.21 Comparison of the sun penetration same day in a south (above) and west (below) room

Generally, glare is the main cause of occupants' dissatisfaction with their visual environment with an average frequency level of 3.0, a little higher than 'sometimes'. The venetian blind in this case becomes the main means of manual control for converting direct sunlight into a softer, reflected light and reducing its intensity to illuminate the rooms in the building.

6.2.1.5 Effect of Noise Disturbance from the Outside

7. Generally, do you feel noisy when you are in this room?

A. Very Often B. Often C. Sometimes D. Rarely E. Never

The sources of noise that affect the occupants in the Arts Tower are complicated by many factors both inside and outside the building. Generally they can be grouped under three broad headings in terms of the sources' location and origin:

- *Road traffic and building construction noise* There are two medium-busy roads to the east and south of the building. Therefore vehicular traffic is identified as one of the major factors contributing to a relatively high noise level in this building. In addition, the development of Jessop Campus, which is about 300m away from the southwest of the Arts Tower, also becomes a fixed noise source during the survey period. Sometimes noise from the plant and equipment on the construction site can reach over 90dB(A).

- *Airflow over the building* In this group are such sources as the vibration of cladding and other architectural features, separated flows, and aerodynamically excited cavity resonances. The high-rise nature of the building and the windy climate of Sheffield can sometimes intensify this aerodynamic noise level to a very high degree. In addition another source in this high-rise building is from wind- and stack-induced flow through door cracks and into lift shafts and service chutes.

- *User activity and lift electronics* High density of occupancy, especially during the standard semester day can produce a high level of noise inside the building and easily penetrate into occupied rooms arranged according to a compact architectural plan. Furthermore, constant bleeping from the emergency lift phone and alarm can be an additional source of annoyance in the building.

Mainly because of these potential issues, this building has a quite noisy environment with regard to the specified and recommended acceptable noise levels for general office buildings. However, from the survey results, noise isn't regarded as a serious problem by the respondents. In total 18.0.4% feel the noise disturbance does affect their work with 'very often' at 4.8% and 'often' at 13.2% respectively. However, more than one third of responses (39.2%) hold the 'neutral' attitude that it only 'sometimes' disturbs. The biggest part doesn't consider noise to be a problem with 40.2% 'rarely' and 2.6% 'never' (Figure 6.22). This may be explained by the ability of the human ear and brain. Normally, the occupants are accustomed to the environment and their ear and brain can voluntarily discriminate and deemphasize those background meaningless noises. Not until they are loud enough to affect any specific activity to a certain level can they start to feel discomfort in terms of the aural environment.

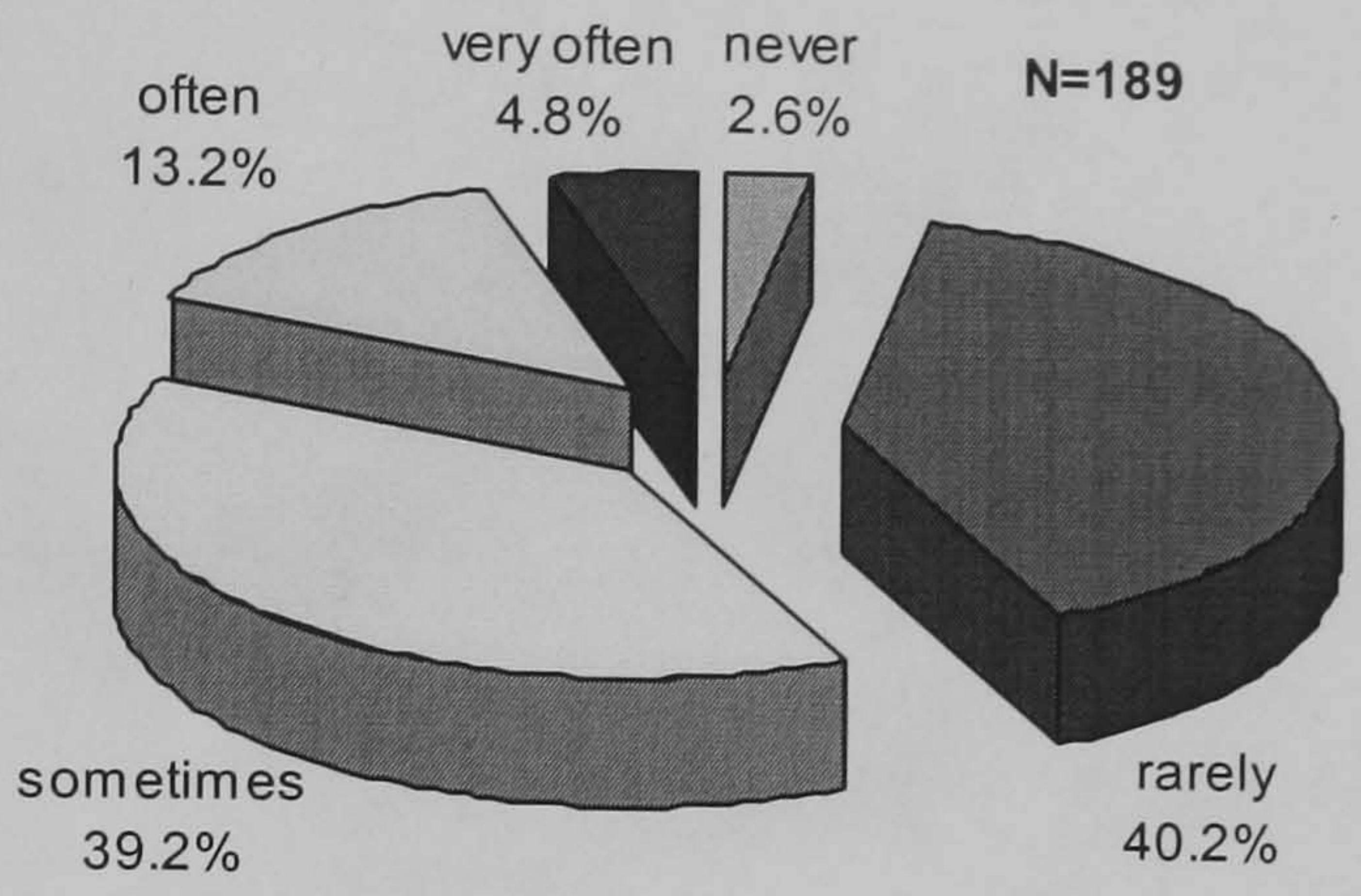


Figure 6.22 Breakdown of the noise disturbance (Arts Tower)

With respect to the orientation difference, Figure 6.23 presents an even trend with the minimum value (2.5) from the north and the maximum value (2.8) from the south. Considering the direction of noise sources mentioned above, it is not surprising to see the south one has the highest ratio of noise complaints – busy traffic, loud construction sites and prevailing wind directions can all provoke the frequency of high noise levels. And from the weather record of wind speed and direction in Sheffield, around 50% of the time the wind speed within 4m/s is from the south and the west while the higher wind speed mainly comes from the west (see Chapter Five). This probably leads to the result that the responses from the west are slightly higher than those from the east (2.7 vs. 2.6). Due to the fact that the north room is farther from those outside noise sources than the rooms with other orientations, it becomes the 'quietest' in an expected way.

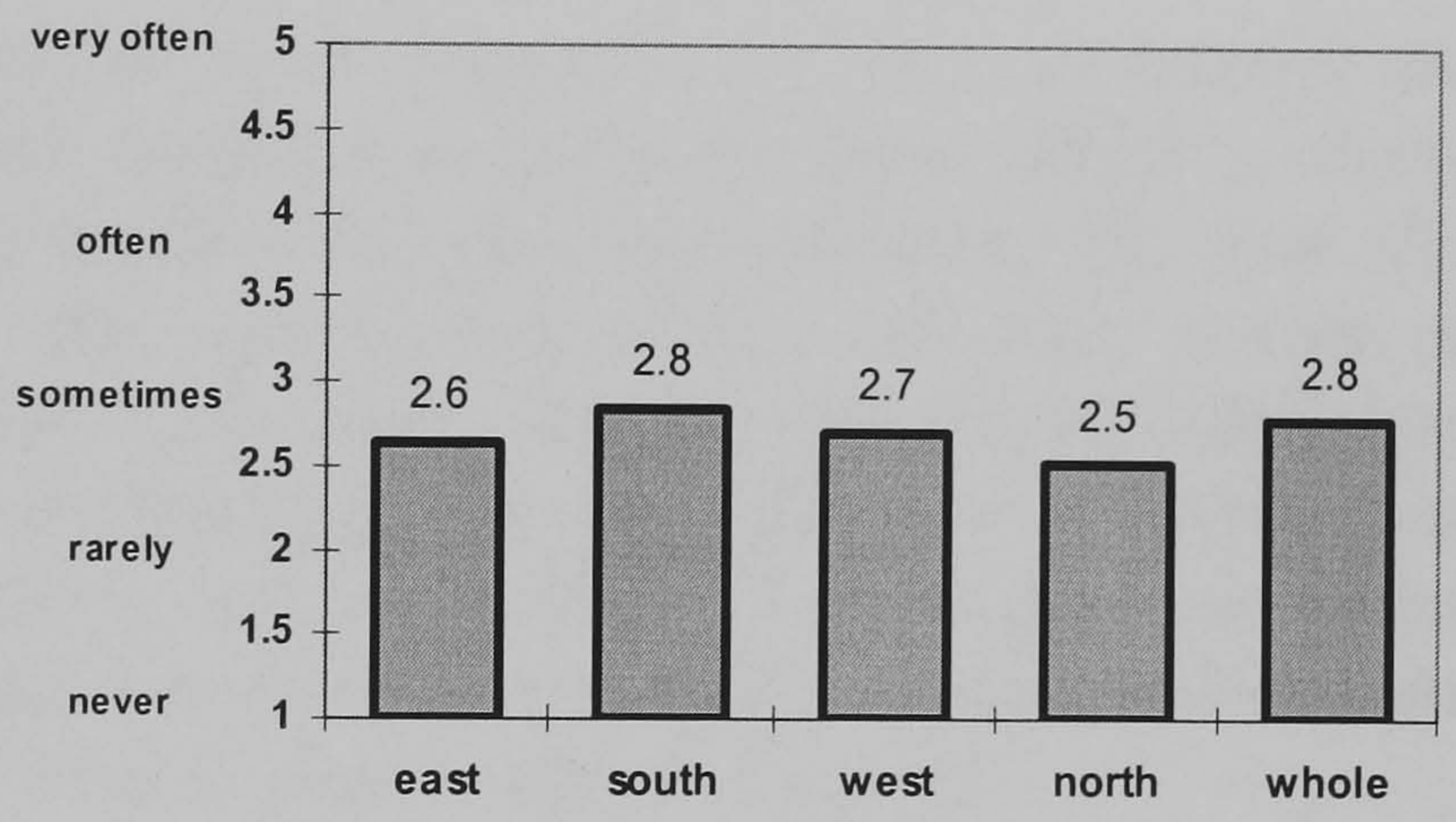


Figure 6.23 Distribution of the noise disturbance based on orientation (Arts Tower)

Generally, the compact of the architectural feature, the high-rise nature and its situation in an urban area unavoidably make for a high noise level in the Arts Tower. However, this is mainly background noise and the sources are intermittently affected, thus this problem doesn't influence the occupant working frequently or seriously. The average value for all responses is between 'rarely' and 'sometimes' (2.7).

8. When you use the venetain blinds in this room, do you feel it is .... to control (such as open or/and close the slats; adjust the angle of slats)?

A. very easy B. fairly easy C. a little difficult D. quite difficult E. never use it.

6.2.1.6 Internal Blind Status

In this investigated building, the venetian blind is a key element used to adjust the indoor environment. It is movable which allows the occupant to easily respond to changing conditions, such as glare, radiation level, daylight, overheating or other thermal factors. It is especially efficient at converting direct sunlight into a soft and reflected light and reducing its intensity so as to illuminate the rooms in the building [10]. However, there is some reason to suspect that as time passes, the condition of these blinds is not good enough to allow easy manual control.

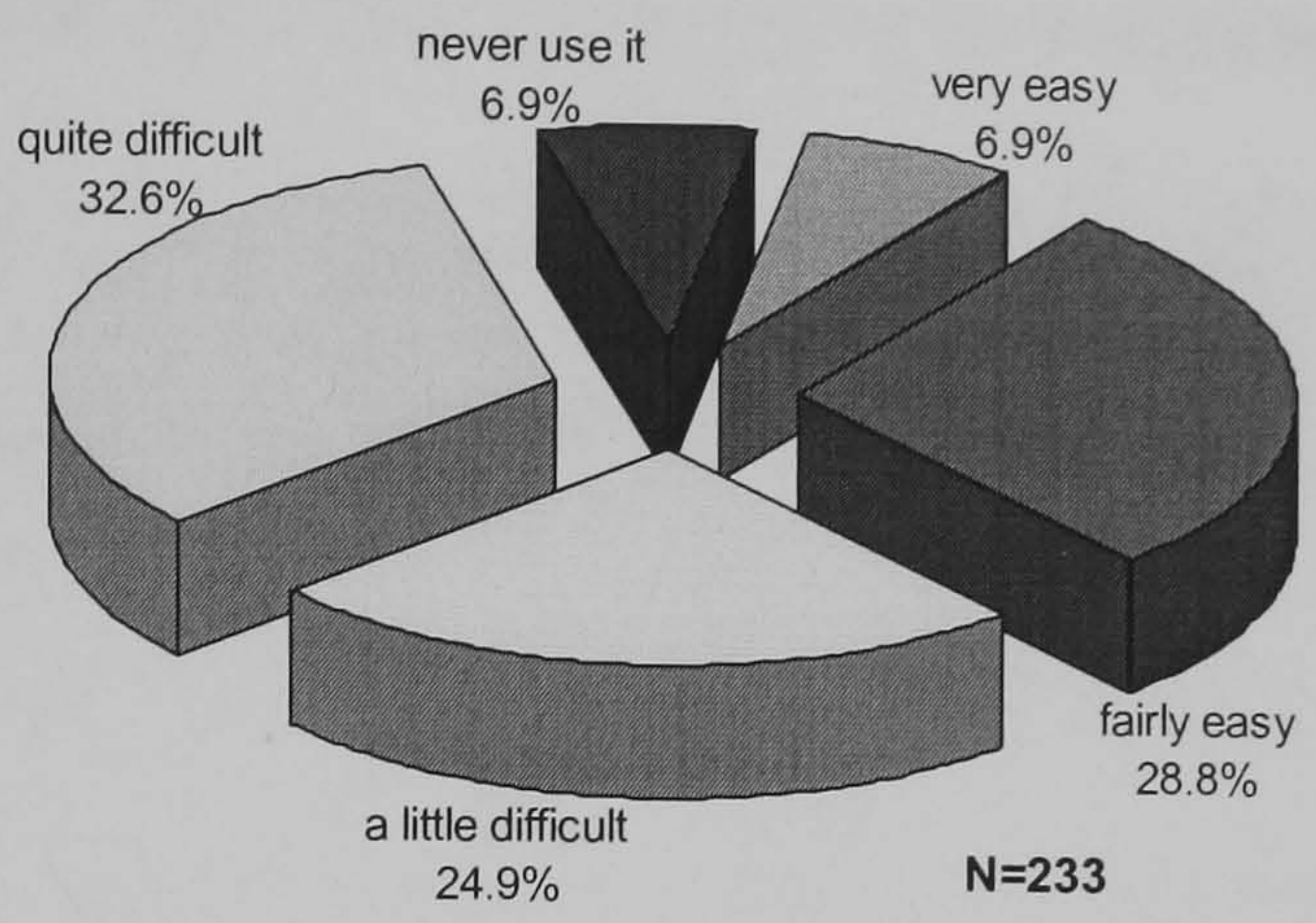
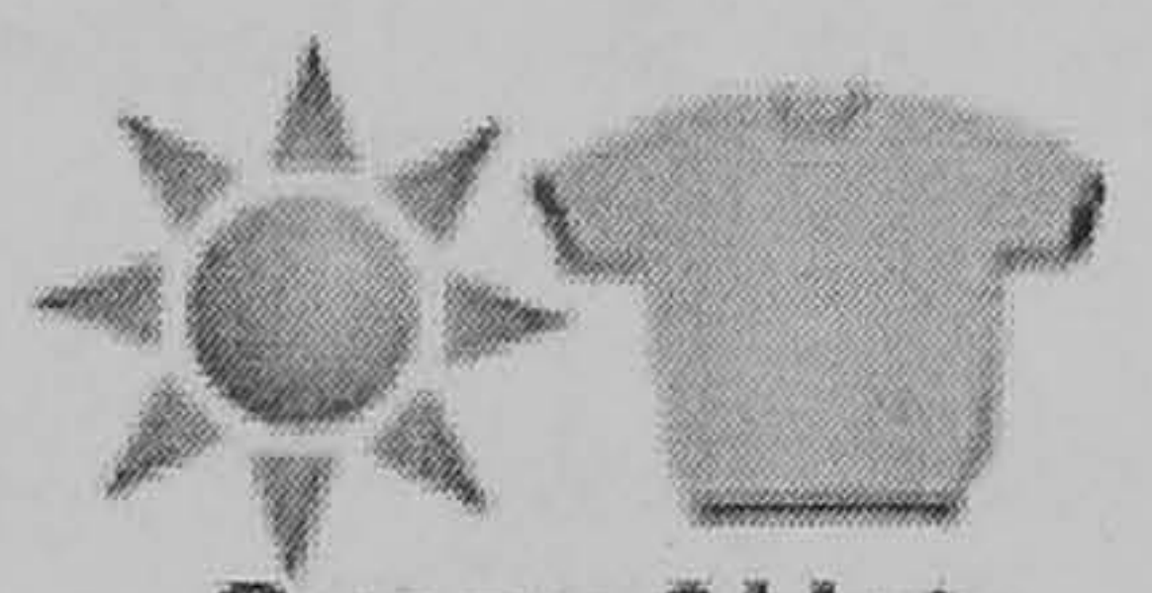


Figure 6.24 Breakdown of the internal blind status (Arts Tower)

Figure 6.24 indicates that more than half of the respondents (57.5%) feel that they are difficult to control with ‘a little difficult’ coming in at 24.9% and ‘quite difficult’ at 32.6% respectively. The ‘quite difficult’ segment even occupies the largest part of the whole pie. Around one third (35.7%) select easy and there is even a very small number of responses who apparently ‘never use’ (6.9%). Generally, although internal blinds helps to control the thermal and visual environment in the building’s rooms, its status may prevent the occupant from making its use a priority in maximising environmental benefits. These results will be used and discussed in a more detailed way in Data Analysis II when occupant’s actual manual control of blind is related to.

6.2.1.7 Occupant Control of the Built Environment

9. Thinking back, under such environment below in your office, what did you do normally? Note: it is the ways you *actually* select not you are assumed to do.

	 Sunny &Cold	 Sunny &Hot	 Overcast &Cold	 Overcast &Hot
Door	Open	Open	Open	Open
	Close	Close	Close	Close

...

Based on the architectural design, the ways that occupants can respond and control their working/studying environment are classified in Table 6.2. The solid diamond ‘◆’ represents the control strategy that has a great impact on this specific environment while the hollow one ‘◇’ means only a minor impact. For example, the position of the blind has an influential effect on the solar radiation penetrating into the room thus affecting the radiant and/or air temperature inside. When there is only diffused daylight available, its impact on the temperature of the room is not as evident as in previous one. Also, when it comes to an extreme/unbearable situation, the occupant can choose to leave the room although this seems to be the last resort in expressing dissatisfaction with the environment.

Manual control	**Thermal effect**		**Visual effect**	**Acoustic effect**
	Temperature	Air movement	Illuminance	Noise level
Door (opened/closed)		◆		◆
Electric lighting (off/on)			◆	
Window (opened/closed)	◇	◆		◆
Blind (up/down)	◇/◆		◆	
Place change (yes/no)	-	-	-	-

Table 6.2 Environmental control strategies by the occupants of the Arts Tower

Practically, it was observed that occupants in this building also use other alternatives to satisfy their own individual requirements for a suitable environment. For example, 56 rooms were recorded as having been equipped with an electrical fan. The figure went up to 32 with table lamps and 30 with extra heaters. These alternatives confirm the fact that by their own experiences, the occupants try to participate extra in controlling their built environment beyond what the conventional architectural service can provide. However, they are not included in the analysis due to the small occupation proportion (29.5% on average) of the total number of investigated rooms.

This study focuses on the premise that the occupants' control of the built environment occurs as a reaction to the vagaries of hour-by-hour change in weather such as air temperature and/or sunshine intensity. Therefore, the different weathers are generally divided into four situations: sunny cold; sunny hot; overcast cold and overcast hot. It has to be mentioned that although the survey emphasizes that the respondent has to pay attention to what they actually select but not what they are assumed to do, it is still based on participant's memory after the events have actually take place. The information collected here is treated not only as one of the sources of research materials, but also as data checks because self-answering can be biased, particular through forgetfulness and other subjective issues. In Data Analysis II further work will be done to validate in reality what occupants' response to the outside/inside environment are and how they operate the window and blinds.

Door

Figure 6.25 presents behaviour patterns for door opening under different environmental conditions in terms of room orientations and whole samples. The concept of confidence is used to construct an interval for a population mean. For example, it is observed that in the sample of 228 respondents, 38.8% will change their door from close to open in a sunny day from cold to hot. The corresponding confidence interval is then 38.8%±5.064% (approximately [44.9%, 33.7%]) (Table 6.3). Broadly, it can be seen that only when the thermal environment changes between cold and hot, the ratio of 'opened' and 'closed' has a visible variation. Specifically, when it is overcast, the 'closed' ratio drops from 76.4% to 37.9%. Of these 76.4% responses, 50.0% choose to have their door changed from 'closed' in a cold day to 'opened' in a hot day. When it is sunny, the 'opened' ratio rises up to 71.1% on a hot day. Even when the temperature drops to 'cold', there are still 32.3% responses showing that the door is kept at the 'opened' position.

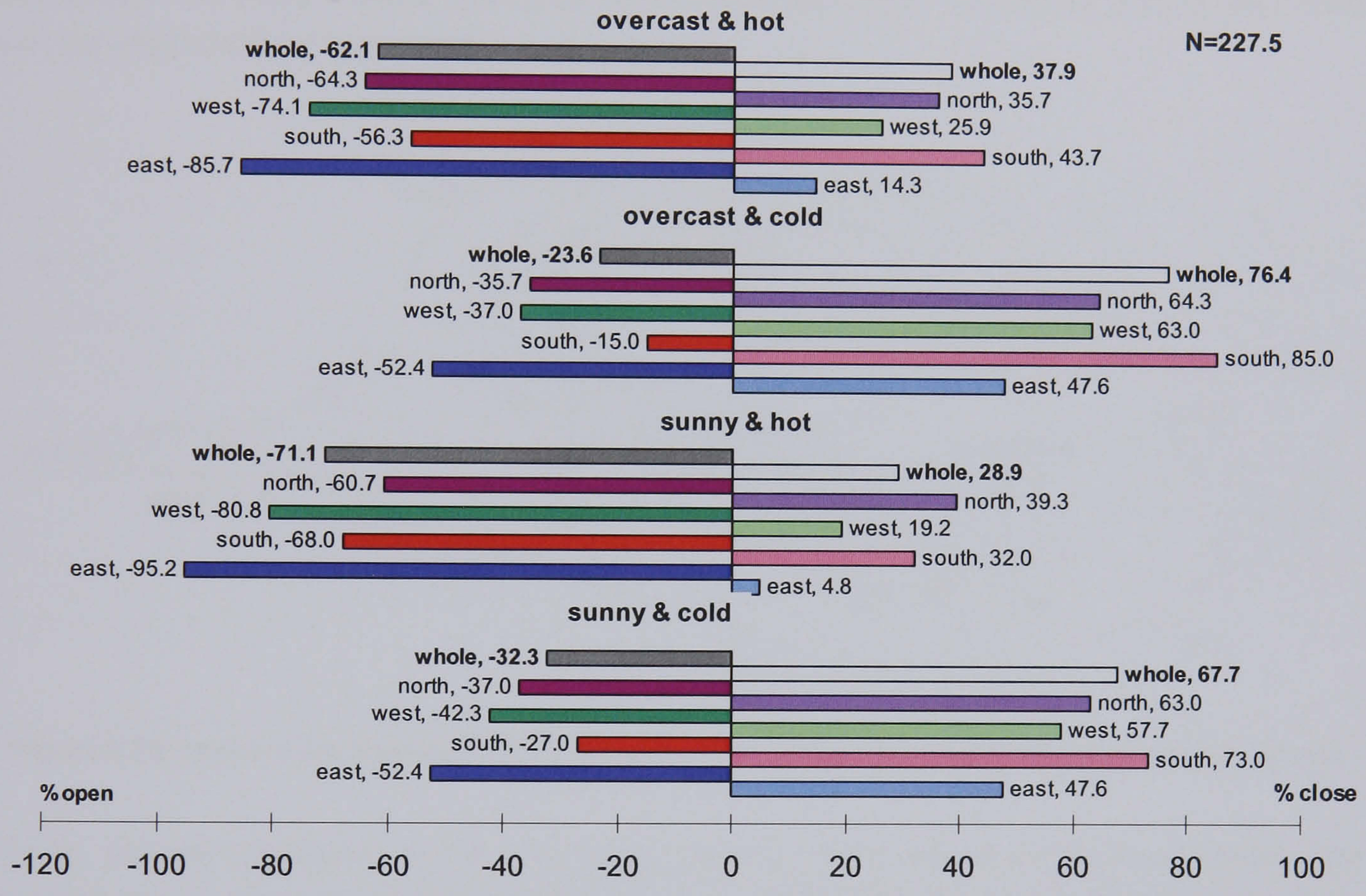


Figure 6.25 Respondent's behaviour pattern in terms of door control under different weather conditions based on orientation

Confidence	Sunny & cold	Sunny & hot	Overcast & cold	Overcast & hot
Sunny & cold		5.064	1.139	3.896
Sunny & hot			6.203	1.168
Overcast & cold				5.035
Overcast & hot				

Table 6.3 Statistical values of confidence (Significance level=0.05) (door operation)

It is expected to see that no matter how the environment changes, there are always some doors kept closed, considering the requirement for 'fire door', and this is indicated by 10.3% of the respondents. Certainly, other factors such as privacy, noise level can also affect occupant preference to keep the door closed. The minimum value occurs when the weather is sunny and hot with just 28.9% of responses for leaving the door 'closed', while on an overcast and cold day; there are still 23.6% responses for opening the door. Due to the fact that this is the easiest way to increase indoor air movement, the result indicates the poor ventilation that makes air stuffy is always a problem no matter what the weather conditions for some respondents. In terms of orientation distribution, the result shows a high consistency. On an overcast and hot day, the response from the east room has the highest ratio for the 'opened door' (85.7%), followed by the west (74.1%). The north is in the third place with 64.3% while the south has the lowest ratio (56.3%). These ratios change respectively when it comes to other different weather conditions but this order remains the same all the time except on sunny and hot days, where the south is a little higher than the north one (7.3%). This can be explained by two factors:

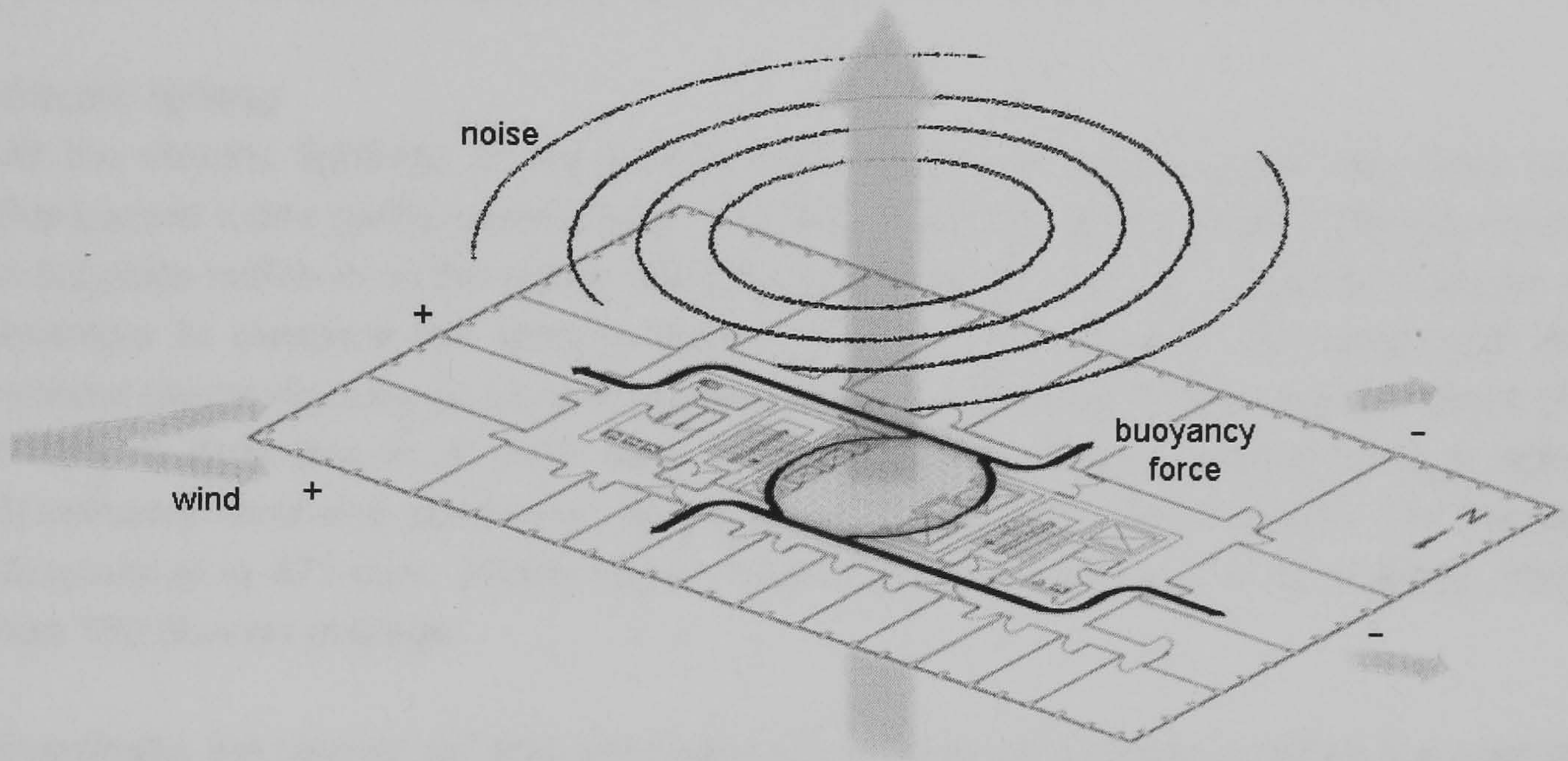


Figure 6.26 Impact of the buoyancy force, wind and noise on the built environment based on orientation

Firstly, natural ventilation in the Arts Tower mainly comes about in two ways: prevailing wind pressure from the outside, and the stack effect from lift shafts and service ducts from the inside. Wind pressures may oppose or assist buoyancy forces resulting at such times. If the stack effect in this case is the dominating consideration, the distance from the core of the plan becomes crucial in terms of the air exchange rate. It gradually decreases while the distance from core increases (Figure 6.26). Therefore, comparing with the south and north, the east and west need to change the door position (opening size) to get the same effect with respect to air velocity [10]. Furthermore, the prevailing wind direction from the west and south west, on the other hand affects the pressure distribution over the building shell and involuntary infiltration. It always produces a positive pressure zone on the windward side – the south and west façade - while the negative is on the leeward –opposite the east and north. Very approximately the infiltration rate is normally higher on the windward face of the building than on the leeward one [11]. Therefore, it can be seen that rate of 'opened door' is higher from east than west while the north is higher than south. Only when the weather is hot and sunny, and overheating becomes a clear issue especially to those in the south rooms, does it enhance the requirement for higher air velocity, and thus, in this case, under such weather condition, the south has more ‘opened doors’ than the north.

Secondly, the noise level normally increases when the door position is changed from ‘closed’ to ‘opened’ because it decreases the transmission loss of sound and provides a relatively ‘free’ path for the noise source which is produced by the elevator, emergency phone and alarm. Also the central hall of the building is the intersection of horizontal and vertical transport for occupants which further intensifies the sound energy from the point source. Similarly with stack effects, the impact of noise from the central hall to the west and the east is not as strong as to the north and the south. Thus the ratio difference of the ’opened door’ is strengthened between four orientations by noise control.

Electric lighting

All the electric lightings in the investigated rooms are typical panel luminaries with fluorescent tubes giving upward and downward light with mirror louvers fitting beneath. A flat-plate switch is on the wall to control the lighting ‘on’ and ‘off’. Figure 6.27 shows an example to compare the lighting level in a small room towards the south with and without electric lighting on an overcast day which has 5000lux design sky illuminace [12, P187]. It illustrates in a clear way that rooms with electric lighting have a higher illuminance level and more even distribution of the luminous environment. The average illuminance is 571.4lux, 200lux higher than is the case without electric lighting, which has 352.5lux on average.

Practically, the ratio of ‘on’ and ‘off’ shows a great deal of variation between the overcast and sunny day while only slightly changing between cold and hot days (Figure 6.28). Specifically when it is hot, the ‘off’ ratio drops from 69.7 to 24.2%. Of these 69.7% responses, around two thirds (69.6%) choose to have their lighting ‘off’ on a sunny day to ‘on’ on an overcast day. When it is cold, the ‘on’ ratio rises up to the highest (87.9%) on an overcast day. On a ‘sunny’ day, there are still 35.7% responses for keeping the lighting ‘on’. The influence of temperature although it

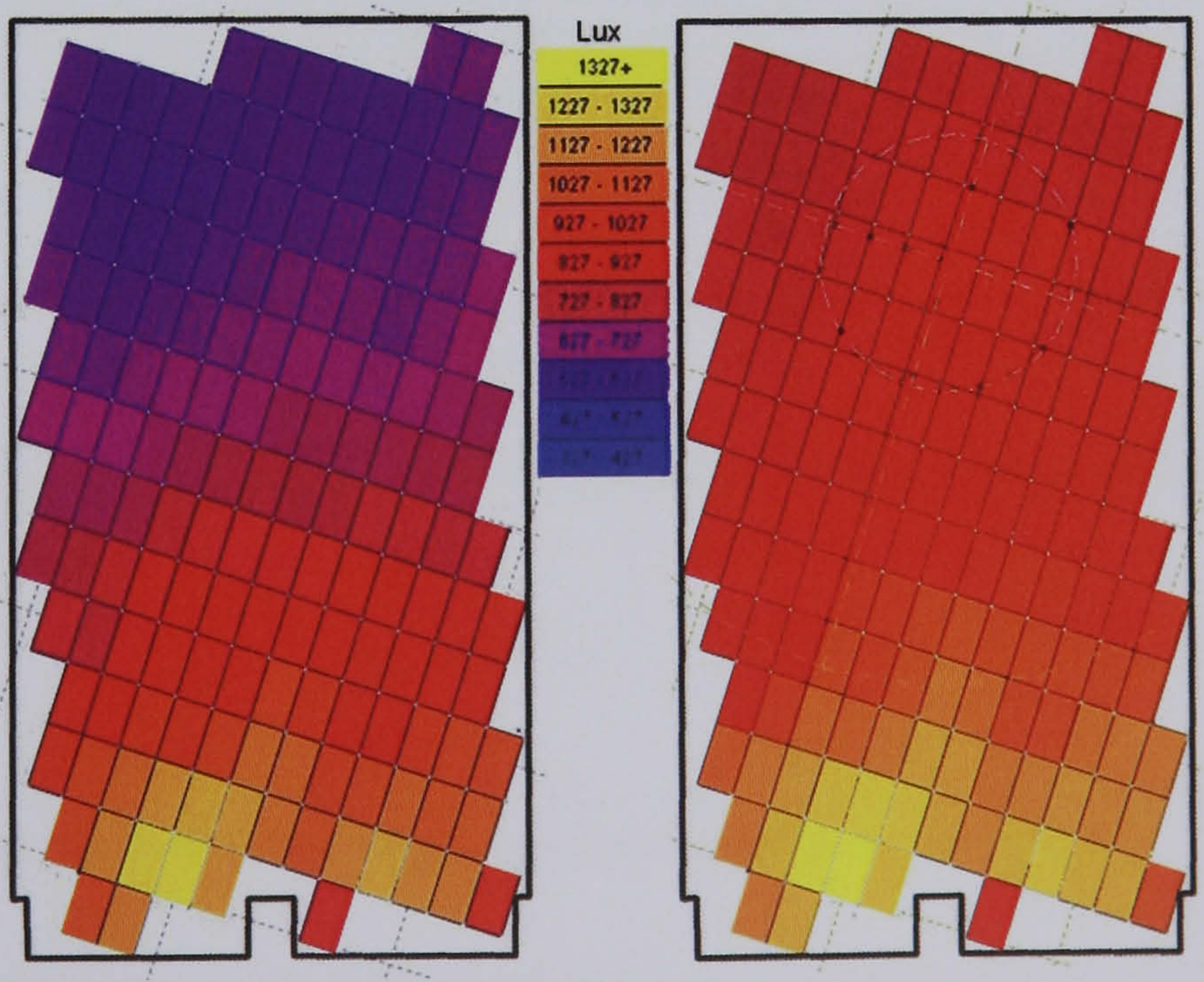


Figure 6.27 Comparison of the illuminance distribution without (left) and with (right) electric lighting on an overcast day in a small room

seems small, displays some noticeable changes. Under the same sky conditions, more responses indicated a preference to have the lighting 'on' on a cold day than on a hot day. It shows 11.5% more when it is overcast while only 5.4% when it is sunny.

In the part of 6.2.1.1 it has been proved that the brighter the visual environment, the higher the satisfaction level of the occupants. And the visual efficiency increases dramatically positively against the task of illuminance. Although over 1000lux, the efficiency curve starts to flatten out (Figure 2.12), and for a working environment it doesn't affect the occupant activity in terms of visual comfort. Therefore, the sky condition becomes less related to the visual environment with the result that many of the rooms have the lighting 'on' when occupied no matter whether the sky is clear and bright or overcast. However, it was not expected to see this issue is applied to such a high degree. Even on a sunny and hot day, there are still 30.3%, roughly one third, of the total number continuing to switch the electric lighting 'on'.

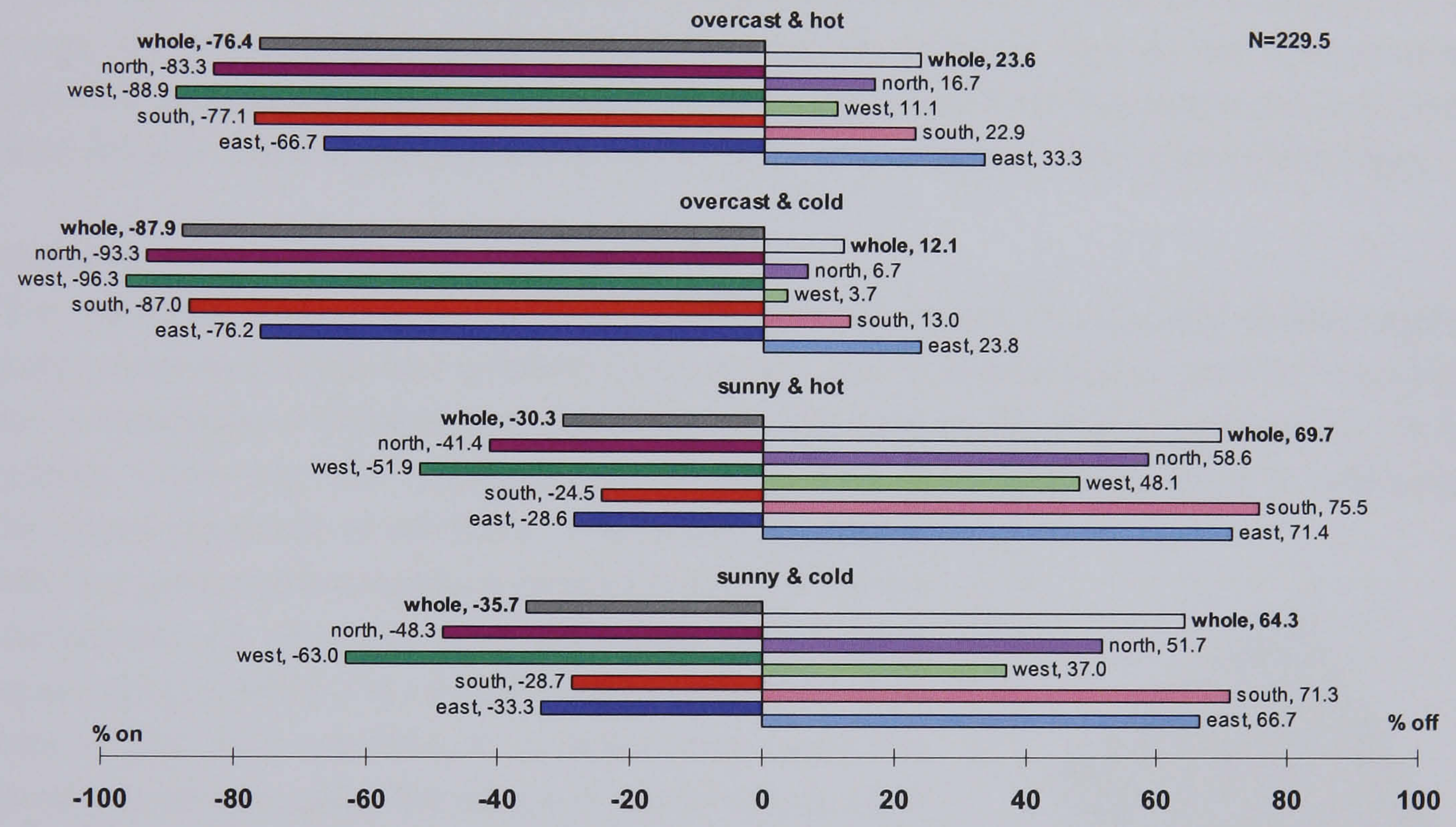


Figure 6.28 Respondent's behaviour pattern in terms of electric lighting control under different weather conditions based on orientation

Confidence	Sunny & cold	Sunny & hot	Overcast & cold	Overcast & hot
Sunny & cold		0.699	6.739	5.247
Sunny & hot			7.437	5.946
Overcast & cold				1.491
Overcast & hot				

Table 6.4 Statistical values of confidence (Significance level=0.05) (AL operation)

In terms of orientation distribution, on an overcast and hot day, the responses from the west rooms display the highest ratio of lighting 'on' (88.9%), followed by the north

(83.3%). The south is in third place with 77.1% while the east has the lowest ratio (66.7%). These ratios change respectively when it comes to other weather conditions but the west and north always have the highest ratios. When it is overcast, the south is higher than the east while, when sunny, the east is higher than the west. This probably presents a balance of results between the two extreme situations of the visual environment of the building. The west side of the building, mostly of the time receives the sunlight for half of the day when the sun is in a low position with a strong intensity. This not only results in a high frequency of glare problems (see 6.2.1.4) but also a high contrast sensitivity of sharp shadows and shading within the whole environment. The difference in the luminance of each object within the same field of view can create discomfort and affect the visual performance very much [5]. One way to alleviate this phenomenon is to increase the indoor illuminance then soften the difference and this makes the occupants from the westward rooms prefer to leave the lighting 'on' all the time. However, the north rooms always have the lowest values for solar and diffused radiation. It directly affects the average illumiance of the indoor visual environment. As a result, the ratio of lighting that is 'on' from north is relatively high all the time. It also explains why on a sunny day the south has a lower ratio of lighting that is 'on' than the east since its glazing can provide a combination of the highest solar and diffused light.

Window

The perimeter rooms are all naturally ventilated by means of vertically sliding upper sash windows at each bay between the columns. The aperture size is variable, allowing for a maximum of 500mm opening except in the case of the sealed windows at each corner. Generally, the desire for air movement is the motivating force in affecting occupant operation of windows. The British Standards Method gives schematically a proposed formula for the calculation of the air flow with two single-sided openings [13, P65]. Figure 6.29 shows the volume flow rate of the air's variation in a small room with two windows on one side. The above is based on the wind speed and the following is based on the outside temperature when the inside is fixed at 25°C. It can be seen that in terms of increasing the air velocity, increased window opening sizes, higher wind speeds, and greater temperature differences can all have the same effect.

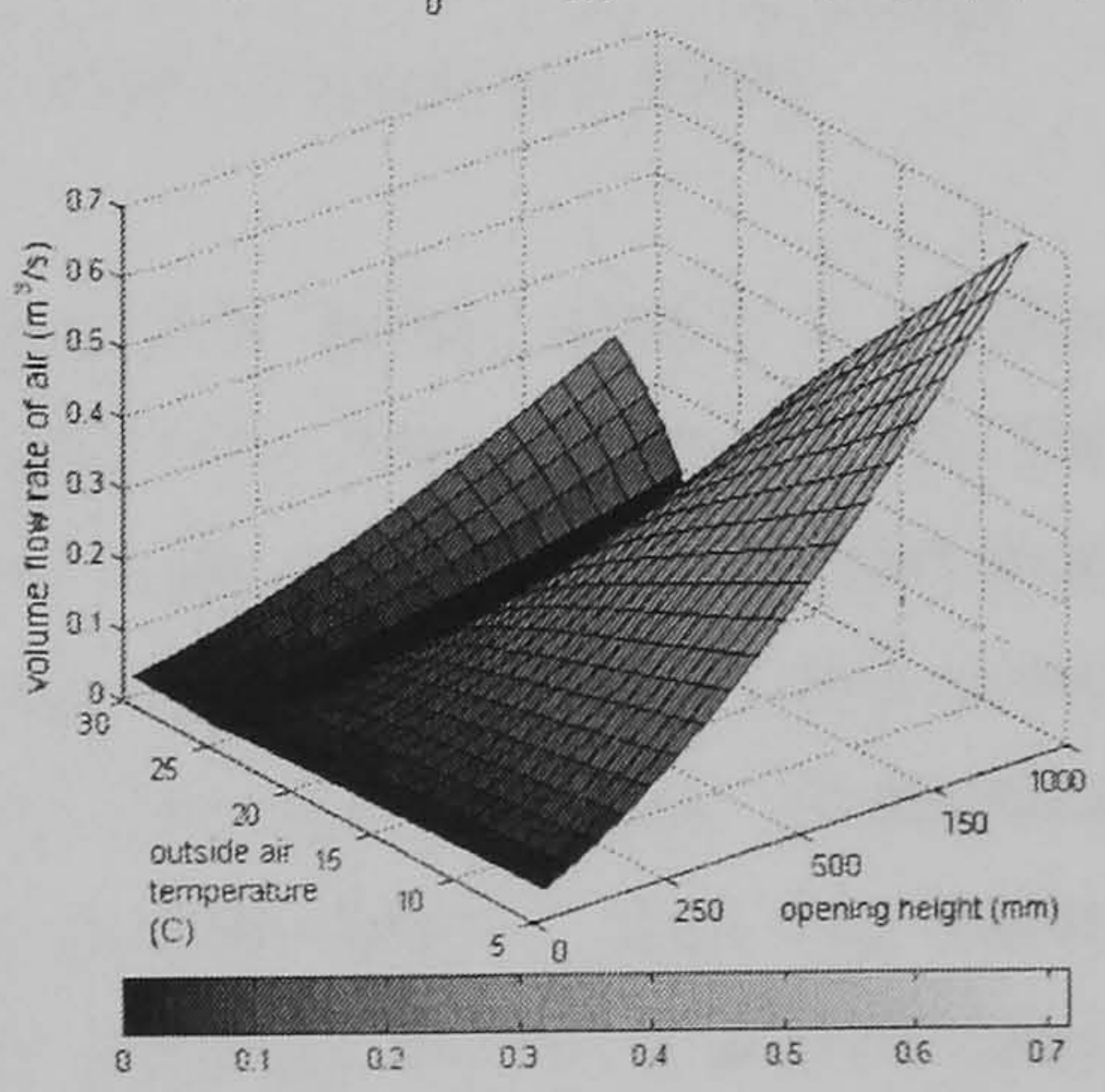


Figure 6.29 Flow rate in a small room with one side two windows

From Figure 6.30, the ratio of 'opened' to 'closed' windows shows a great deal of variation between cold and hot days while only a slight change between overcast and sunny days. Specifically, when it is overcast, the 'opened' ratio rises up from 17.3 to 74.0%

which means that of the 82.7% who prefer the window to be 'closed' on an overcast and cold day, more than two thirds (67.7%) of responses choose to have their window changed from the 'closed' position on a cold day to the 'opened' one on a hot day. The 'opened' ratio reaches its high point of 87.9% on a sunny and hot day. When it drops to 'cold', there are still 36.6% responses for keeping the window 'opened'. The sky condition, although not as influential as the temperature, has a discernable impact, especially when it is cold. Most responses leave the window 'closed' (82.7%) on an overcast day but on a sunny day, 19.3% change it to 'opened'.

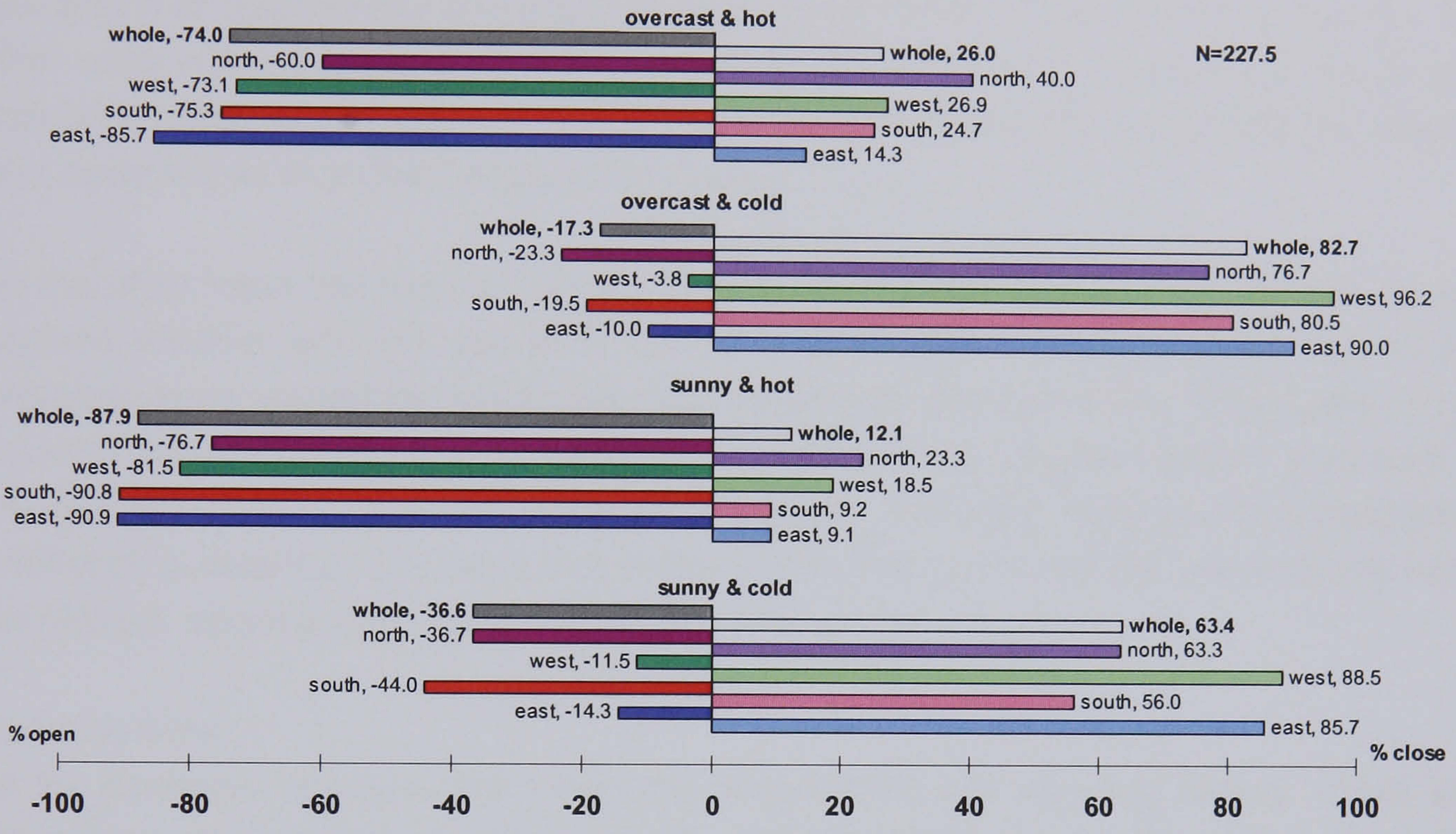


Figure 6.30 Respondent's behaviour pattern in terms of window control under different weather conditions based on orientation

Confidence	Sunny & cold	Sunny & hot	Overcast & cold	Overcast & hot
Sunny & cold		2.104	2.496	4.860
Sunny & hot			9.157	1.800
Overcast & cold				7.357
Overcast & hot				

Table 6.5 Statistical values of Confidence (Significance level=0.05) (Window operation)

Taking an overall view, the operation of the 'window' and the 'door' share a similar pattern due to the same thermal effect on indoor air velocity. They both reach the highest ratio of 'opened' on sunny and hot days while the lowest are on overcast and cold days. However, to affect the air velocity, window control is based on the wind pressure induced while door control mainly benefits from the stack effect. Therefore more responses indicate a preference for door control on a cold day in case the warm air is removed from the inside and replaced by the cold air outside. When it is overcast, 74.0% keep the window 'opened' on a hot day while 62.1% select the door 'opened' position (11.9% less). Among these 62.1% responses, 48.0% select both the window and the door in the 'opened' position. On a cold day, 17.3% keep the window 'opened' while 23.6% select door 'opened' (6.3% more). From the 23.6% responses, only 3% select 'opened' for both of them.

In terms of orientation distribution, it becomes a little complicated and does not present a visible variation feature like the 'door' or 'artificial lighting' pattern. However, the responses from the south rooms have a relatively high ratio for the 'opened window' which is always in the 1st and 2nd place perhaps because of the amount of solar radiation that reaches the south of the building envelope is always higher than for the other ones under the same weather conditions. Highly frequent overheating results in a high preference for the 'opened window' not only to increase the air velocity but also to take away hot air from the inside of the room.

On the other hand, the results from the west room displayed a relatively low ratio for the 'opened window' which is always in the 3rd and 4th place. This is perhaps due to the prevailing wind, especially winds with high speeds (more than 4m/s). This comes from the west most of the time (see Chapter Five) and thus the 'opened window' may lead to draught problems such as window rattle and paper scattering which is not a practical if ventilation is desired. This issue also explains why the responses from west rooms have the highest 'opened door' ratio at all times.

Venetian blind

All the perimeter windows are fitted with 50mm width slat venetian blinds. These are adjustable and movable by tilter wands and automatic cord locks. Apart from the position 'up' and 'down', 'half down' is also considered as a way to balance the physical environment and people's appreciation of the view .Figure 6.31 illustrate sun penetration when the blind and its slat are in different positions – up, down, half down and down at an angle - in a small south-facing room under a uniform sky condition with 40,000lux designed sky illuminance [14, P313]. It clearly shows that the room with the blind up has a brighter environment than with the blind down while the latter has more uniform and diffused daylight and thus effectively avoids glare and thermal discomfort.

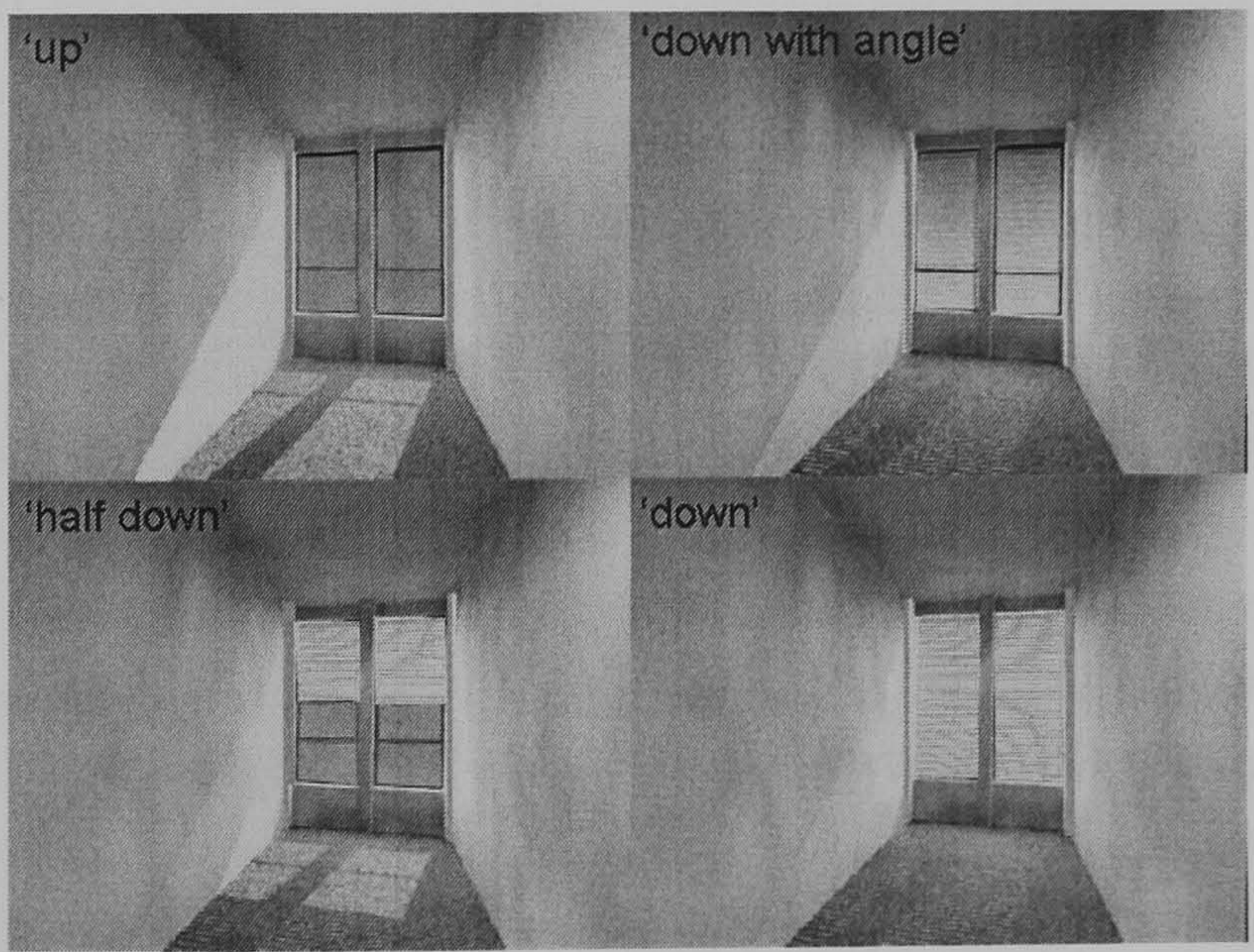


Figure 6.31 Sunlight penetration when the windows are occluded by the venetian blinds

However, the result in Figure 6.32 doesn't show the blind operation is affected by temperature very much – 0.3% difference when it is sunny while 5.0% when it is overcast. Instead, the sky condition is the dominating factor although its impact is not as dramatic as the other control strategies such as electric lighting. When it is hot, the 'up' ratio drops from 37.4 to 14.3%. Of that 37.4% of responses, 72.0% choose to change their blind from 'up' on an overcast day to 'down' or 'half down' on a sunny day. When it is cold, the 'up' ratio rises up to a high point of 42.5% on an overcast day.

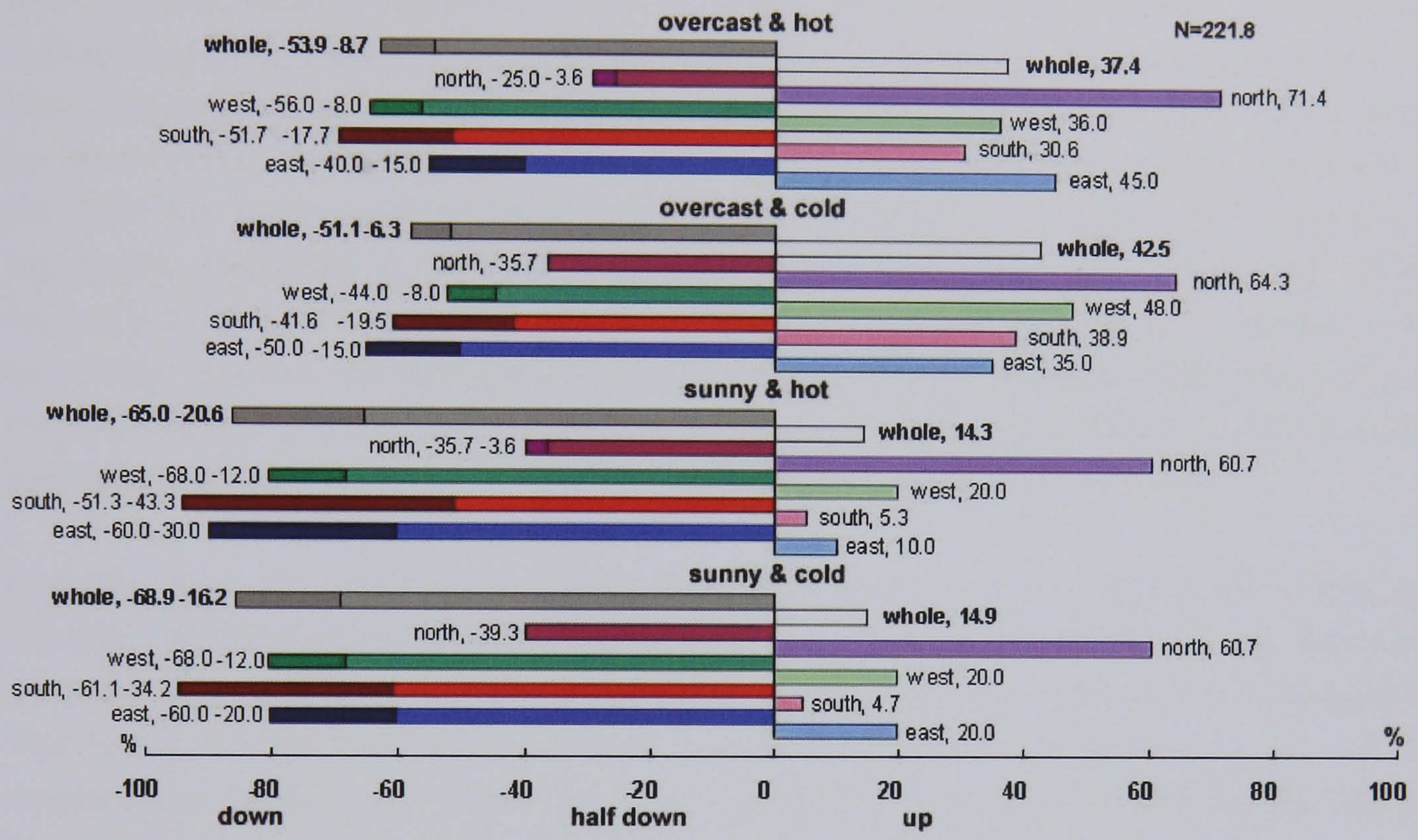


Figure 6.32 Respondent's behaviour pattern in terms of venetian blind control under different weather conditions based on orientation

Confidence	Sunny & cold	Sunny & hot	Overcast & cold	Overcast & hot
Sunny & cold		0.068	3.648	2.977
Sunny & hot			3.716	3.044
Overcast & cold				0.671
Overcast & hot				

Table 6.6 Statistical values of Confidence (Significance level=0.05) (Blind operation)

Generally, the largest proportion of possible blind positions under all weather conditions is the 'half down' position with small variation from 51.1% on an overcast and cold day to 68.9% on a sunny and cold day. This indicates that the blind is not always the first option when it comes to changing an unsatisfactory environment. The visual control is mainly by means of electric lighting switching (on and/or off). And the thermal control is by way of the 'opened' window and door to increase air velocity. Only when exposed to glare and/or radiation asymmetry by direct sunlight, which other strategies can do little about, can the blind actually be operated to alleviate such extreme environmental discomfort. Most of the time the blind tends to be kept 'half down' to avoid these uniquely blind-solvable problems from happening and still retain direct eye contact with the outside world. It also explains why only a small portion of responses (on average 12.5%) have their blinds in the completely 'down' position in the four weather conditions. This result also confirms the most fundamental function of windows in providing pleasant views is unique and cannot be substituted.

In terms of orientation distribution, a distinct character is observed. The north room represents a situation in which diffused daylight and radiation is received most of the time without serious problems such as glare or radiation asymmetry, thus always maintaining a very stable and high ratio of 'up' blind positions. The minimum occurs on both cold and hot sunny days with 60.7% while the maximum (10.7% more) takes place on an overcast and hot day (71.4%). On the other hand, the south room represents a situation the maximised average global solar radiation is received. The variation is significant, especially between the sunny and overcast days. When it is cold, 38.9% keep the blind 'up' on the overcast day while being reduced to only 4.7% on the sunny day. When it is hot, the value changes from 30.6% to 5.3%. Although blind control is not the most highly prioritized alternative, its efficiency in converting direct sunlight into soft and reflected light still plays an important role in built environment control.

Both the east and west rooms have the same value for the 'up' blind on a cold day (20.0%). And the west is slightly higher (20.0% vs10.0%) on a hot day. While, when it is overcast, the 'up' blind position for the west and the east increase greatly in frequency. The figure for the east is higher than the west on a hot day with 45.0 and 36.0% respectively. On the other hand, the figure for the west is higher than that for the east on a cold day with figures of 48.0 and 35.0%. This perhaps indicates the respondents from the east prefer the high temperature but those from the west ask for a low one due to their own experience with the sunlight. Compared with the east façade, the west always receives solar radiation with stronger intensity and for a longer time than the east. This effect is strengthened by the fact that the south edge of the Arts Tower is 18° due east.

Place alternative

All the respondents involved in the questionnaire survey have their own fixed working and/or studying places (rooms) so they cannot normally change their own working environments. However, from the feedback of some occupants, they may work at home or other available places when it comes to extreme/unbearable situations. Figure 6.33 presents the result from occupant's response in such situations.

Generally, most of the responders stay in their working place no matter what the weather situation, especially those in the north room. Because this room normally has a uniform and stable environment, the ratio is always the highest for staying put for all the different weather conditions. However, weather with bright sunlight and high temperature leads to the biggest proportion of responses for having an alternative place for every orientation except the north (17.9% on average). In this case, the south has the highest ratio with 21.9% of responses for leaving. Even on an overcast day, the hot weather can still result in 8.0% and 9.1% of responses from the south and the east selecting an alternative place.

On the other hand, overcast and cold days mean dullness and cold, especially in winter. Even with the central heating on, the time and level control are sometimes not flexible enough to fulfil the occupant's requirements. Responses from four room orientations, all to a certain level choose to move to another place with a maximum 9.1% from the east to a minimum of 3.4% from the west. In this case, it further proved that overheating and cold temperature are two prominent aspects which produce the dissatisfaction felt by the occupants of this building.

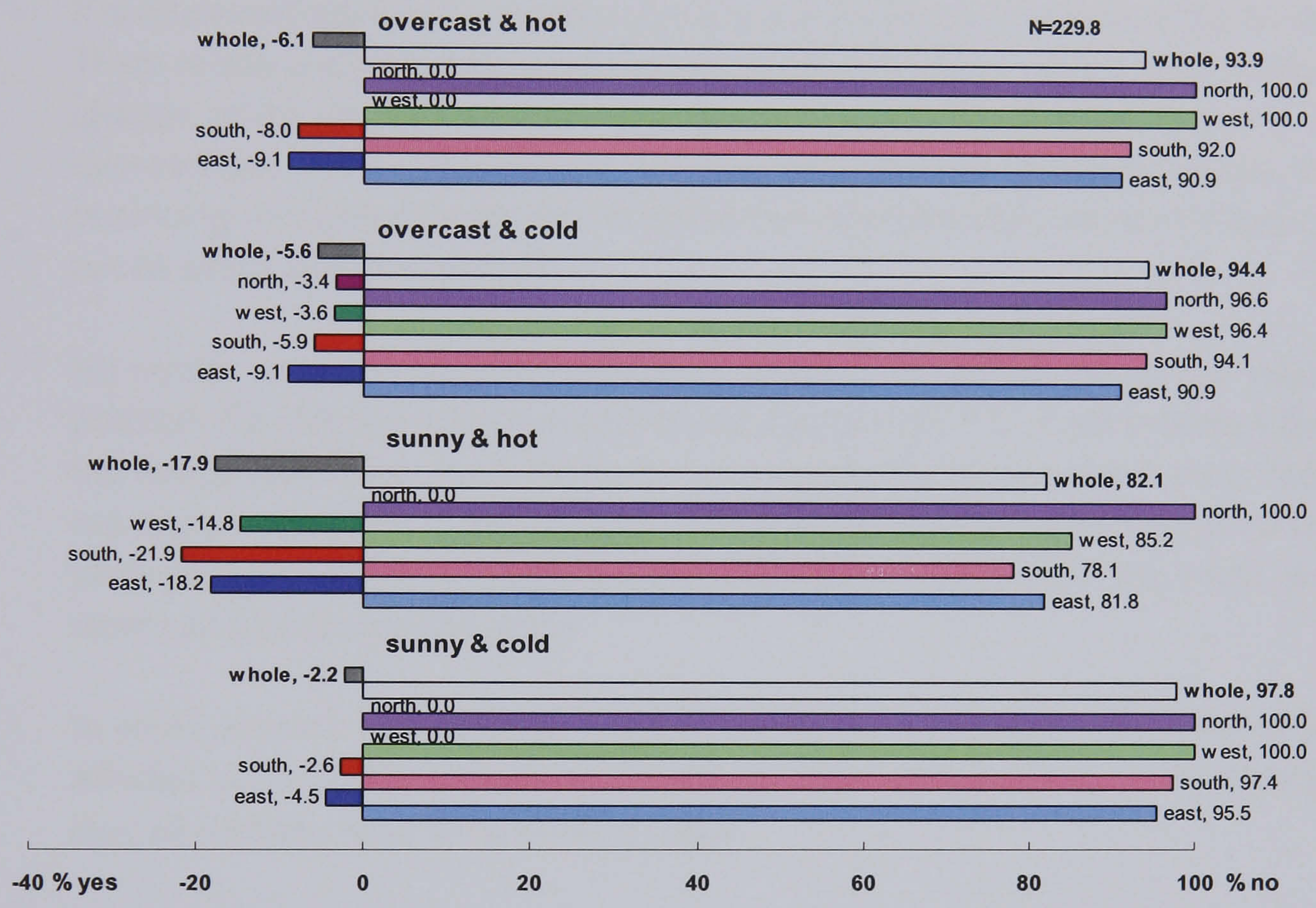


Figure 6.33 Respondent's behaviour pattern when it comes to extreme situation

Confidence	Sunny & cold	Sunny & hot	Overcast & cold	Overcast & hot
Sunny & cold		2.033	0.446	0.509
Sunny & hot			1.587	1.524
Overcast & cold				0.063
Overcast & hot				

Table 6.7 Statistical values of Confidence (Significance level=0.05) (Place alternative)

Overall, the figures of 6.25,28,30,32 and 33 in this part lead to following summary:

- When temperature goes up from cold to hot, more than half of the responses (on average 53.5% in sunny and overcast situations) choose to have their door from changed from 'closed' to 'opened'. 73.8% applies to window use under the same conditions. It is observed that more responders prefer window operation on a hot day while door operation on a cold day to control the air velocity of the room.

- When cloud cover goes up from sunny to overcast, 80.8% of occupants switch their lighting from 'off' to 'on' on a cold day, a figure which slightly reduces on a hot day (69.2%). There are another 28.3% responses for always keeping the lighting 'on' no matter what the weather situation. On an overcast and cold day, 87.9% of occupants leave their lighting on but at the same time, only 42.5%'s blinds are in the 'up' position. They indicate that the electric lighting weakens the natural daylight impact on the visual environment of the building rooms.

- It is not temperature but conditions in the sky that causes operation of the blinds. There is only a slightly difference displayed in the proportion of the blind position change when the temperature changes no matter whether on a sunny or overcast day. Although, sunshine intensity and time are considered to be the overriding motivating factor, the variation between overcast and sunny days is not as significant as expected.

- No matter what the weather conditions, most of the blinds are in the 'down' position (72.7%) including the 'half down' position (59.7%). This indicates that the widely held deign assumption that occupants like large glazed areas does not apply in the case of this building. And orientation has a great impact on the blind position, with a tendency towards maximum occlusion in the south and minimum occlusion in the north.

- In some extreme hot and cold weather situations, 8.0% responses tend to be affected so unsatisfactorily as to choose an alternative place to work although they all normally have fixed working place.

6.2.2 ICOSS Building

The structure and content are roughly same with the Arts Tower survey. Due to its own environmental features, questions are also to do with occupant's perception of temperature, humidity, air movement and lighting in terms of different seasons. Finally, the respondents are asked to evaluate their working environment overall. The analysis is mainly tilted towards the laboratory environment where most of the daily activities of occupants take place. Therefore in total eight rooms, including four open-plan, three secure, and one north-east facing laboratory were involved in the questionnaire survey.

6.2.2.1 At the Point of Survey

In total two days were spent collecting the questionnaires. The weather on these days (16th and 27th Feb/06) was very typical of winter in Sheffield: cold and humid with an average daily temperature 5.5°C, RH 74.0%; cloudy and windy with 2.8hours of sunshine and 9.5m/s wind speed from the west. The central heating system was switched on during the standard working hours.

1. **Please evaluate the overall environment in this room *at this moment* by ticking a score in each row?**

	Very	Fairly	Little	Neutral	Little	Fairly	Very	
Cold	-3	-2	-1	0	1	2	3	**Hot**
Dark	-3	-2	-1	0	1	2	3	**Bright**
Quiet	-3	-2	-1	0	1	2	3	**Noisy**

2. **Do you feel comfortable toward the overall environment in this room *at this moment*?**

Very dissatisfied		Fairly	Little	Neutral	Little	Fairly	Very satisfied
Thermal	-3	-2	-1	0	1	2	3
Visual	-3	-2	-1	0	1	2	3
Acoustic	-3	-2	-1	0	1	2	3

Measurement: Air temperature_____C RH___% Sound level ______dB Illuminance _______Lux

Thermal perception and comfort level

Figure 6.34 shows the distribution of air temperature that was measured simultaneously when respondents answered the questionnaire. Generally, the inside temperature was relatively stable over these two days. The span of peak-to-peak air temperature was very small each day (less than 4.9°C) with a very flat regression line near 0 (neutral). Accordingly, roughly a quarter (25.7%) remains neutral and more than half of the responses (57.1%) show their positive attitude towards the thermal satisfaction level. The result indicates that occupants in this building have a relatively high satisfaction level although it clearly shows that higher temperature results in lower satisfaction level (Figure 6.35).

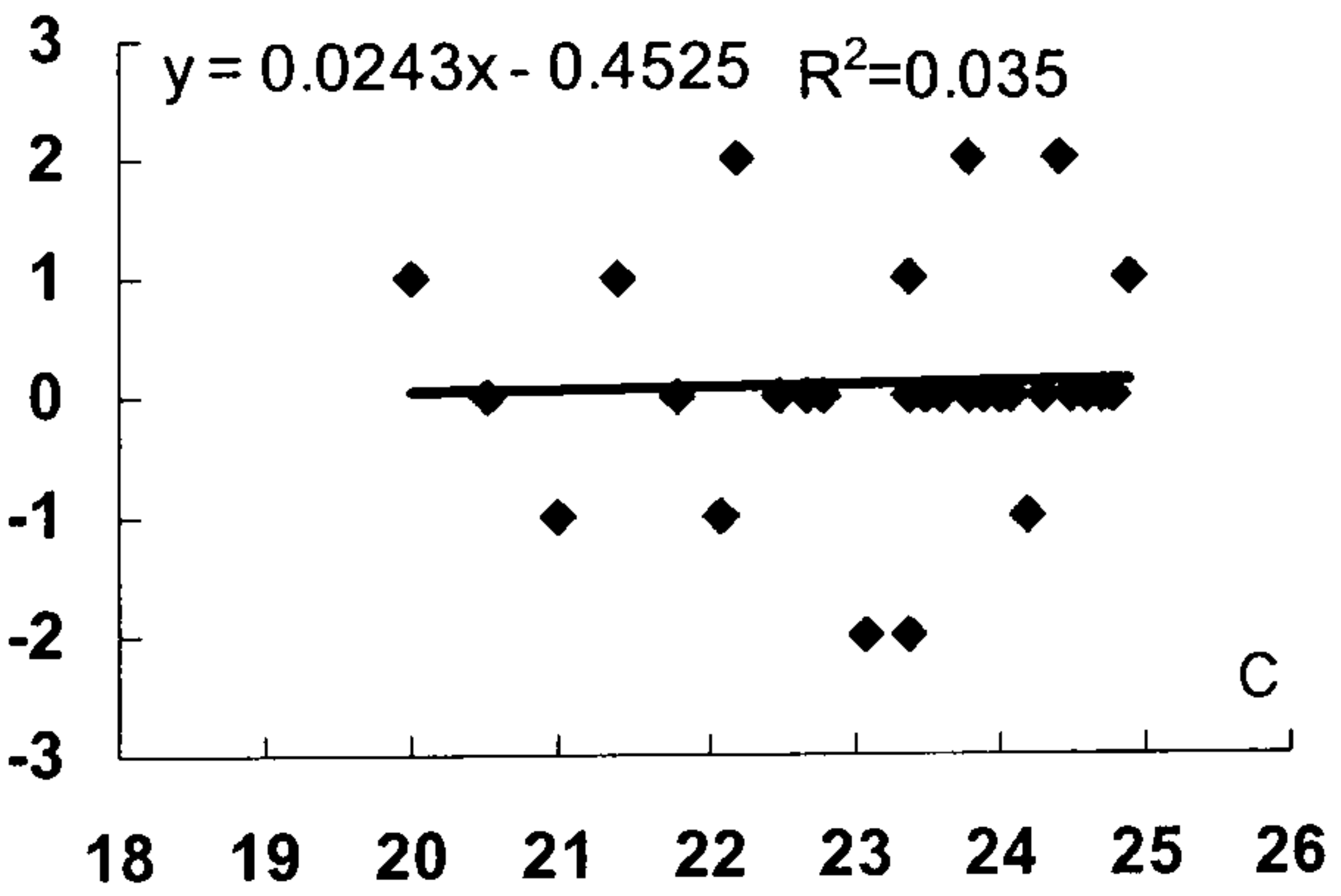


Figure 6.34 Relationship of perception and air temperature (ICOSS)

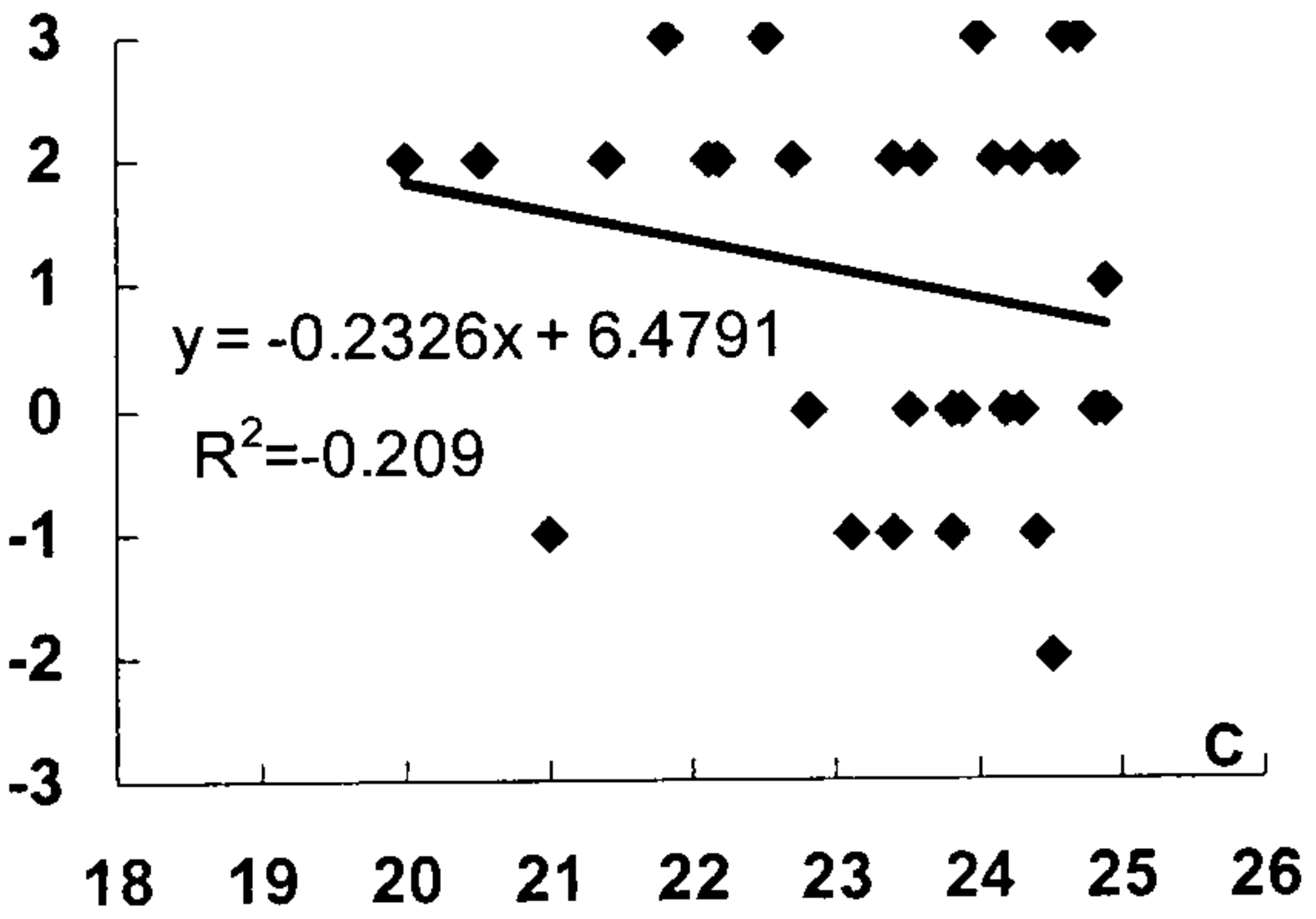


Figure 6.35 Relationship of satisfaction level and air temperature (ICOSS)

Average air temperature was 23.4°C in moderate conditions. However, it has to be noted that compared with the high humidity outside (average 74.0%), the value inside was quite low with an average of 27.6%. The main reason for a low RH can be explained by the advanced natural-ventilation system that the building has. Relative

Humidity (RH) depends on two variables, which are moisture content (MC) and temperature. The RH increases along with MC if the temperature is fixed. If MC is fixed, RH falls as temperature increases. The quantity relationship of the three factors is described in the Psychrometric Chart (CIBSE) above (Figure 6.36). Normally, the RH of the indoor environment is higher than regarded which depends solely on the difference between the inside and the outside due to the fact that evaporation and respiration from the occupants and plants can increase the moisture content. In this case, the advanced natural-ventilation system accelerates the air exchange rate and as a result the impact from occupants and plants in terms of moisture content is decreased. When the fresh air with low temperature and high humidity comes into the building, it heats up from 5.5 to 23.4°C which makes the RH drop down accordingly, but only a little higher than it is supposed to be with 27.6% on the day of survey.

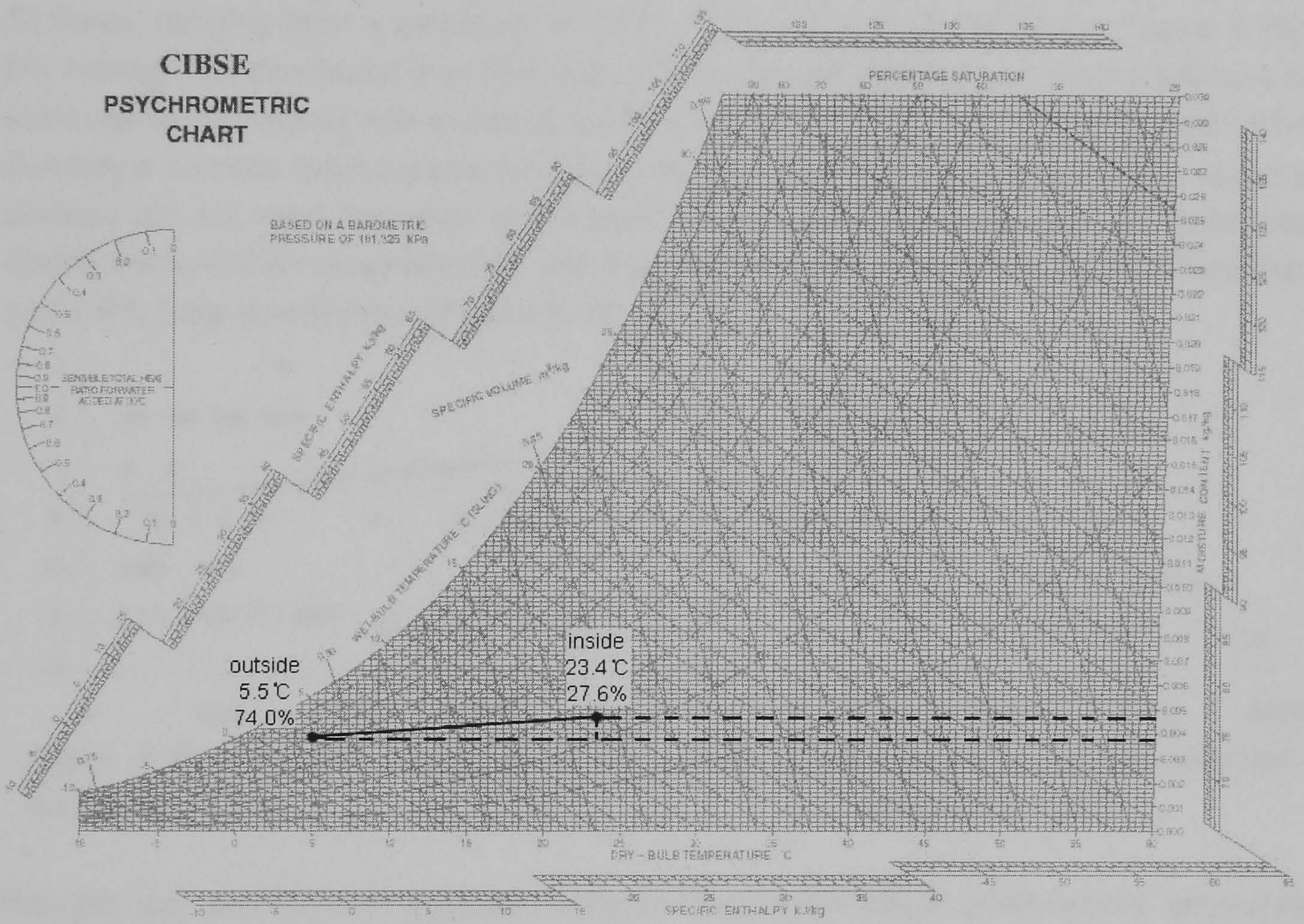


Figure 6.36 Impact of the air temperature on the relative humidity from the ICOSS Building survey in the Psychrometric Chart

Visual perception and comfort level

Generally, the visual environments of these stations are quite varied due to the fact that the deep plan inevitably influences the amount of desired daylight to be introduced into the laboratory. It can be seen from Figure 6.37, which simulated an overcast day with 5000lux design sky illuminance. The daylight factor reduces rapidly with increasing plan depth from the side window. The highest relative brightness is near the south glazing edge, while the lowest is in the centre of the room space. The positive impact of large glazing on the distribution of daylight received is also noticeable. Compared with the secure lab which just has glazing in the north and a small window towards the west, the open-plan lab has a brighter and more uniform lighting distribution as a result of both south and north facing glazed areas.

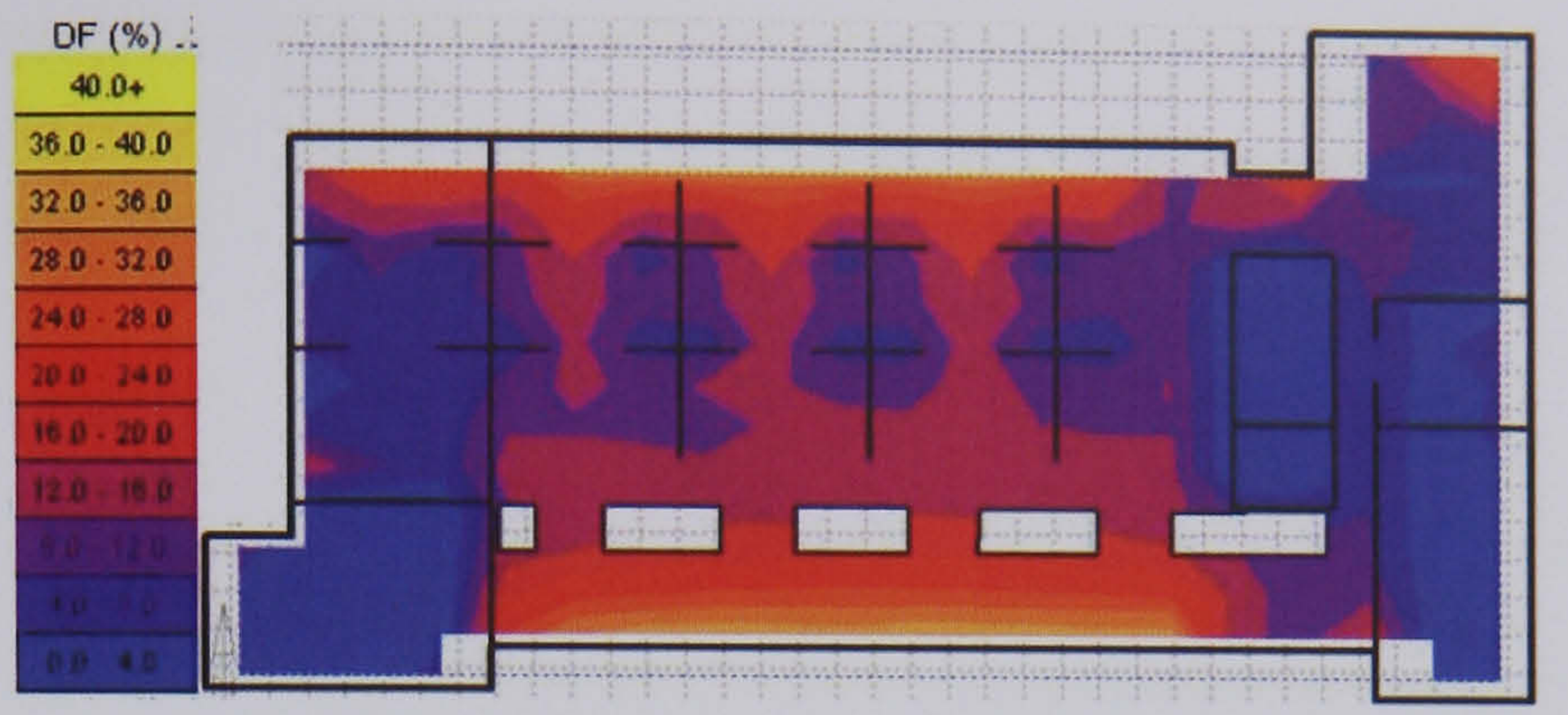


Figure 6.37 DF distribution on the working plane on an overcast day

From the record of measurement, the span of peak-to-peak illuminace was more than 12 times, ranging from a minimum of 132.0 to a maximum of 1610.0lux (Figure 6.38). On average the illuminace was 514.3lux, which was just within the recommendations of most agreed standards and codes of practice for lighting. Although more than half of the illumiance records gave figures less than 500lux (54.3%), which meant these working stations did not meet the lower limit of the visual requirement, just 8.6% of responses clearly showed their dissatisfaction with the visual environment (5.7% a little dissatisfied and 2.9% fairly dissatisfied) (Figure 6.39).

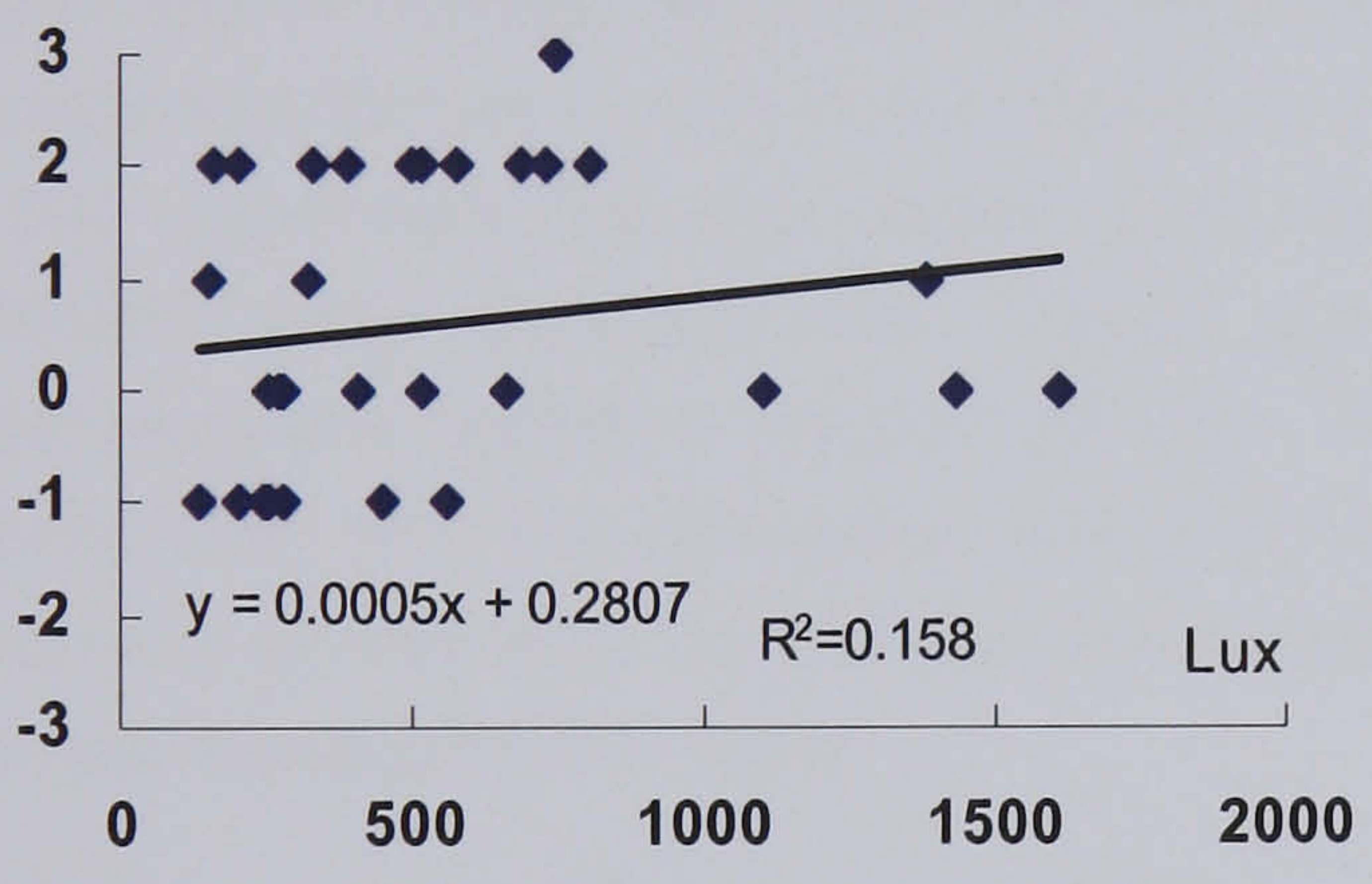


Figure 6.38 Relationship of perception and illuminance (ICOSS)

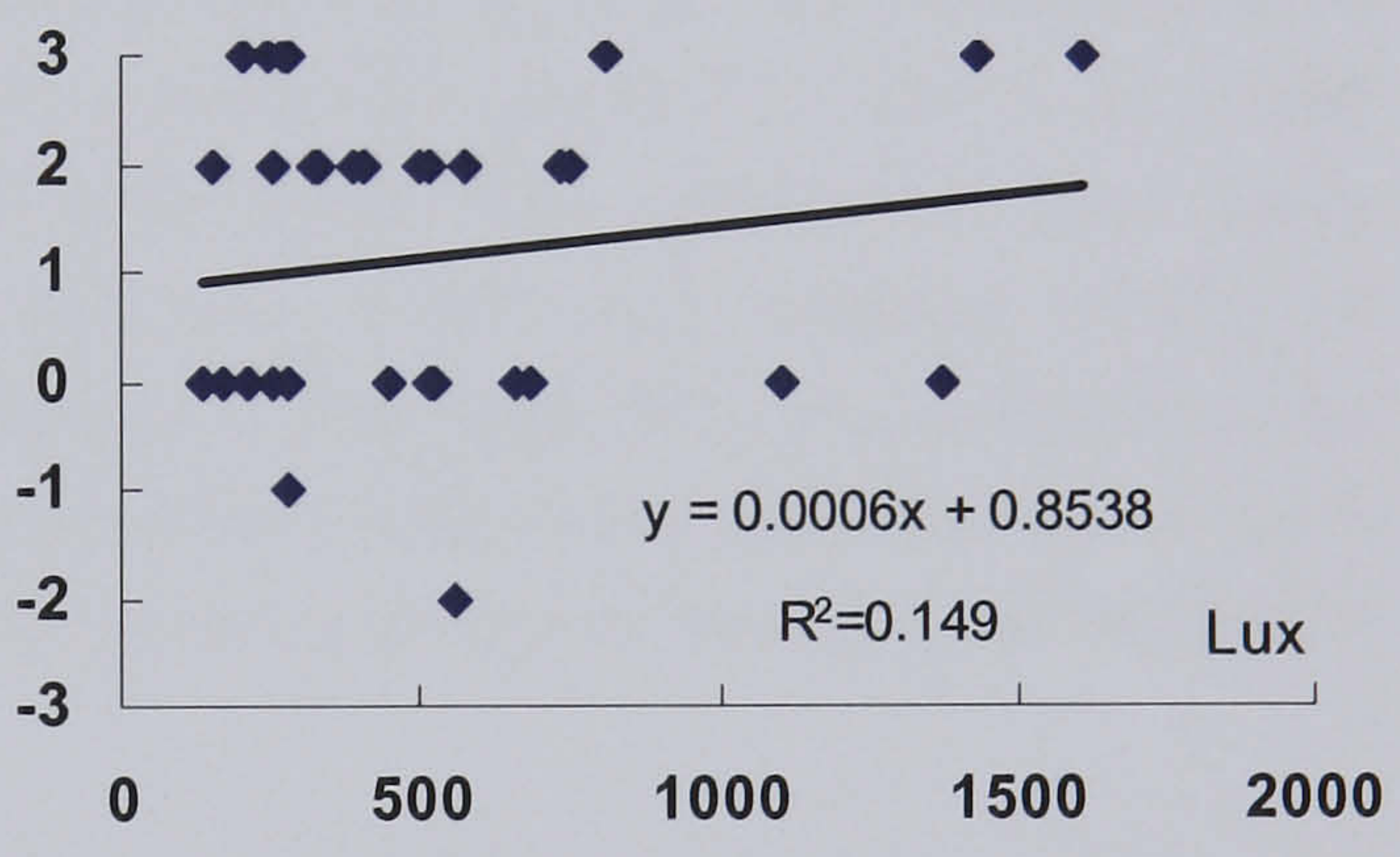


Figure 6.39 Relationship of satisfaction level and illuminance (ICOSS)

Roughly half (54.3%) hold a positive attitude towards the visual environment, especially the distribution for 'fairly satisfied' (31.4%), which reaches up to the second highest satisfaction level. The result confirms that the perception of what is 'bright' does affect the satisfaction level with regard to the visual environment: Brighter the responders feel, higher their satisfaction gets. Although illuminance is not distributed evenly in terms of daylight received due to the large interior area, quite a lot responses (31.4%), a figure which occupies the largest proportion, still feel that it is 'very bright'. The average perception is positive with 0.6 between 'neutral' and 'a little bright'. The corresponding satisfaction level even reaches to 1.1, which is higher than 'a little satisfied '.

Acoustic perception and comfort level

The acoustic environment of the different working stations is quite varied because the

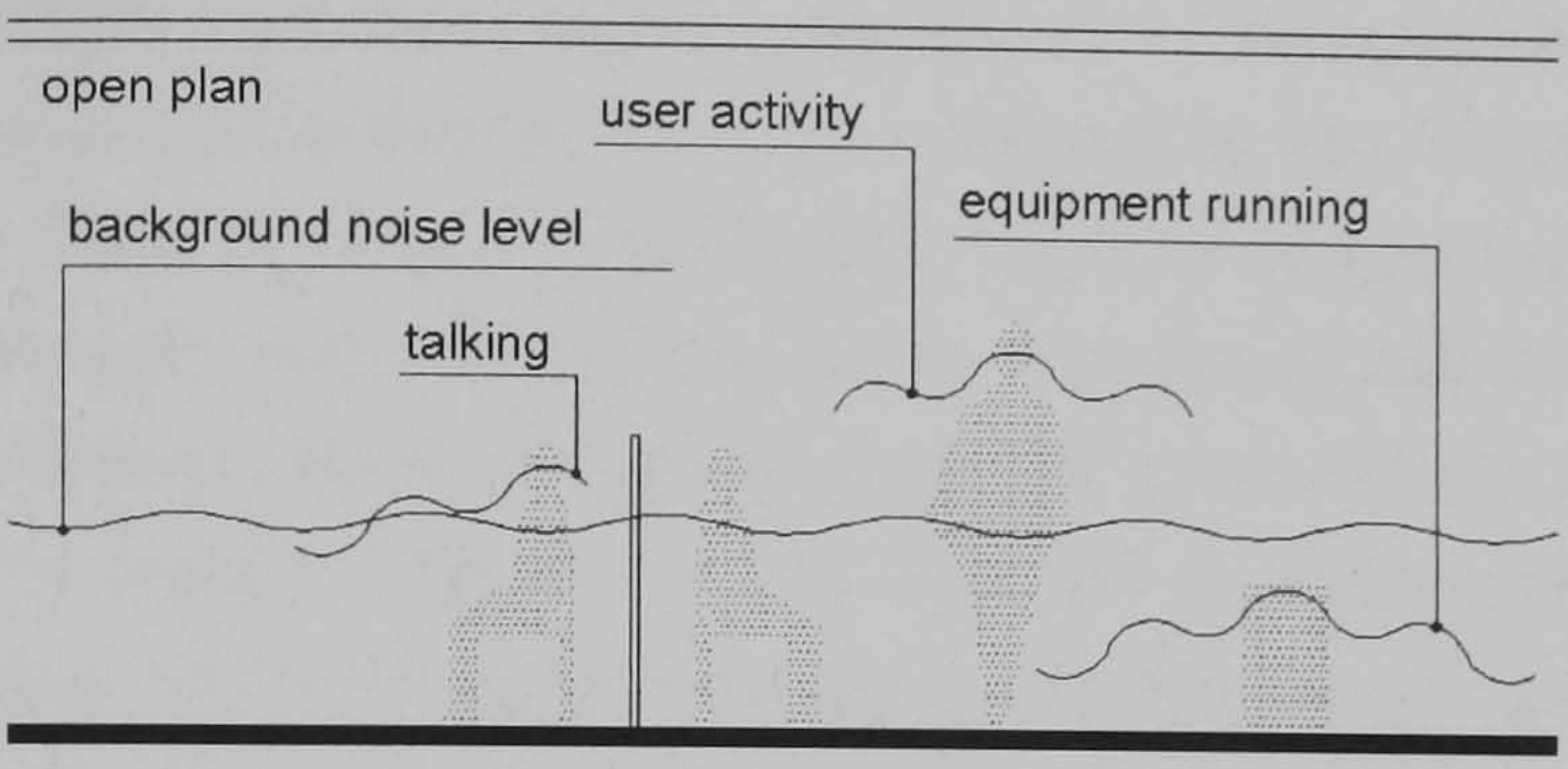


Figure 6.40 Noise source in an open-plan laboratory

noise sources are not only outside traffic, and/or construction work, but also come from the inside. Figure 6.40 illustrates the main noise produced in the open-plan laboratory. The circumstances, such as the outside noise, phone answering, equipment running, user activity etc, may all affect the sound level of the environment. From the site measurement, the maximum value recorded was 62.3dB while the minimum was just 38.8dB which was 23.5dB lower (Figure 6.41). However, most records were in the range between 45 and 50dB thus occupying 42.9% of the total measurements made. It could be seen the laboratory was a quite noisy environment with only a small number of records (5.7%) for less than 40dB. But most of the respondents hold a 'neutral' attitude toward it with its regression line above.

None of the responses indicate feeling 'very dissatisfied', although 22.9% show 'dissatisfied' (Figure 6.42). The occupant is quite capable of voluntarily discriminating and de-emphasizing the background noise in terms of the overall aural situation. Especially in modest situations like this case, the level of satisfaction experienced by occupant in fact be mainly due to nervous effect psychologically [5,P153].More than half of the responses (54.3%) clearly show their satisfaction. The distribution from 'fairly satisfied' even occupies the biggest part (34.3%). There are another 22.9% of responses that hold to a 'neutral' altitude. Therefore in this case, the results do not show conclusively that the occupants had a serious problem with noise disturbance at least when the survey was carried out. But it does indicate that higher sound level will result in lower dissatisfaction level.

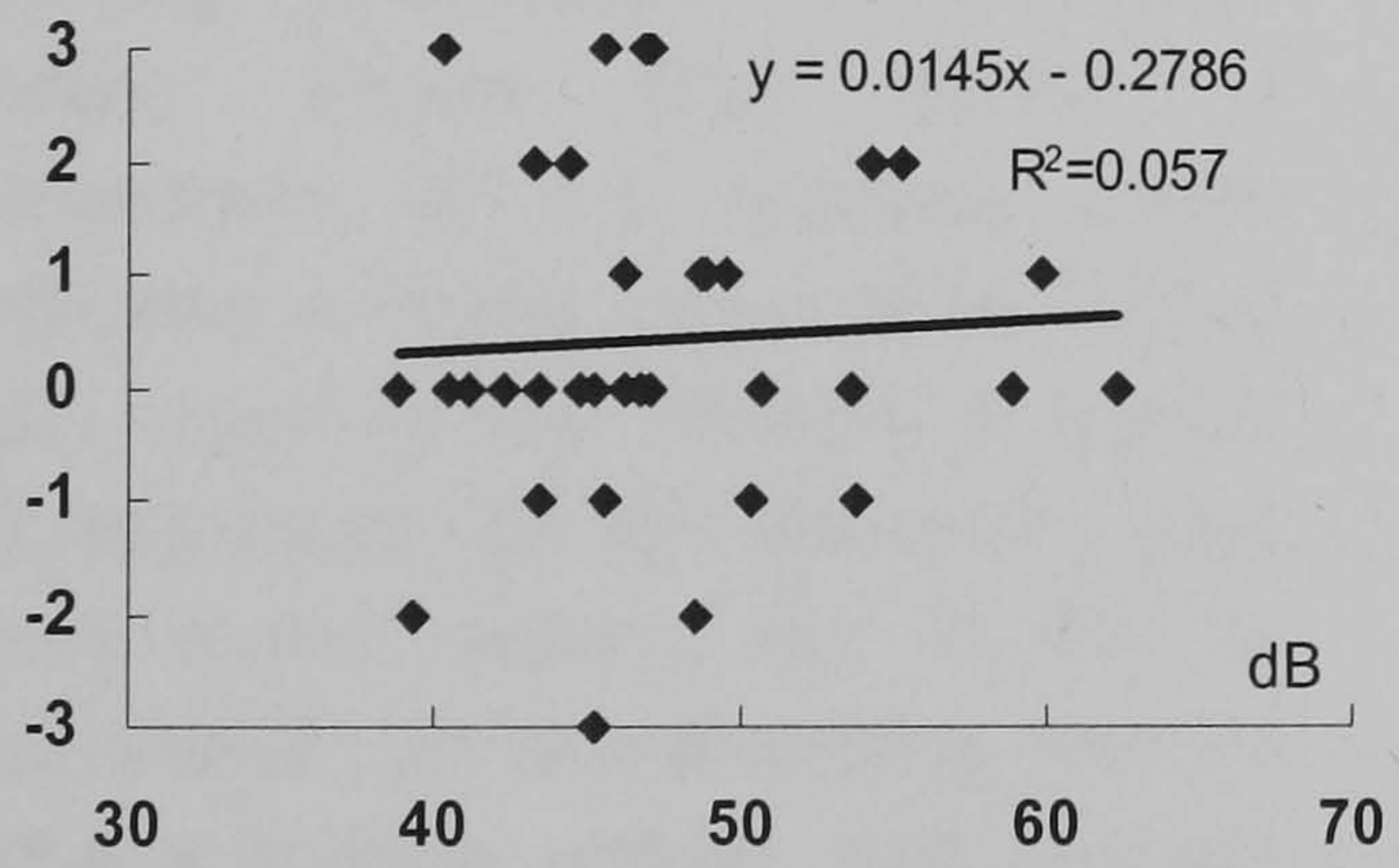


Figure 6.41 Relationship of perception and sound level (ICOSS)

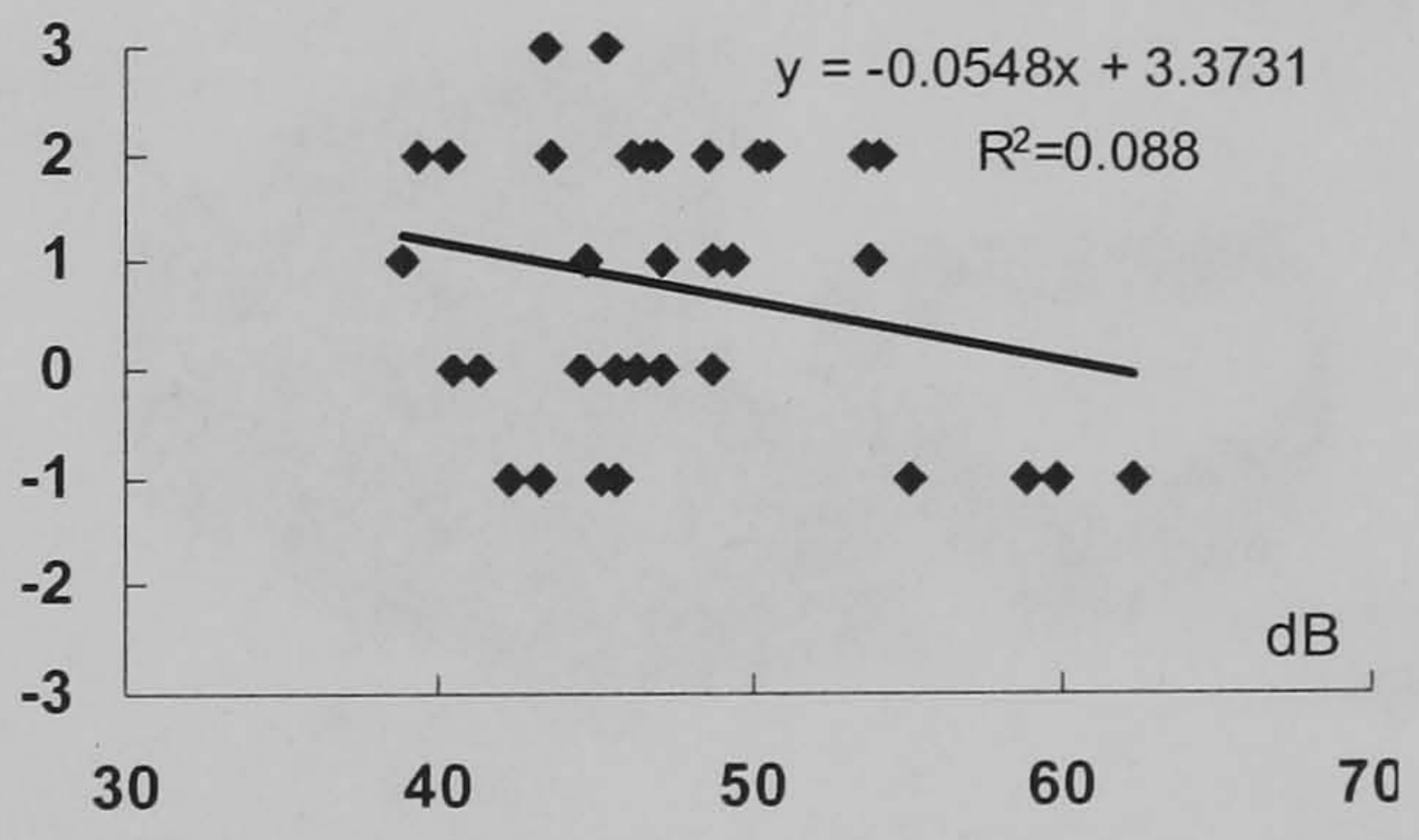


Figure 6.42 Relationship of satisfaction level and sound level (ICOSS)

The physical parameters, occupant perceptions and satisfaction levels with regard to thermal, visual and acoustic aspects are summarized in Table 6.8 for comparison purposes. In general, the average temperature (23.4°C) and illuminance (514.3lux) are both within the comfort criteria while the noise level (47.6dB) is a little high. It is reasonable to see the acoustic environment with the highest proportion of dissatisfied responses (22.9%), followed by the thermal environment (17.2%). Meanwhile, the visual one gets the lowest proportion with only 8.6% of total dissatisfaction. But the responses on average give all three aspects positive perceptions. Among them, the visual has the highest value (0.6), approaching 'a little bright', followed by the acoustic (0.4), which is between 'neutral' and 'a little quiet'. The lowest one is for the thermal environment, which is just above the 'neutral' at a value of 0.2. Accordingly, their comfort levels are positive as well, with the visual being highest (1.1), then the thermal (1.0). The acoustic is the lowest in rank order but still with the 0.8 that approaches to 'a little satisfied'.

Built environment	Average physical parameter	Average perception level	Average comfort level
Thermal	23.4°C	0.2	1.0
Visual	514.3 Lux	0.6	1.1
Acoustic	47.6 dB	0.4	0.8

Table 6.8 Comparison of average physical parameter, respondent perception and satisfaction level between thermal, visual and acoustic environment (ICOSS Building)

6.2.2.2 View Appreciation

5. Does the view outside affect your appreciation of this room??

A. Not at all B. hardly C A little D. Somewhat E. Very much

The main body of the ICOSS building is less than 18m high with 4 flours. It is located in the centre of the campus area and is surrounded by many other buildings (see Chapter Five). Although the field of view through the windows is not large, with just the sky and ordinary buildings and the open-plan design further limiting the occupant's decision to choose the seat toward window, the view still affects the occupant's appreciation of the working environment to a certain extent. Figure 6.42 shows a breakdown of this question which indicates a highly appreciative feeling with regard to this. Roughly a quarter of responses (23.5%) expresses their 'very much' opinion and 20.6% for 'somewhat'. An overwhelming majority have a positive altitude with average 3.1 preferences while one third 35.2% remainders show negative toward it.

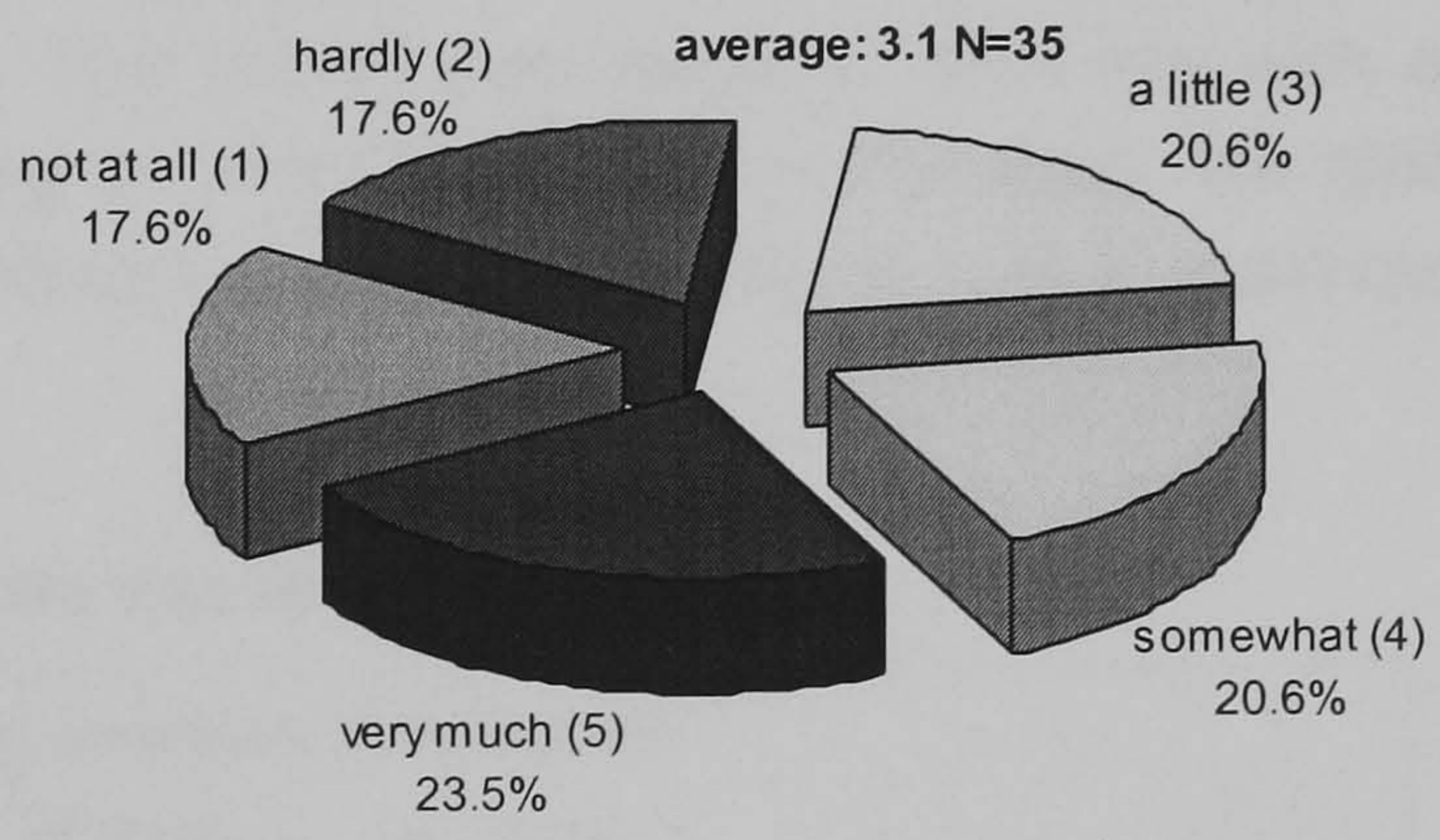


Figure 6.43 Breakdown of view appreciation (ICOSS Building)

6.2.2.3 Effect of Glare Disturbance on the Built Environment

4. Does the reflection on the computer screen affect your work due to discomfort glare?

A. Not at all B. hardly C A little D. Somewhat

E. Very much

The ICOSS building is a free-standing

building. The surrounding buildings do not have a great impact on it in terms of shadow cast. The working area near the north façade is found to experience no serious problems arising from glare. For the south one, due to the work stations being located 5 metres away from the glazing façade, they only experience direct radiation for a limited period of time when the solar altitude is low. Figure 6.44 shows the patterns for direct sunshine penetration on some typical days. It can be seen that from spring to autumn, the sun's penetration is not enough to reach working stations and produce glare disturbance, while in winter, especially in Dec, glare may be a direct cause of disturbance and lead to immediate discomfort and potential fatigue to the occupant.

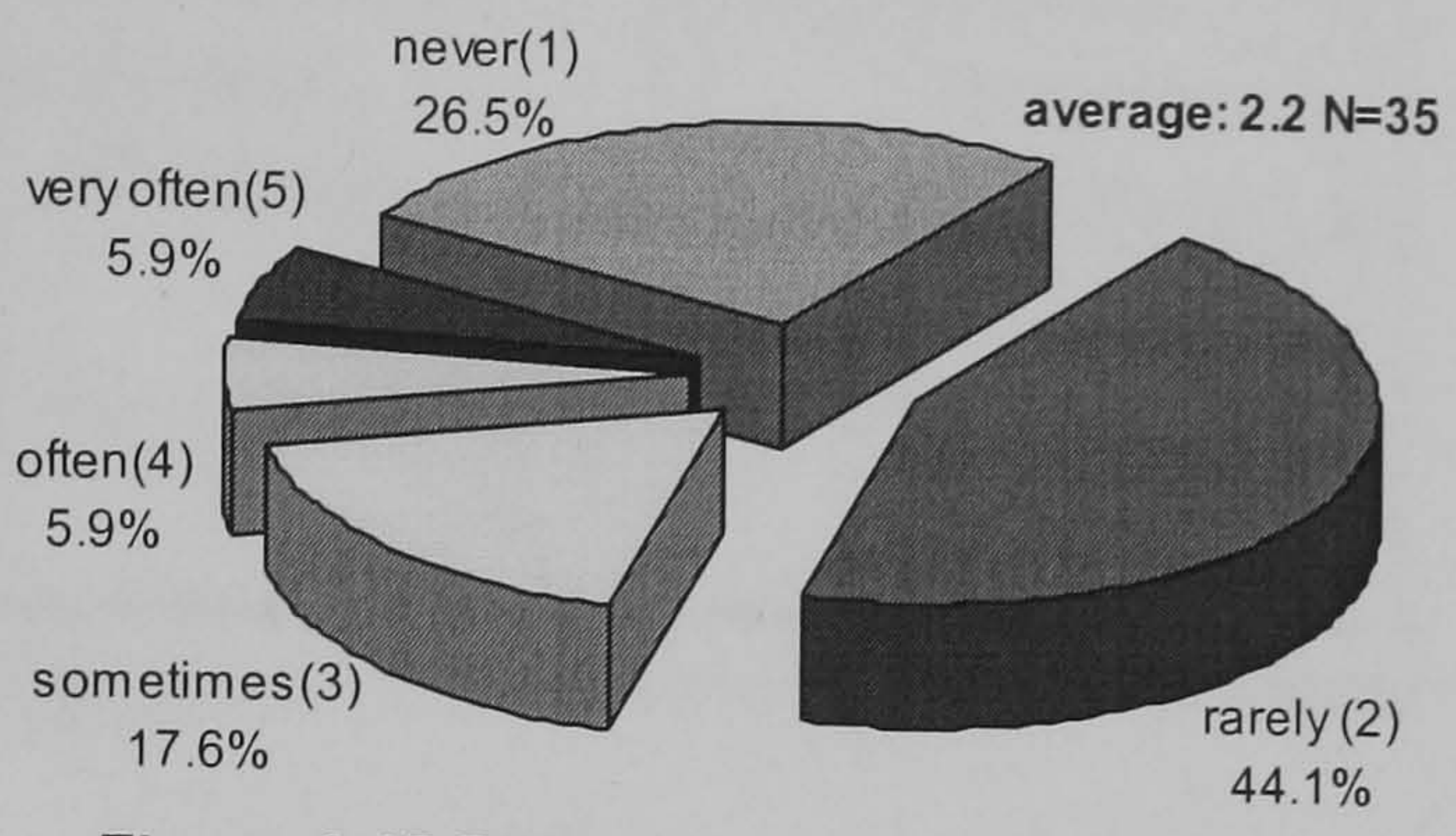


Figure 6.45 Breakdown of glare disturbance (ICOSS Building)

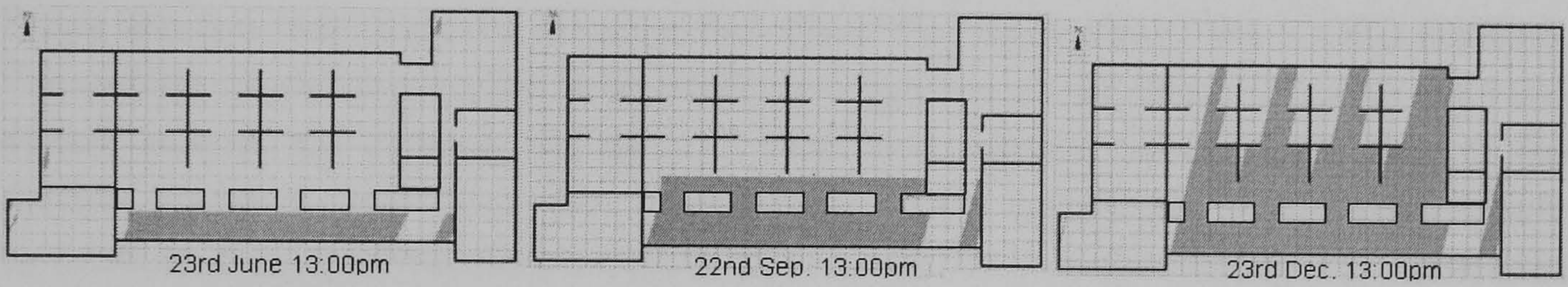


Figure 6. 44 Patterns of direct sunshine penetration on some typical days

Figure 6.45 indicates the glare does not have a high negative impact on the working environment. Only 5.9% of responses show this problem occurring 'very often', while another 5.9% feel it does happen 'often'. The biggest response is 'rarely', which takes up 44.1% of all responses while over a quarter (26.5%) are not affected by this at all. Generally, the glare that causes occupants' dissatisfaction occurs on some working stations and even then only sometimes. The overall perception is quite low with an average frequency level of 2.2, a little higher than 'rarely' (2). In this case, the glare problem can be helped by encouraging occupants to use the internal rolls to maximize their visual comfort and lighting quality.

6.2.2.4 Effect of Noise Disturbance from the Inside/Outside

7a. Generally, does the noise from the OUTSIDE affect your work in this room?

A. Very Often B. Often C. Sometimes D. Rarely E. Never

7b. Generally, does the noise from the INSIDE affect your work in this room?

A. Very Often B. Often C. Sometimes D. Rarely E. Never

In a real-life building, background noise always exists. When its noise level is fixed in a certain range, it cannot cause disturbance to the occupant. On the other hand, the sound level in an enclosed room is generally uniform throughout the source room. It is greatly reduced when it has to pass through walls, and which may, therefore, lower the background noise level thus having little effect on the receiver. However, in an open plan, the walls are a relatively insignificant part compared with sound attenuation in an enclosed room. The sound level from the source decreases with distance and thus the amount of intruding noise the other ones receive may not be below the background noise and cause discomfort. And in this case the partial-height barrier between the workstations can do only a little to reduce the noise level due to the diffraction effect (Figure 6.47) [15].

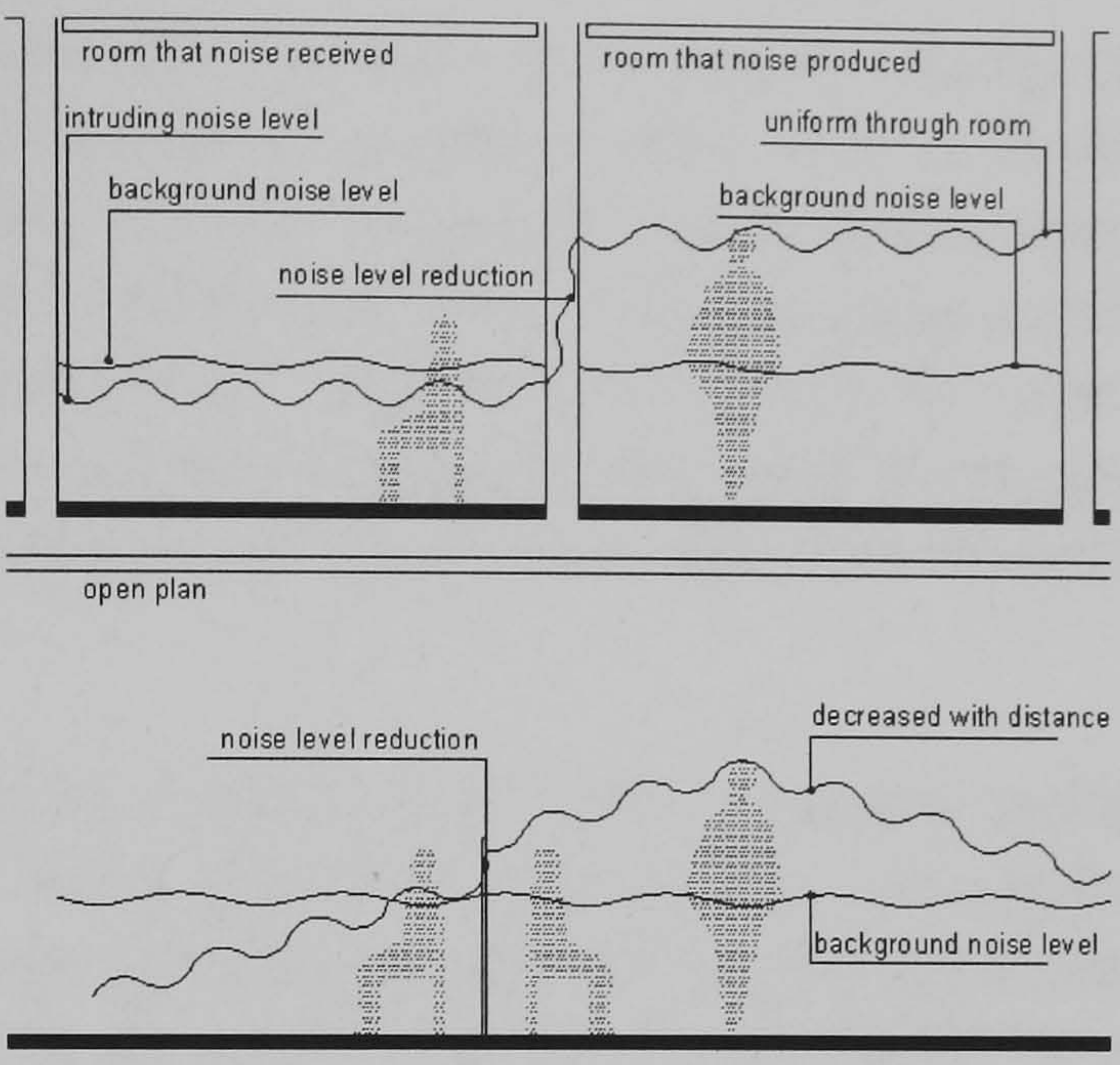


Figure 6.46 Comparison of noise transmission in an enclosed room and open-plan one

There are two main sources of noise that affect the occupants of the ICOSS Building. The outside noise sources are street traffic and building construction. Although the three streets around the building site are not busy, this building is just in the area of the Jessop Campus and thus the construction noise generated is an unavoidable by-product that is encountered during the survey time. Furthermore, the open-plan nature of the building means that the fact that many occupants are working together leads to potential acoustic problems. High density occupancy especially during the standard semester day inevitably produces a high level of noise inside the building and easily affects other occupants. Mainly due to these potential issues, the laboratory in this building has a quite noisy environment comparing with the acceptable noise level for a general office building that is specified and recommended.

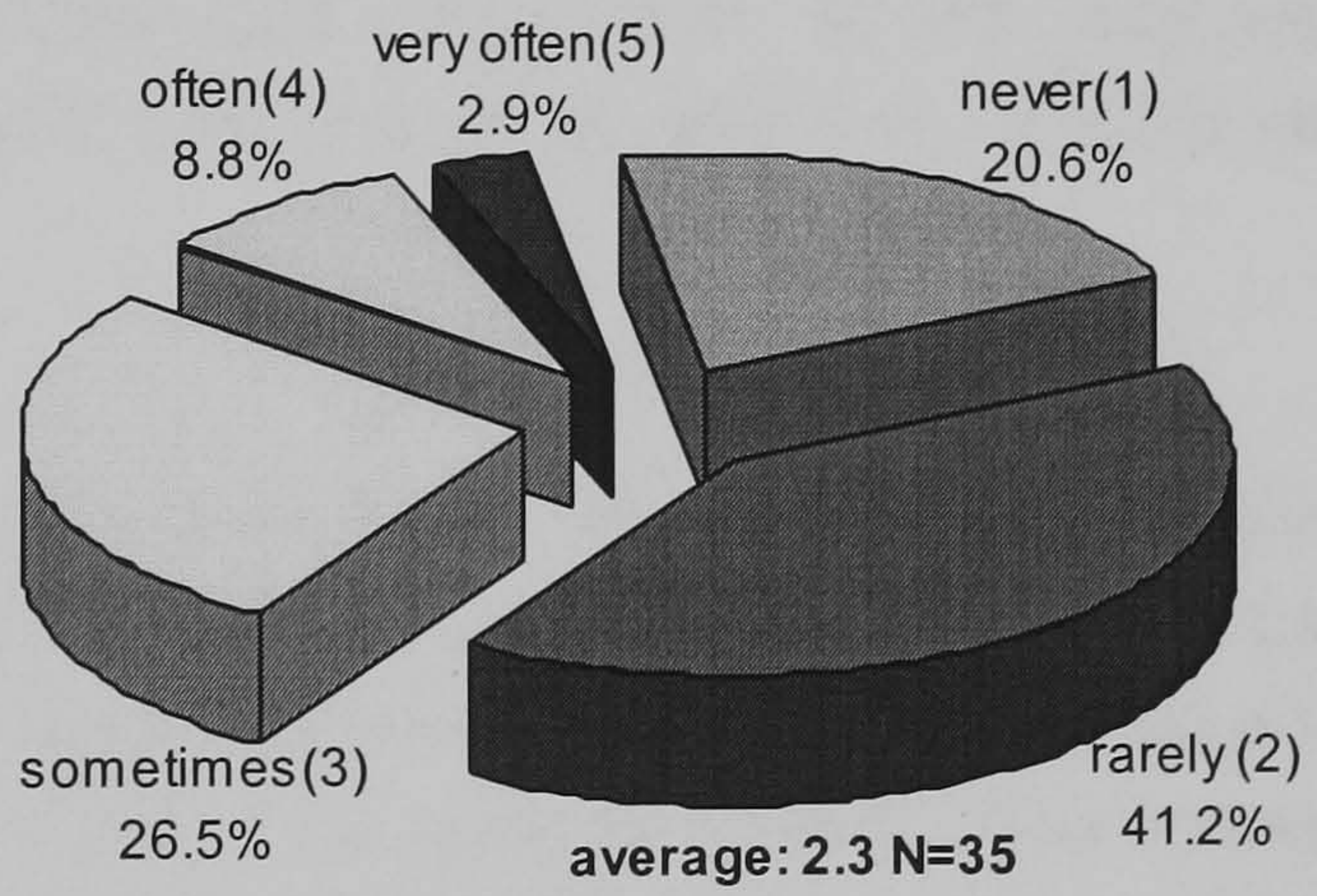


Figure 6.47 Breakdown of noise disturbance from the outside (ICOSS Building)

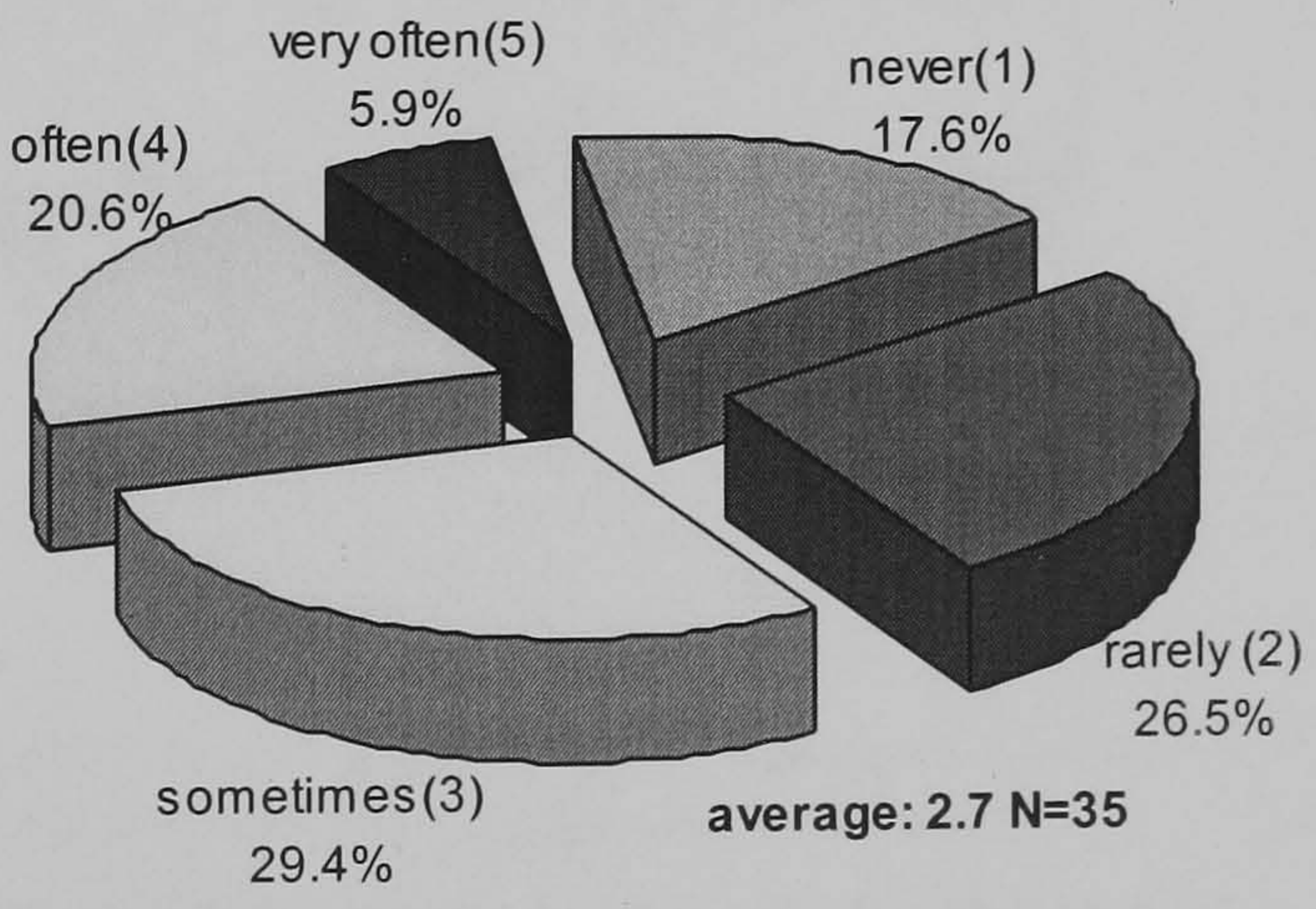


Figure 6.48 Breakdown of noise disturbance from the inside (ICOSS Building)

However, from the survey results, the noise problem isn't regarded as a serious one by the respondents. The breakdown of noise disturbance from the outside in Figure 6.47 shows that in total only 11.7% feel that noise affects their work either 'very often' (2.9%) or 'often' (8.8%). More than a quarter of responses (26.5%) hold a 'neutral' attitude that feels it 'sometimes' disturbs them. The biggest segment is accounted for by responses that indicate noise is not a problem with 41.2% for 'rarely' and 20.6% for 'never'. But when it comes to noise from the inside, the distribution alters a little with a higher disturbance frequency. 26.5% responses (14.8% increasing) feel the noise from the inside affects work with 5.9% for 'very often' and 20.6% for 'often', while 44.1% do not feel affected by the noise inside. Although it still holds the biggest segment, the proportion drops 17.7% comparing with the noise disturbance from the outside (Figure 6.48).

Generally, due to the fact that this building has a significant amount of exposed thermal mass, reverberation can be a problem. Some effort has been taken to reduce the potential for this by including soft furnishings and acoustic baffles. The average values are between 'rarely' and 'sometimes' with the figures for inside noise disturbance being a little higher than those for the outside: 2.7 for the inside and 2.3 for the outside.

6.2.2.5 Seasonal Perception of the Built Environment

The ICOSS Building is designed based on environmental considerations in terms of energy performance, and its active façade plays a very important role in the passive use of solar energy and air flow promotion. The main issues of concern are how environmental design considerations in general and ventilation considerations in particular affect the occupant's perception of the built environment. In this study, the analysis is focussed on four aspects: occupant response to temperature, humidity, air movement and illuminance.

Temperature

From the record of measurement, the building temperature maintains a high degree of stability. Figure 6.49 shows the average air temperature in a laboratory involved in the survey from May/05 to Mar/06. The outdoor temperature reached its maximum 30.4°C in June and the minimum on a Feb night (-2.7°C). The span of peak-to-peak interior temperature remained between 18.1 and 26.3°C, less than 8°C variation, which clearly resulted in a rather distinctive environment.

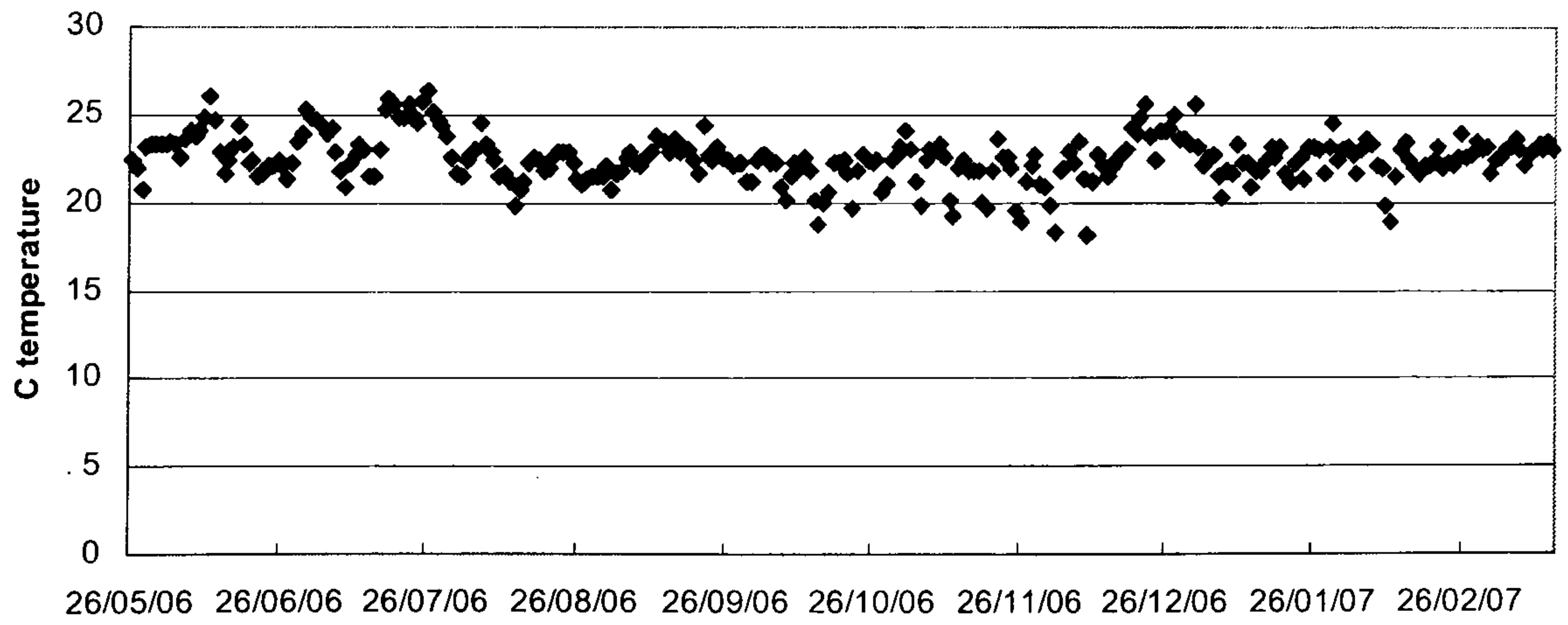


Figure 6. 49 Average air temperature in a laboratory from May/06 to Mar/07 (ICOSS Building)

Figure 6.50 shows the distribution of survey responses with regard to the temperature over four seasons. It can be seen that most of the responses hold a 'neutral' feeling toward the temperature. Of the four seasons, the transition period of time has the highest proportion for 'neutral' with 66.7% in spring and 65.2% in autumn. None of the responses feel 'very cold' or 'very hot' in spring and autumn. But a small group consider it is 'a little cold' and 'fairly hot' so that each has 16.7% distribution in spring. In autumn, apart from those who prefer 'neutral', the rest spreads from 'fairly cold' to 'fairly hot' with the responses who feel 'cold' a little higher than those who feel it to be 'hot' (21.7% vs. 13.0%). In summer, the perception of the 'neutral' part drops slightly to 57.1%.

Apart from a very small proportion (4.8%) who still feel 'a little cold', the rest of them consider it 'hot' (38.1%) with either 'a little hot', 'fairly hot' (14.3% each) or 'very hot' (9.5%). In winter, the situation is a little complicated. The 'neutral' part, although still occupying the biggest part (39.4%), drops to the lowest figure among the four seasons. The perception during winter is distributed everywhere from 'very cold' to 'very hot'. This can be explained to a large degree by the effect of cold air and solar radiation. When it is cold and overcast, the central heating levels and times may not meet individual needs. Cold radiation from the large glazing areas and air draughts further take away heat from the body thus intensifying the occupant's perception of a 'cold' winter. While on a sunny day, the low altitude of sun path may result in a large area of solar penetration. The occupant, therefore, is easily heated up by the radiation even though the surrounding air temperature is still low.

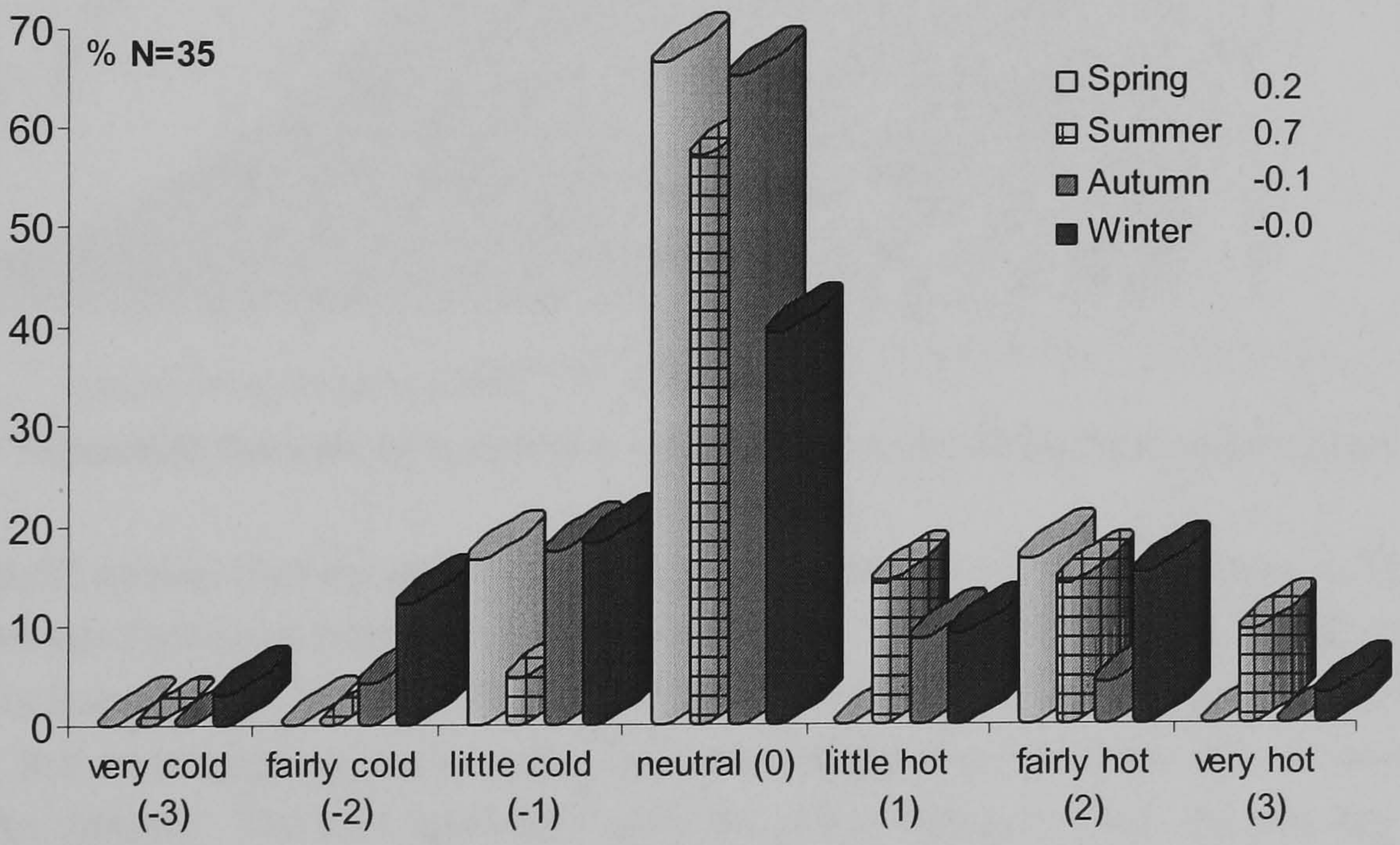


Figure 6.50 Distribution of respondent perception with regard to the air temperature in four seasons

Taking an overall view, the occupants in this building basically hold a neither 'cold' nor 'hot' attitude with an average value of 0.1 given to the temperature variation over the course of the whole year. Spring and summer have positive values while autumn and winter are negative neutral. Of the seasons summer approaches the level of 'a little hot'

(1) with a value of 0.7 on average. These results indicate that in summer the building tends to be on the warm side while in winter there is a slight tendency for the building to be cool - which is may be expect.

Humidity

The humidity inside the building has a closed relation with the temperature difference between the inside and the outside in this advanced natural ventilation building (see 6.2.1.1). Figure 6.51 presents the average air temperature and relative humidity outside seasonally and the air temperature as measured inside the building from 2006 to 07. Because the occupants and plants in this case have but little effect on increasing RH by means of evaporation and respiration, the temperature outside is low and changeable while on the inside it is high and stable leading to a reasonably dry indoor environment.

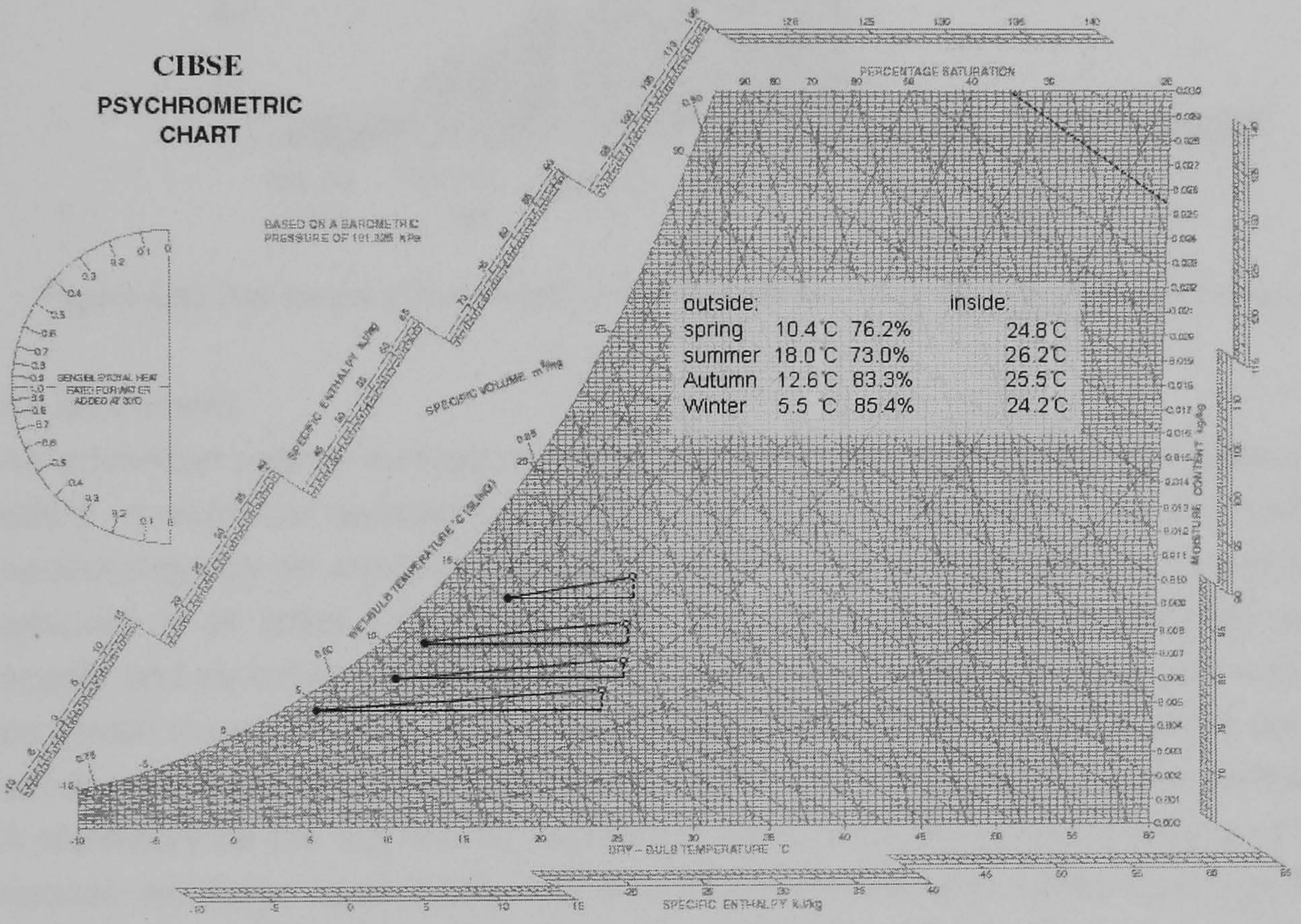


Figure 6.51 Seasonal air temperature and relative humidity in the Psychrometric Chart

Figure 6.52 shows that there is little difference between the four seasons as far as the occupant perception of humidity is concerned. The result confirms that the environment of this building is 'dry' because none of the responders feels 'sticky' in any season. Indeed, the vast majority seem quite able to tolerate the humidity with an average of 70.9% for 'neutral'. The rest don't feel 'very dry' either, although they do feel 'dry' at least to some extent. In total 10.3% feel 'fairly' dry and 18.7% feel 'a little' dry. The distribution does not show a distinct difference over the four seasons. The 'driest' perception occurs in winter, which is quite reasonable given the great air temperature difference between the inside and the outside, followed by autumn and summer. In this case, the season that is nearest to 'neutral' is spring with the lowest average 'dry' perception (24.0%). Generally, the occupants of this building feel the environment to be 'neutral dry' in every season. The average value for all the responses from each of the four seasons is negative (-0.4), between 'neutral' (0) and 'a little dry' (-1). The perception of RH has a similar distribution pattern with the winter slightly higher (-0.5) and spring slightly lower (-0.3).

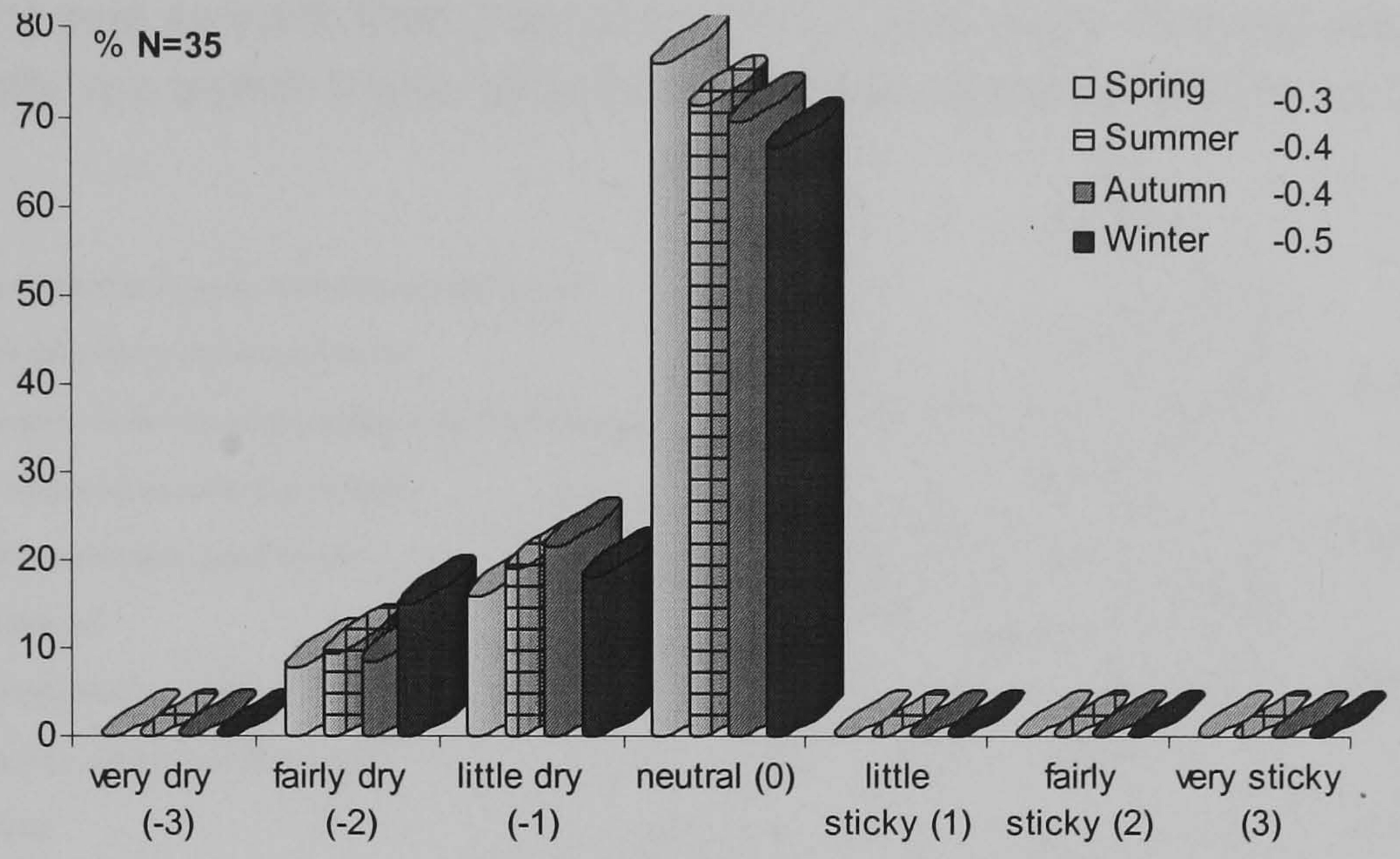


Figure 6.52 Distribution of respondent perception with regard to the relative humidity in four seasons

Air Movement

An advanced natural ventilation system encompasses the building that utilises the stack effect, in which air warmed by internal sources of heat promotes air flow and does not necessarily rely on wind pressure. By a control management system, an air flow can be assured at all times including at night. The intended ventilation strategy both for air supply and air exhaust are illustrated in Figure 6.53. Basically, here, cold winter air can be drawn in over the perimeter heating elements and in summer operable windows can enhance airflows and create air movement without disrupting the basic airflow strategy. A clerestory on the top floor is included in the design to provide a means of increasing natural ventilation to all floors. The clerestory windows offer further openings to vent the warm air out of the building during hot periods of time. This south-edge located stack, in principle, has many advantages: it assists buoyancy driven flow, has a more reliable ventilation performance, has terminations that are less susceptible to wind effects, enables the external façade to be sealed (in this case, a 100% area on the south and 70% on the north facade) and can, if necessary incorporate low-powered axial fans to encourage airflow under particularly adverse conditions.

One of the main issues of concern in this survey, therefore, is whether the system is capable of providing appropriate air movement and how this affects an occupant's perception of air movement in this building. Figure 6.54 shows a broad consistency over the four seasons. Apart from winter, the other seasons have a quite even proportion of 'neutral' results, with 72.7% in autumn, 66.7% in spring and 65.0% in summer. Only a small group considers it 'fairly draughty', 'fairly stuffy' and 'very stuffy' with each occupying less than 5% of total distribution. Quite a few responses do feel the built environment either 'a little draughty' (on average 11.7%) or 'a little stuffy' (on average 14.9%). Similar distribution with 'temperature' perception, the result of 'air movement' perception in winter also has the smallest 'neutral' part among four seasons which drops to 54.5%. The rest spreads from 'very draughty' to 'very stuffy'. Broadly the responses who feel 'stuffy' are slightly higher than those who feel 'draughty' (24.2% vs. 21.2%).

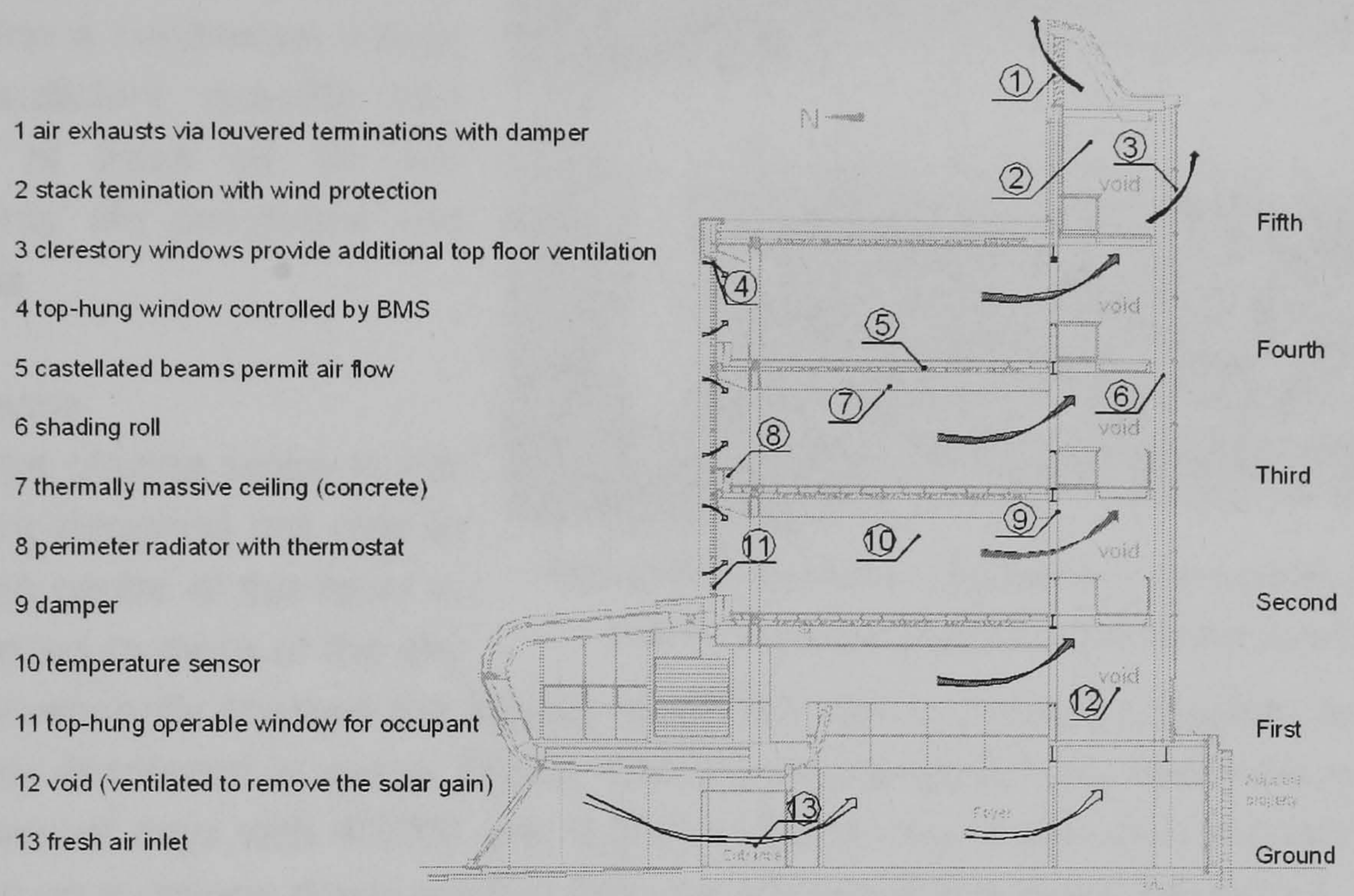


Figure 6.53 The ICOSS Building showing the natural ventilation strategies

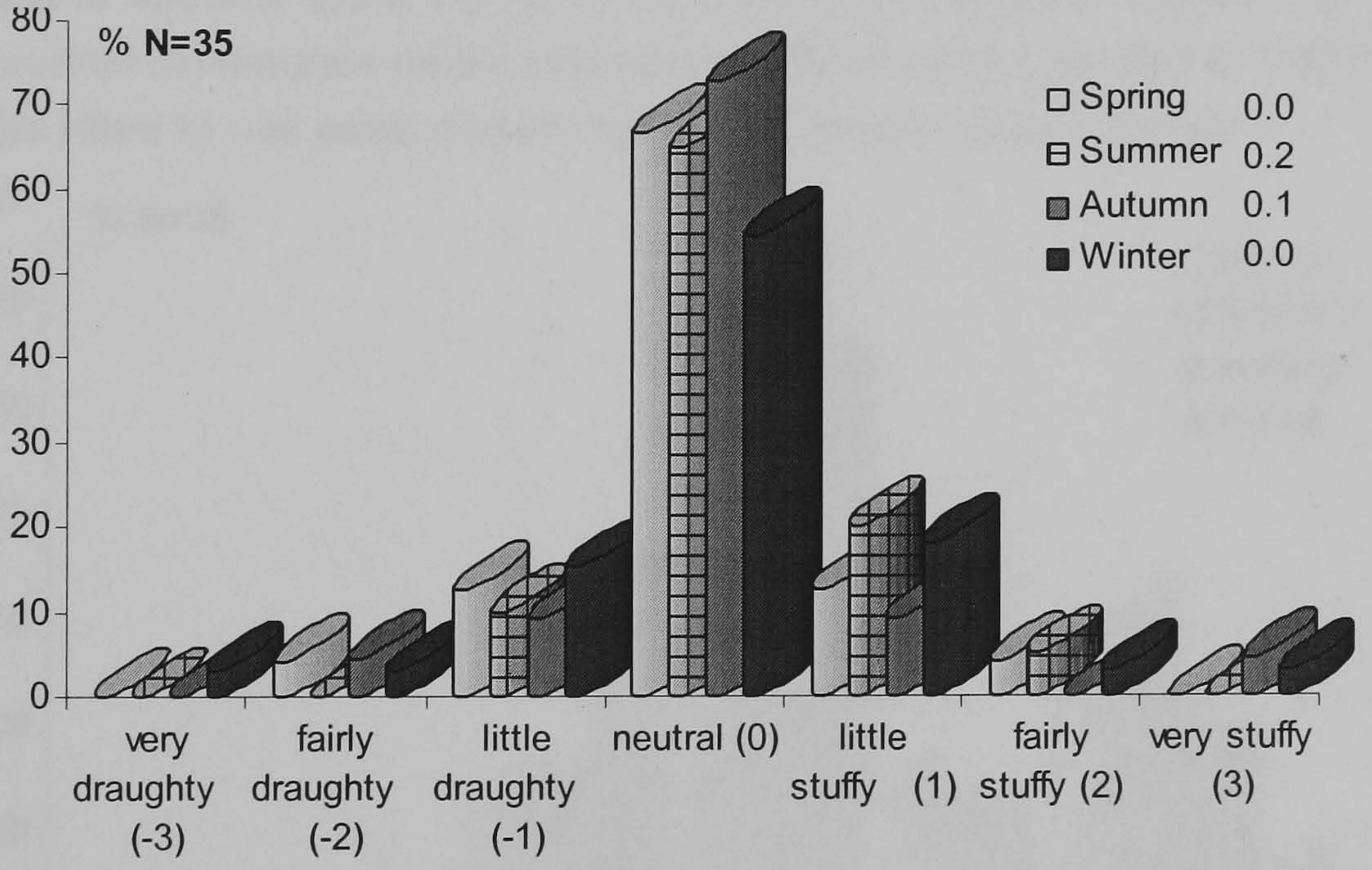


Figure 6.54 Distribution of respondent perception with regard to the air movement in four seasons

Overall, the occupants basically hold that it is neither 'draughty' nor 'stuffy' with an average 0.1 value given to the air movement variation over the whole year. When it comes to spring and winter, however, the respondent perception approaches nearest to 'neutral' (0), but in summer and autumn, it is 'neutral stuffy' with values of 0.1 and 0.2

respectively. These results indicate that in summer and autumn with a high indoor air temperature the building normally needs to have increased air velocity in order to provide a continuous supply of a sufficient quantity and quality of fresh air for the occupants' life processes and activities.

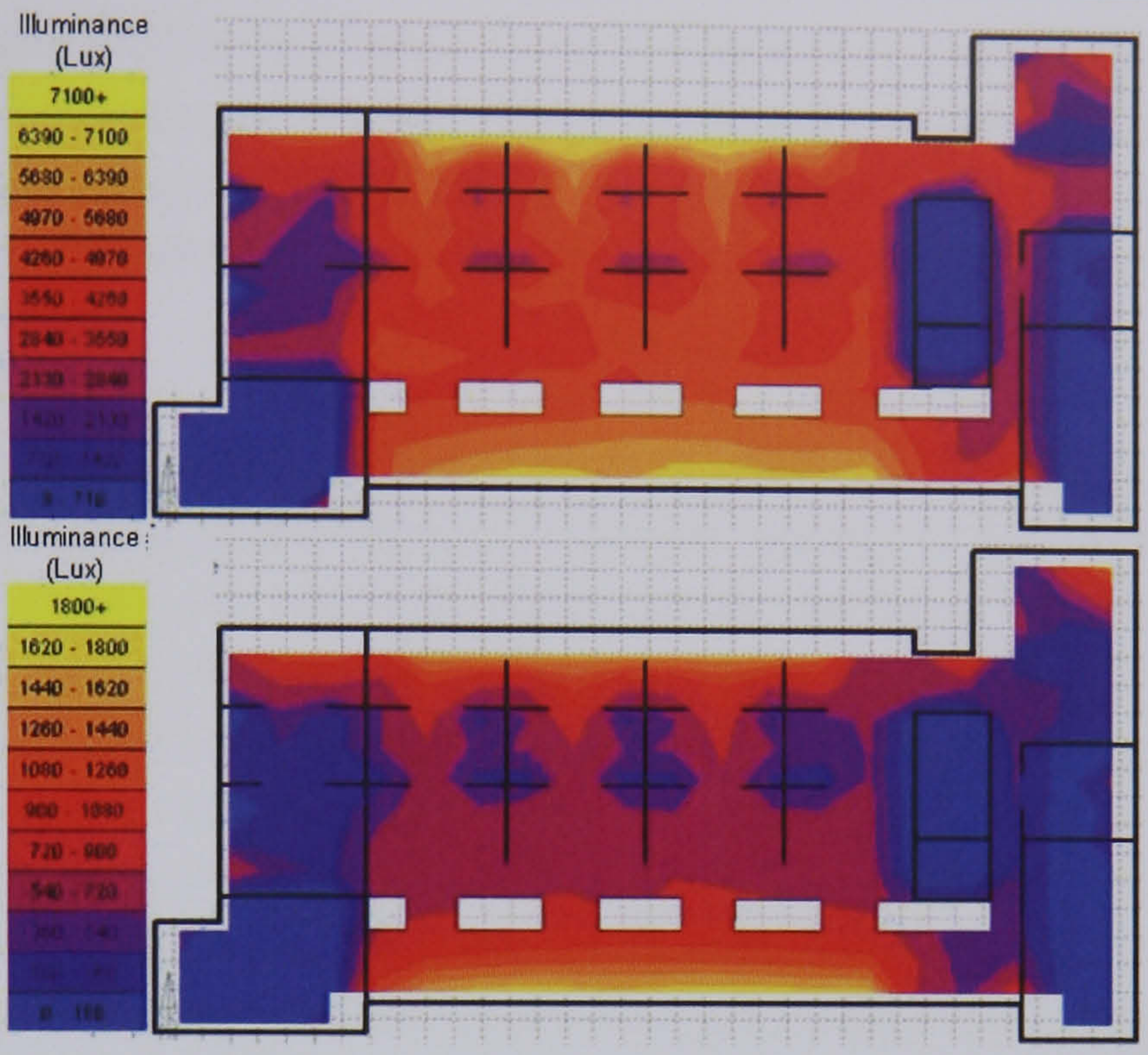


Figure 6.55 Illuminance distribution on the working plane in uniform (above) and overcast (below) sky conditions

Illuminance

The large glazing areas in this case are designed not only to allow the centre of the room to be exposed to more of the sky and consequently improve the lighting levels but also to allow the daylight to be more uniformly distributed in space. Figure 6.55 shows the daylighting level both on uniform and overcast days with 40,000 and 5,000lux design sky illuminance respectively. The variation on a uniform day is evident (the average value is 5 times difference). In the lab area, the lowest reaches 1900lux in the centre of the secure lab while the highest illuminance is 4800lux more with over 6700lux near the north façade. On an overcast day, the overall illuminance drops dramatically, fluctuating from 260 to 1500lux. Some of the spaces have to use extra electric lighting to create visual comfort.

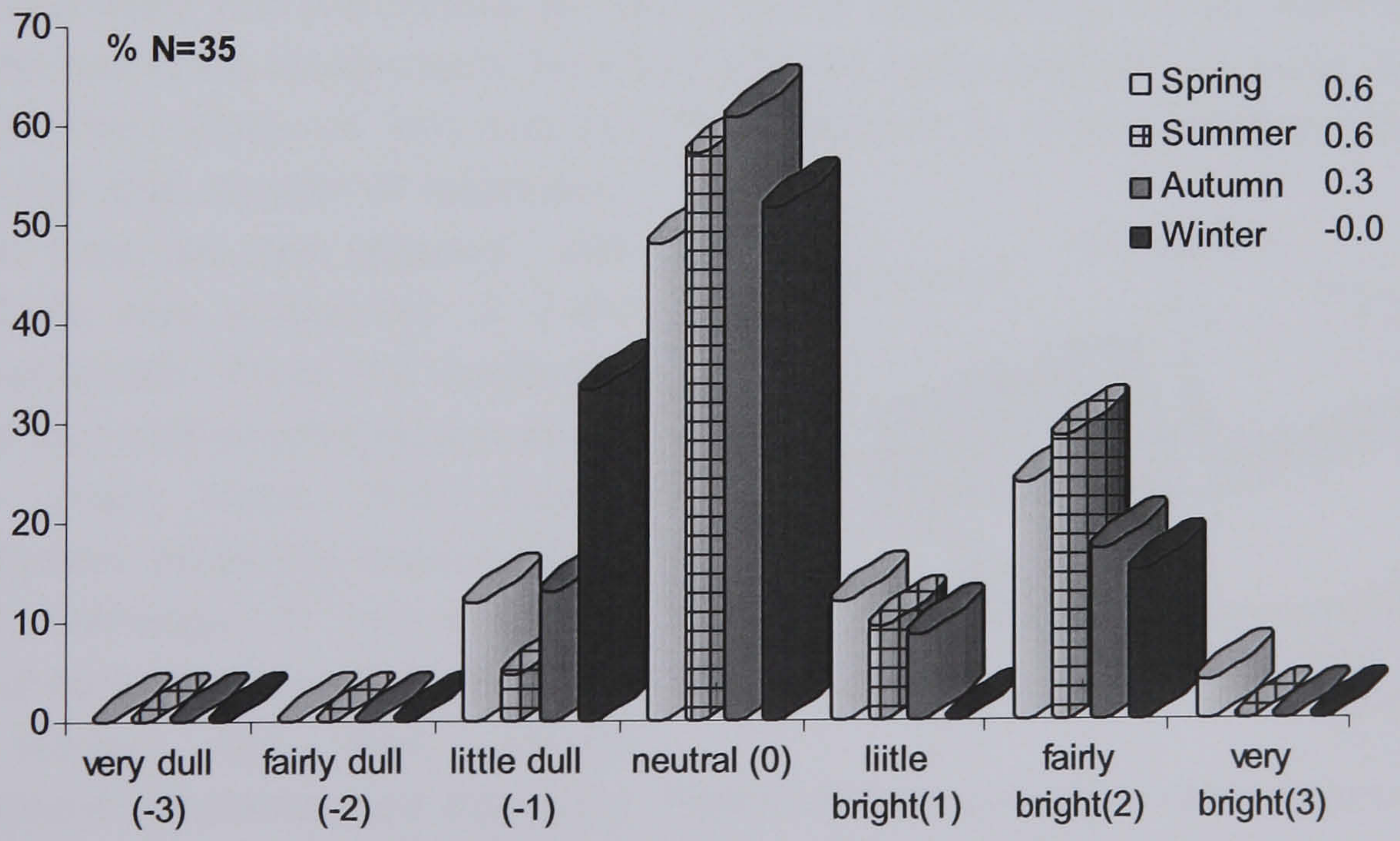


Figure 6.56 Distribution of respondent perception to the lighting level in four seasons

Still, the majority of responses feel 'neutral' towards the lighting level (Figure 6.56). In each of the four seasons, the responses for 'neutral' are slightly higher in summer and autumn than in spring and winter. The autumn has the maximum proportion with 60.9% distribution while the spring one has the minimum with 48.0%. Quite a lot response (on average 29.8%) consider the environment 'bright' while none of the responses feel either 'very dull' or 'fairly dull'.

On average there are 15.8% who consider the lighting level 'a little dull'. It has the highest ratio in winter (33.3%), followed by the transition season (spring 12.0% and autumn13.0%). Summer has the lowest with just 4.8%. This can be explained by the sun path variation over the whole year. The daytime in winter is much shorter than in summer. At the same time, the illuminance distribution is very different, even when the sky conditions are clear for both. On the other hand, the low solar altitude may result in high level illuminance due to direct sunlight penetration. This happens because from the figures it can be seen that there are another 15.2% of responses from those who feel it is 'fairly bright' in winter. When shading is required to prevent glare discomfort, the covering roll can produce an internal environment where the lighting level may not comply with current requirements. But in summer, these problems are not serious due to the high solar altitude and long daytime hours. Figure 6.43 compares the sun penetration area between the winter and summer time. It shows in summer that it has a much lower area of penetration than for the same time in winter. The long daytime also enhances the requirements for the lighting level, and, thus, in summer it is reasonable to have the minimum proportion for 'dull'.

6.2.2.6 Overall Satisfaction with the Built Environment

Overall (Figure 6.57), the occupant who works in the ICOSS is quite satisfied with the built environment with 0.9 satisfaction level that is approaching 'a little satisfied' (1). More than half of the respondents (58.8%) prefer the 'fairly satisfied' (1) rating. Another 17.6% may be considered 'very satisfied' (2) or 'neutral' (0). Only a small number, just 5.8% of the total number of responses, feel that they are 'not satisfied', with either 2.9% very dissatisfied or 2.9% fairly dissatisfied. From the feedback, the 'cold' and 'dull' environment in winter is the main issue that causes dissatisfaction. As for the overheating in summer, although it happens, the degree of control and predictability of the stack system can drive natural displacement ventilation and this quite adequately offers thermal comfort.

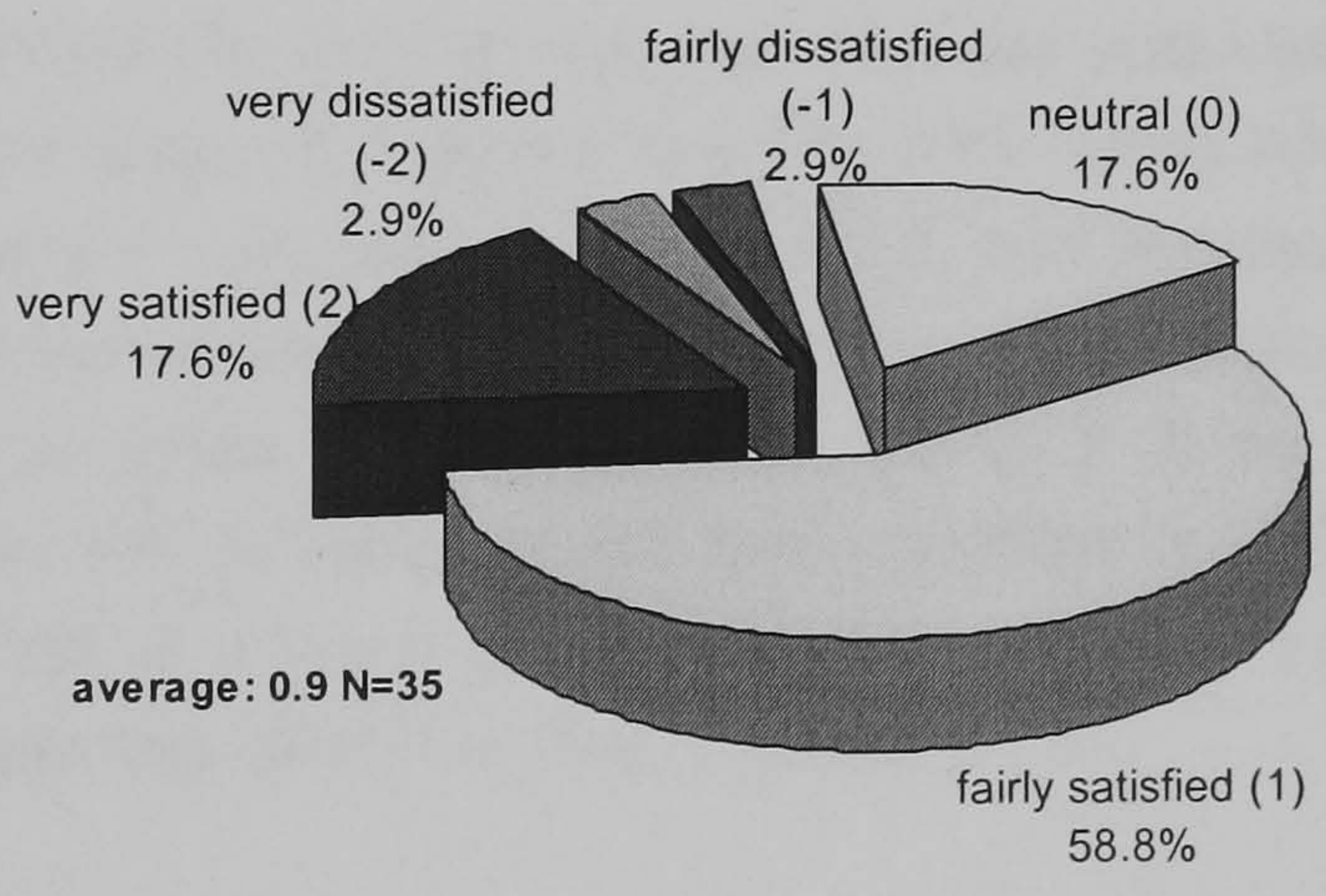


Figure 6.57 Breakdown of the overall satisfaction level from respondent (ICOSS Building)

6.3 Occupant Operation of Windows and Internal Shading Coverings

The preceding section has revealed occupant perception and response to the environment of the investigated buildings. The aim here is to show how occupants control the built environment. It concentrates on how they actually operate the windows and internal shading coverings, rather than on their own views. Several issues have to be addressed before the results are presented.

When it comes to the motivating forces for manual control, not only the unpredictable daily weather pattern, but also noise levels and/or air quality may, up to a certain point, all play an important role [16]. In fact, the individual occupant is far more sensitive than expected and many other complicating factors make a great contribution to behaviour aimed at controlling the environment. However, due to the limitations of time and human resources, not all of them can be discussed and analysed in this study. The short-term fluctuations of solar heat and sunlight are expected to be the cause of the adjustments made by the occupants to their environments in such actions as lowering blinds or opening windows. Therefore, air temperature and sunshine hours are two weather parameters addressed while others, such as wind speed and solar altitude are indicated in a general term. Hopefully, their impact on occupant operation will be explored in a more detailed way in future studies.

Also, an order 4 polynomial trendline is used to graphically display the trends in data and to analyse problems of prediction. In this case it illustrates the relationship between the opened window ratio, blind occlusion and main weather parameters. It is used because the data plotted has a clear fluctuation and the trendlines do not show big differences of more than an order of 4, which determines how many bends (hills and valleys) appear in the curve [17].

The concept of correlation is applied to validate the relationship between the operation of windows/blinds and all variables that affect occupant control. In probability theory and statistics, correlation is a value between 0 and ±1. It indicates the strength and direction of a linear relationship between two random variables. The interpretation of a correlation coefficient depends on the context and purposes. Generally, the nearer it is to 1 (positive) or -1 (negative), the stronger the link between these two variables is [18]. From the previous studies on manual control of window and blinds, the correlation is widely used in this area to analyse the influencing variables (see Chapter One).

6.3.1 Arts Tower

As Chapter Four has discussed, the Arts Tower occupancy is quite fixed in the standard semester day, although flexible the rest of the time. Figure 6.58 shows the results from the questionnaire survey about the occupancy situation when it comes to non-standard

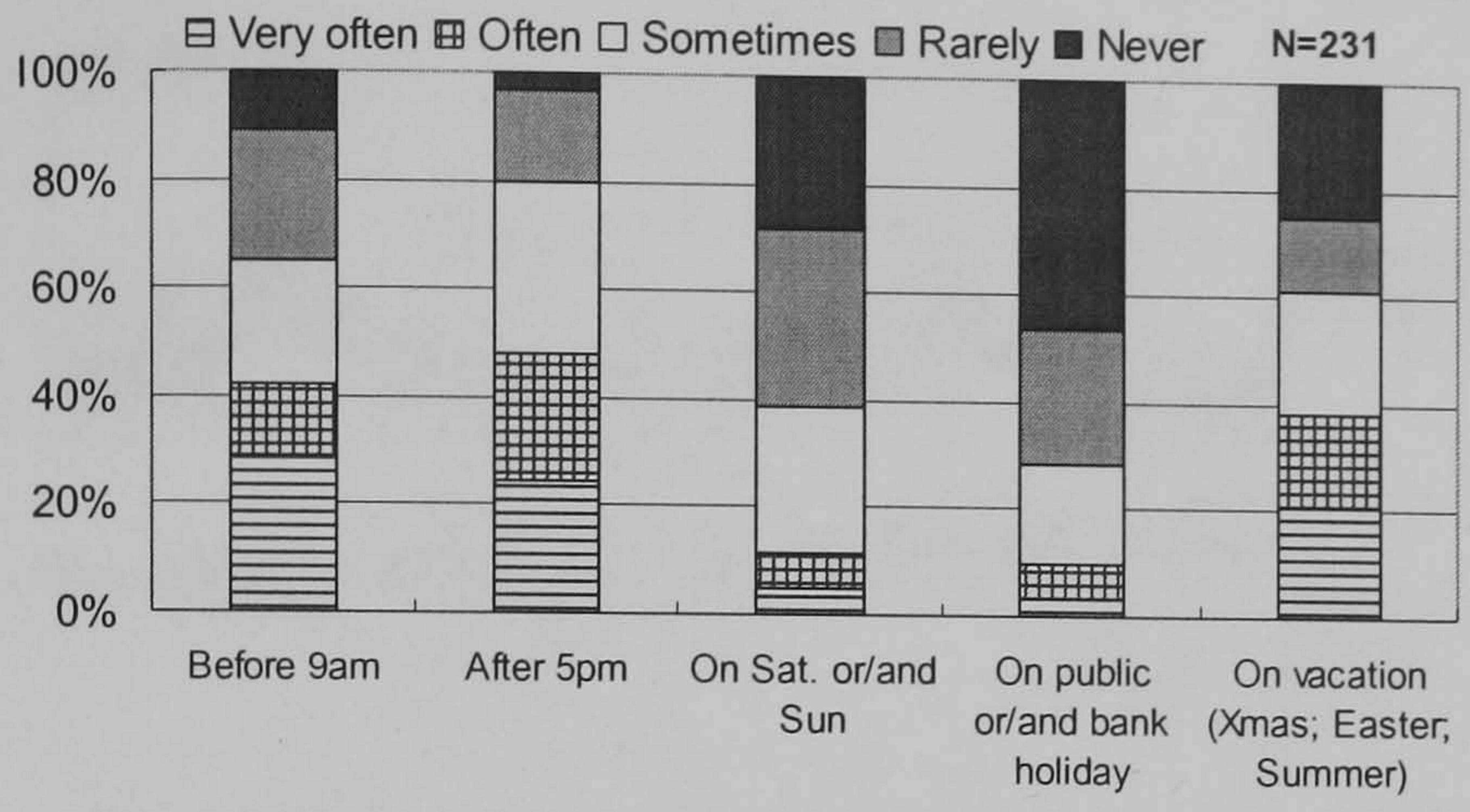


Figure 6.58 Occupancy situation with regard to the non-standard semester time and day (Arts Tower)

semester days and times. Only on weekends (Sat. and/or Sun.) and holidays (public and/or bank), do 'rarely' and 'never occupied' account for over half of the percentages with 61.3 and 71.6% respectively. This fact suggests that on these days, this building has quite a low occupancy density. However, when it comes to 'before 9am', 'after 5pm' and on vacations, the occupation situation is still very high. Apart from occupancy density, the nature of the rooms in the building is also considered as a primary factor possibly influencing user operation behaviour. Here it is divided according to three aspects (Figure 6.59).

- Indoor environment control is only of crucial interest while the building is occupied. Therefore room usage implies different occupancy patterns in term of user activity such as duration (long/short), density (high/low) etc.
- Room orientation determines what time and how long the amount of global radiation both solar and diffused is received. In this case, it implies the different environmental feature that occupants in this building experience.
- Room area, given the height, determines the internal surface to the volume ratio which has a great impact on both ventilation rate and daylight illuminance distribution. Here, it implies a different architectural feature.

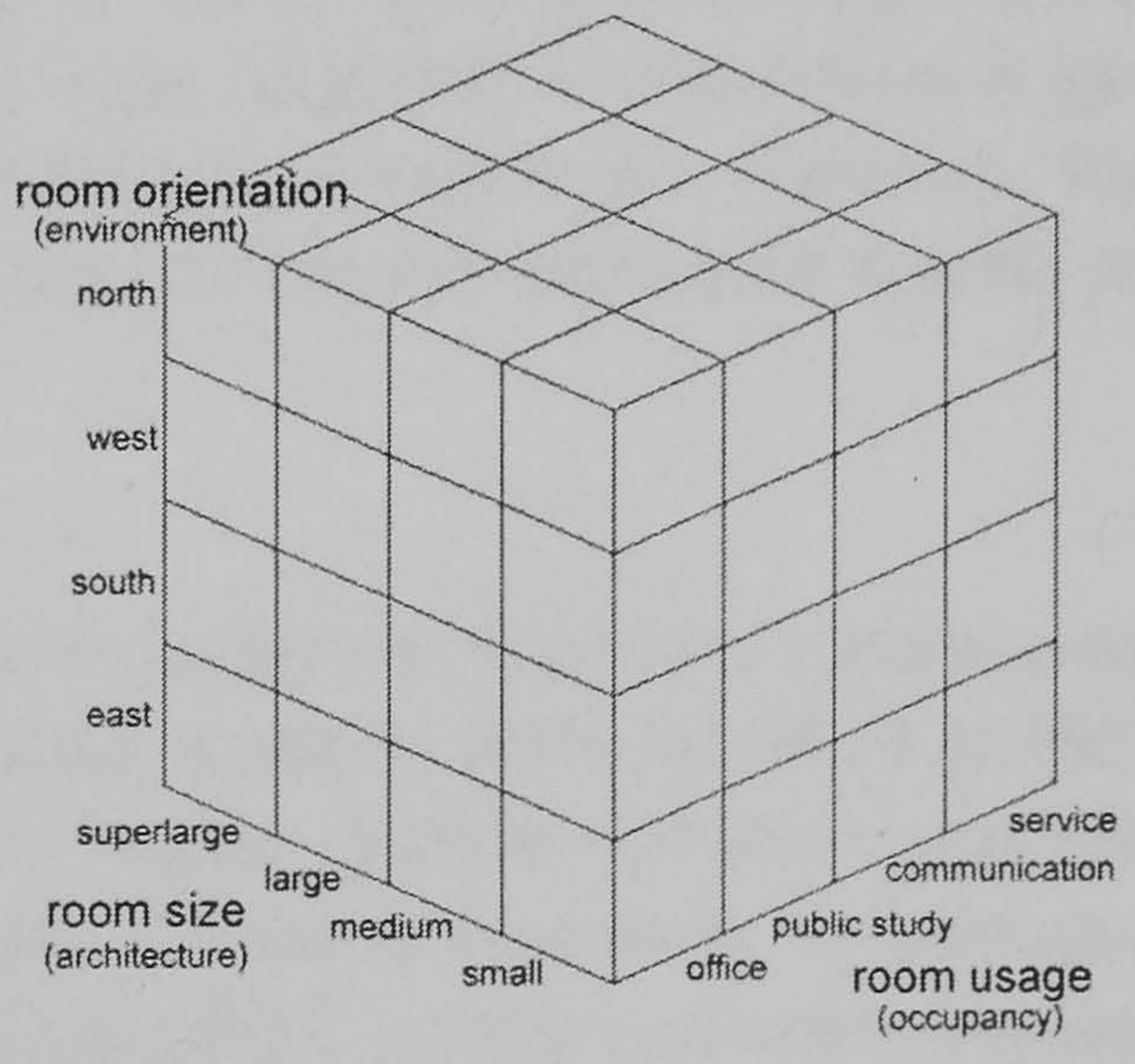


Figure 6.59 Main effects that influence the operation behaviour (Arts Tower)

This study is performed to test the hypothesis that was generated in Chapter One. Specifically, it considers the impact of these three aspects (main effects) and all combinations of each factor (interactions) between them. However, not all combinations can be discussed due to the limitations of time and human resources. Only the ones with high correlation coefficients are presented and analyzed and others, although also important, can only be discussed in future studies.

6.3.1.1 Weather Effect on Operation Based on the Whole Building

Although M.Rea [19] mentions *a more efficient procedure for extracting representative data concerning window blind utilization is desirable*, no such method or tool was found when this study was carried out. Unavoidably, analysis of the photographic data represented a large proportion of the time devoted, as all the positions of windows and blinds set by occupants from photographic slides were carefully input one by one, then examined for accuracy and rating consistency. The average occlusion and total number of windows opened were further calculated based on times and daily records. Positional information abstracted twice per day, was grouped in terms of 'am' and 'pm' for the convenience of analysis.

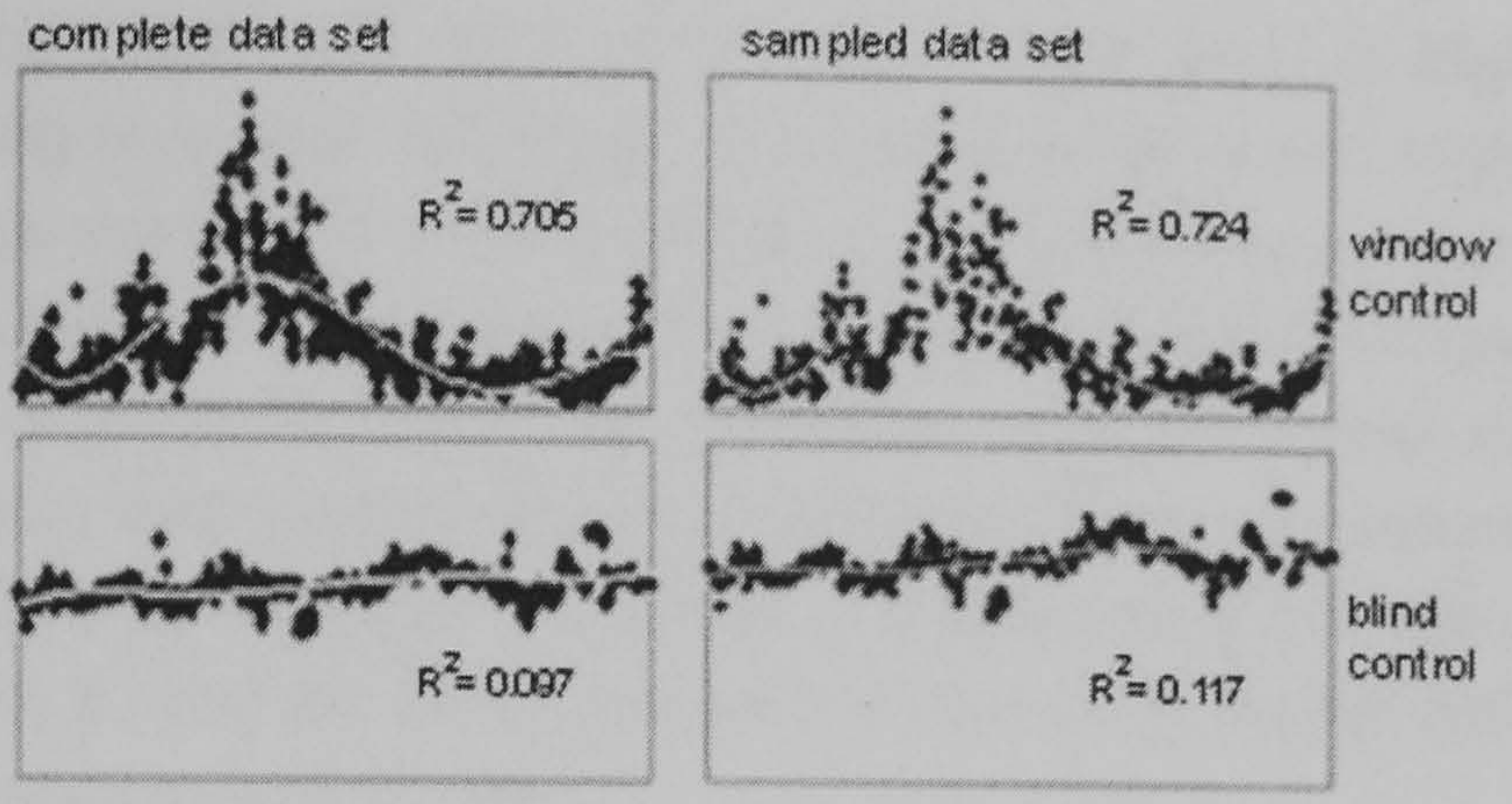


Figure 6.60 Comparison of the statistical results between the complete set and the sampled set (Arts Tower)

Data filtering

From Figure 6.58, it can be seen that the Arts Tower has a very low occupancy density on weekends and holidays, and, thus, the data without the records of these days were sampled. To see if the reduction in the sample size alters the interpretation of the data, two data sets, a sampled one and a complete one were subjected to regression analyse for comparison of the statistical results (Figure 6.60. The charts above are total opened-windows in a time series order going from Jan/05 to Apr/06. The correlation coefficients (R^2) in each chart correspond to the average outside temperature. Similarly, the charts below are average occlusion indices. R^2 in this case is related to sunshine hours at that time. Both of the values are higher in the sampled data set than in the complete one, which means that due to filtering those situations in which there is low occupancy density, the relationship between variables is strengthened. Therefore, the data are redefined without the weekend and holiday records and were used in order to do the further analysis.

Seasonal effects on window operation

A distinct change in user operation between seasons is found in Figure 6.61. It presents the monthly average of the total number of opened windows from Jan/05 to Apr/06. Usually the windows in the Arts Tower are in the 'closed' position no matter what the season is, only when required are they intermittently opened by occupants. On average, 100.1 windows were opened monthly, accounting for 6.2% of total operable windows (1620). Although this represents a small figure for the whole building, the monthly variation responds to the changing seasons and follows a noticeable pattern.

As expected, occupants tend to open fewer windows in winter. The year 2005 began with the lowest average number of opened windows (33.6) in Jan. and also lowest in the period winter I (47.1) which was the average value from Jan/05 to Feb/05. The low trend was maintained until early spring (Mar) with 45.3 on average. After that, a slight increase occurred during the spring time (Apr and May). A sudden increase was found in early summer (Jun) - 2.1 times more than in May (93.8 vs. 197.0). It reached the highest levels of all the surveyed months in Jul. There were around 276.6 open windows in this month, occupying 17.1% of the whole building's operable windows. It was not until Oct that the high trend began to drop steadily from 192.9 to 99.2. From late autumn (Nov/05) to the following year's early spring (Mar/06), it kept to a stable and low rate of 'opened' windows with averages of 52.9 in the period winter II and not until Apr/06 did it go up to 102.9 again, a similar pattern to that of 2005.

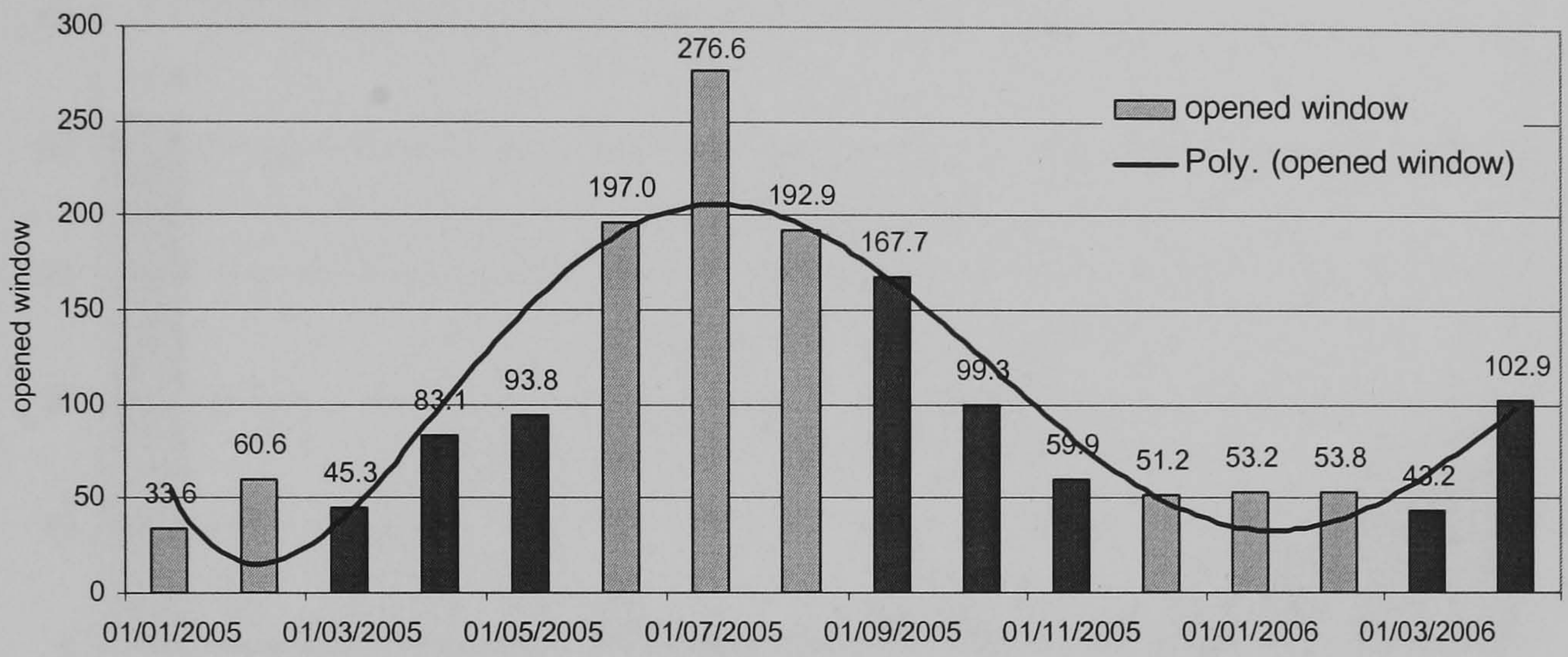


Figure 6.61 Monthly average opened window from Jan/05 to Apr/06 (Arts Tower)

Generally, the variation in occupant window operation was distinct and clear over the four different seasons. In summer 222.2 windows were opened, whereas in winter the figure dropped - about 4.4 times less. Spring and autumn could be looked at as transition periods of time. However, the 'opened window' line had a steep tendency from winter to summer, as demonstrated by the comparison with the relatively gentle gradient from summer to winter. This indicates occupants responding to the changing weather conditions and preferring more windows to be opened in autumn than in spring.

Seasonal effects on blind operation

It has to be noted that the venetian blind in the Arts Tower is the main way of affecting the amount of daylight into a room but not the only method employed. Some of the windows, although only a small number of the total distribution, are equipped with curtains as well. And it is not uncommon to see the windows that are obscured with display material and/or furniture thus further reducing the total area of glazing. These issues are considered and balanced with blind usage due to the similar impacts they have on the visual environment in terms of daylight control.

As Chapter Four mentioned, in the Arts Tower the positional information of the blinds is taken into 15 situations (4.6.3). In a general term, all these 15 blind situations can be observed on the same day in any specific season. Figure 6.62 is the distribution of the frequency at which blind occlusion is recorded. Statistically, 0.0% has the biggest part of the records with 42.9% occupation, which means the majority of blinds tend to be kept up and the windows are not obscured by blinds. 100.0% and 85.7% are followed with the second and third highest distribution. It is interesting to see three major occupations anchoring each end – the maximum and the minimum of the occlusion situations and they together occupy more than two third of the total record (69.8%). On average the occlusion level is approximately 39.8%, which suggests that instead of large areas of glazing, smaller ones may be preferred by occupants.

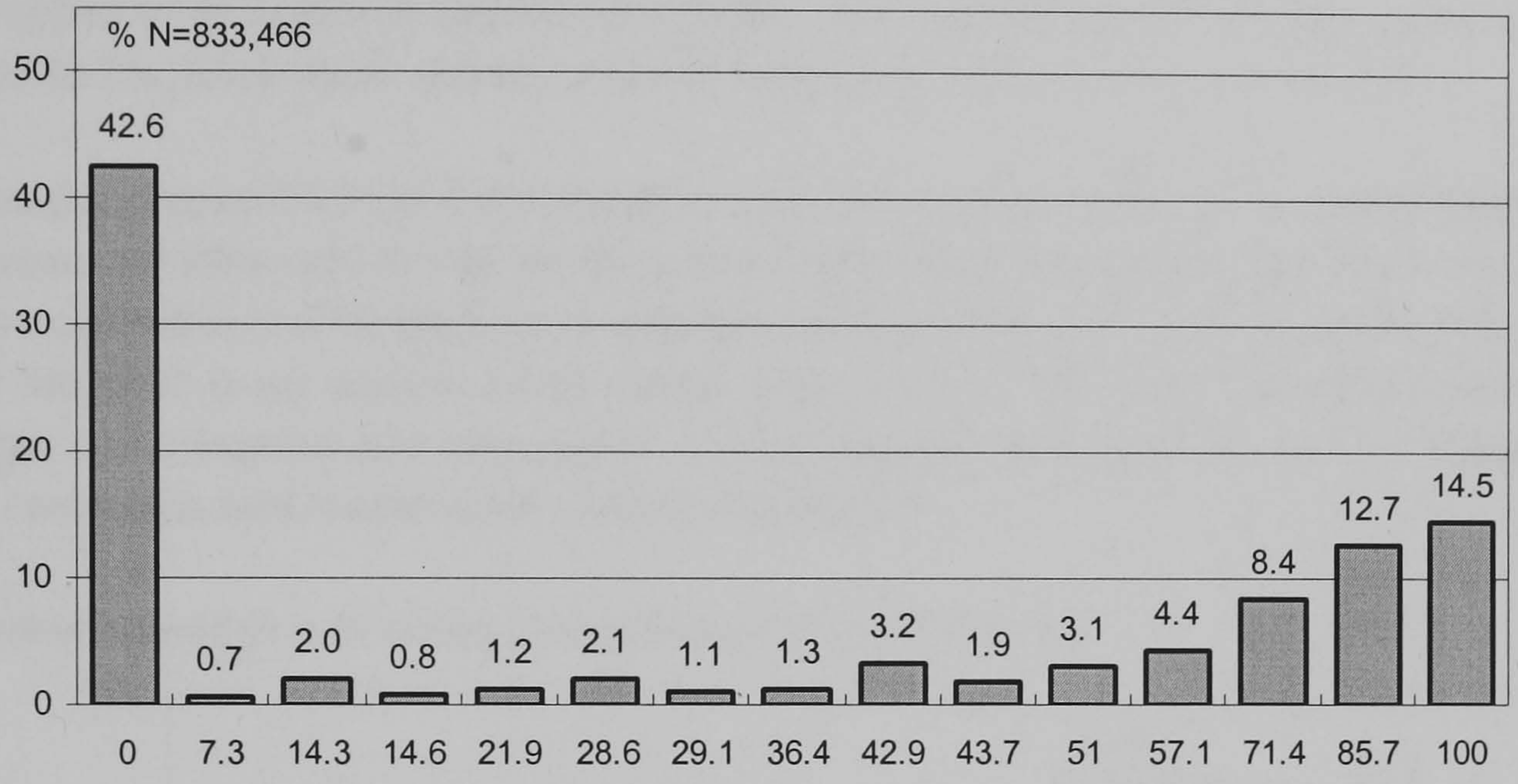


Figure 6.62 Distribution of the frequency at which blind occlusion index is recorded

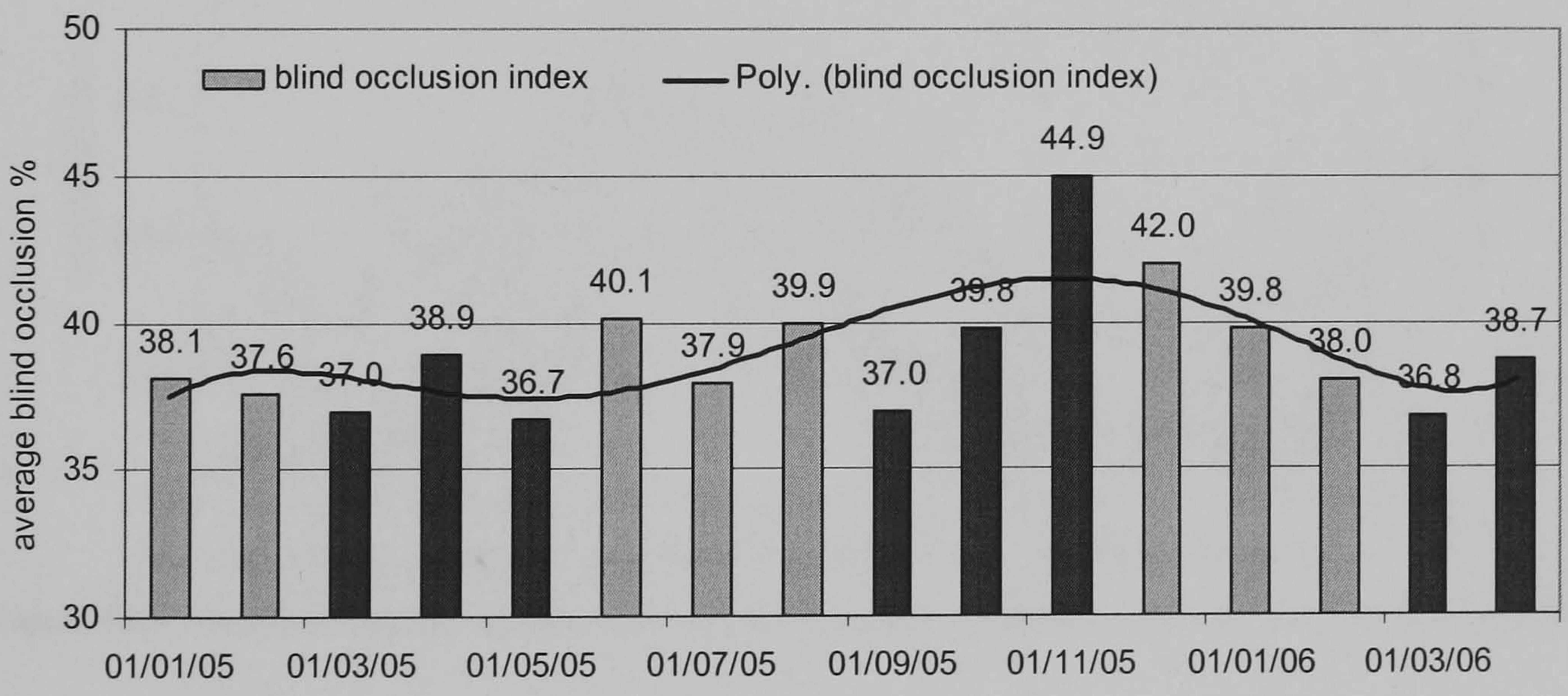


Figure 6.63 Monthly average blind occlusion index from Jan/05 to Apr/06 (Arts Tower)

More specifically, the seasonal variation, although only presenting a moderate change, has some discernable features (Figure 6.63). The average blind occlusion index for the winter I and the spring I were almost same (37.9% and 37.5%). It went up a little in the following summer with 39.3% on average. From autumn to winter, occlusion showed a clear increasing tendency with 43.5% on average. Especially when it came to Nov/05, occlusion reached its highest level with 44.9%. Considering that during the cold months, when low sun angles allow direct insolation deep into buildings, the resulting rise in air temperatures, although welcome from the heating point of view, with the presence of unresponsive central heating system it can also cause overheating and glare disturbance, and this is a phenomenon which matches with the results shown in Data Analysis I. Therefore, it is reasonable to see during this period of time the window having a relatively large rate of occlusion by the blind. After experiencing the highest levels, the blind was gradually raised up with a decrease of 1-2% occlusion and this allowed for of a stable and smooth decline (39.9% on average). In the period of winter II, it dropped to its lowest in Mar/06 with 36.9%, and not until Apr/06 did the occlusion go up to 38.7%, once again sharing a similar pattern to the one observed in 2005.

Generally, Figures 6.61 and 6.63 both to a certain extent present a periodical variation. However, window control has similar pattern with regard to position and slope over two years, while the one for the blind is slightly higher in 2006 than in 2005, which indicates that the blind is not always being raised when there is little sun. This feature can be further demonstrated and analysed in a more detailed way when analysis is related to the correlation with temperature and sunshine hours.

Window operation with outdoor temperature and wind speed

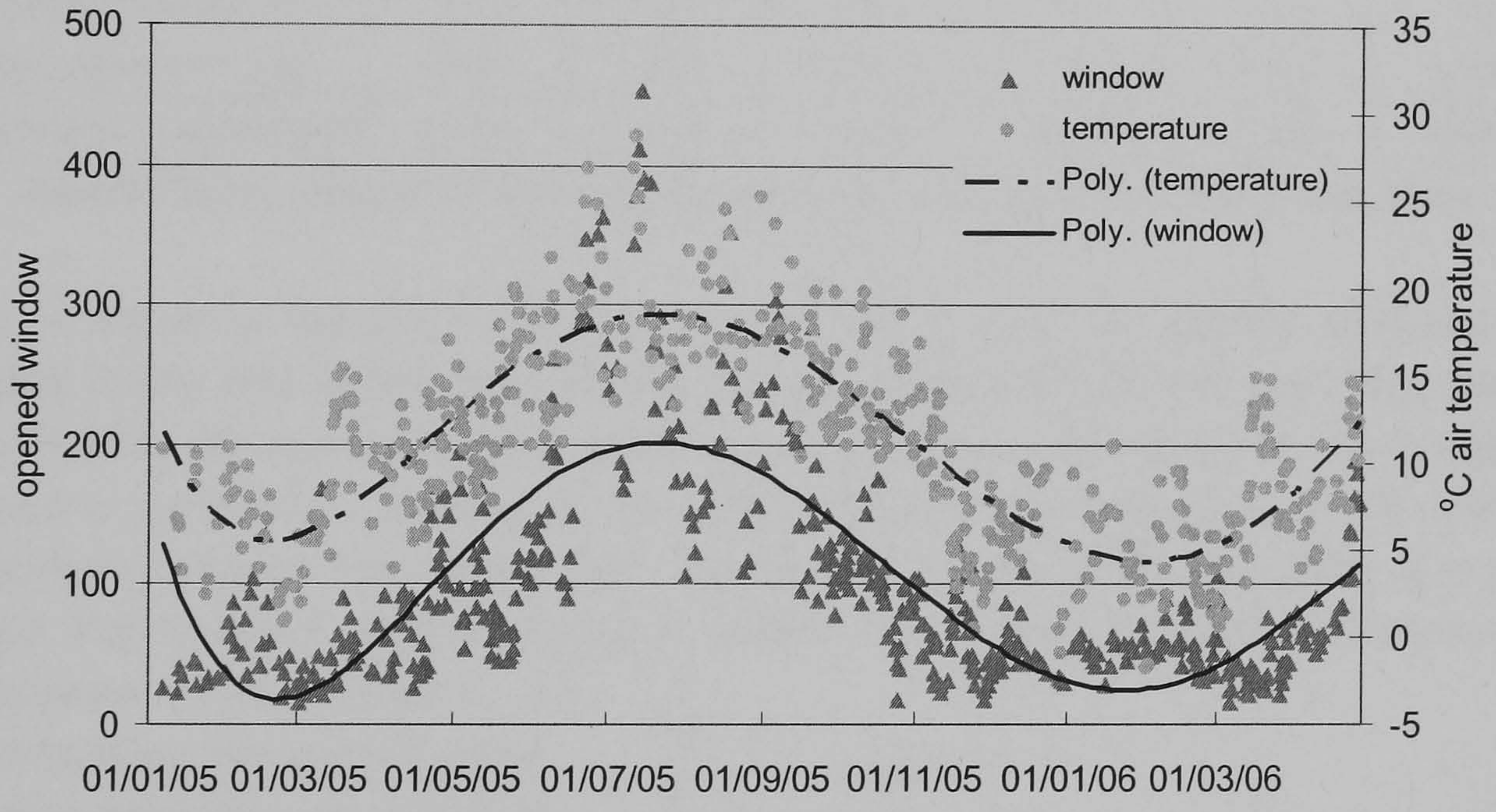


Figure 6.64 Average maximum temperature and total number of opened windows from Jan/05 to Apr/06

From Figure 6.64 it can be seen that the air temperature plays a very important role in determining the occupant's control of window opening as demonstrated by a very high correlation coefficient (0.724). It shows the relationship between average maximum temperature and the total number of opened windows from Jan/05 to Apr/06. The two trendlines follow a similar pattern: the peaks in the total of opened windows are strictly related to those of the outside temperatures. The daily drop or hike corresponds to every shift in temperature. Also the figure shows the two variations happening simultaneously with almost no time lag. It demonstrates that the impact that the short-term fluctuations of air temperature have on the indoor environment of the building is the cause of the window adjustments made by occupants.

Table 6.9 presents some basic values for air temperature and opened windows in terms of seasonal change. The year 2005 began with the lowest average for opened windows (45.5) and it had a low average temperature (5.9°C) as well. The temperature in Spring I increased 17.8% or by 5.1°C, while the 'window' value followed the tendency but instead showed a 6.1% rise from 45.5 to 74.7. In the summer from Jun to Aug, on reaching the highest temperature (28.7°C), a noticeable change happened with regard to opened windows. An average of 220.5 windows was opened, which amounted to 2.7 times more than in the spring and 4.3 times more than in the winter. The correlation gradually increased going from the cold to the hot season. In summer this showed a strong link between temperature and the occupant's control of windows, as demonstrated by the highest correlation coefficient (0.683).

	Winter I	Spring I	Summer	Autumn	Winter II	Spring II
Temperature avg. °C	5.9	11.0	18.2	12.2	5.4	8.5
Opened window max.	86	216	478	304	91	181
Opened window min.	19	16	90	18	6	15
Opened window avg.	45.5	74.7	220.5	102.0	51.8	64.8
Correlation coefficient	0.449	0.528	0.683	0.632	0.306	0.437

Table 6.9 Some values of air temperature and opened windows in terms of seasonal change

When it came to autumn, the temperature and number of opened windows both dropped 20.9% and 24.0% respectively, but the coefficient still remained high (0.632). From Dec/05, the number of opened windows returned to its low level. The correlation dropped to its lowest compared to the other seasons with a figure of 0.306. Through comparison between the results from Jan to Apr in both 2005 and 2006, it is to be noticed that opened window variation shares the same distribution patterns with temperature. This indicates a kind of building 'life style' in which occupant behaviour in this case is periodically repeated in correlation with the outside temperature conditions.

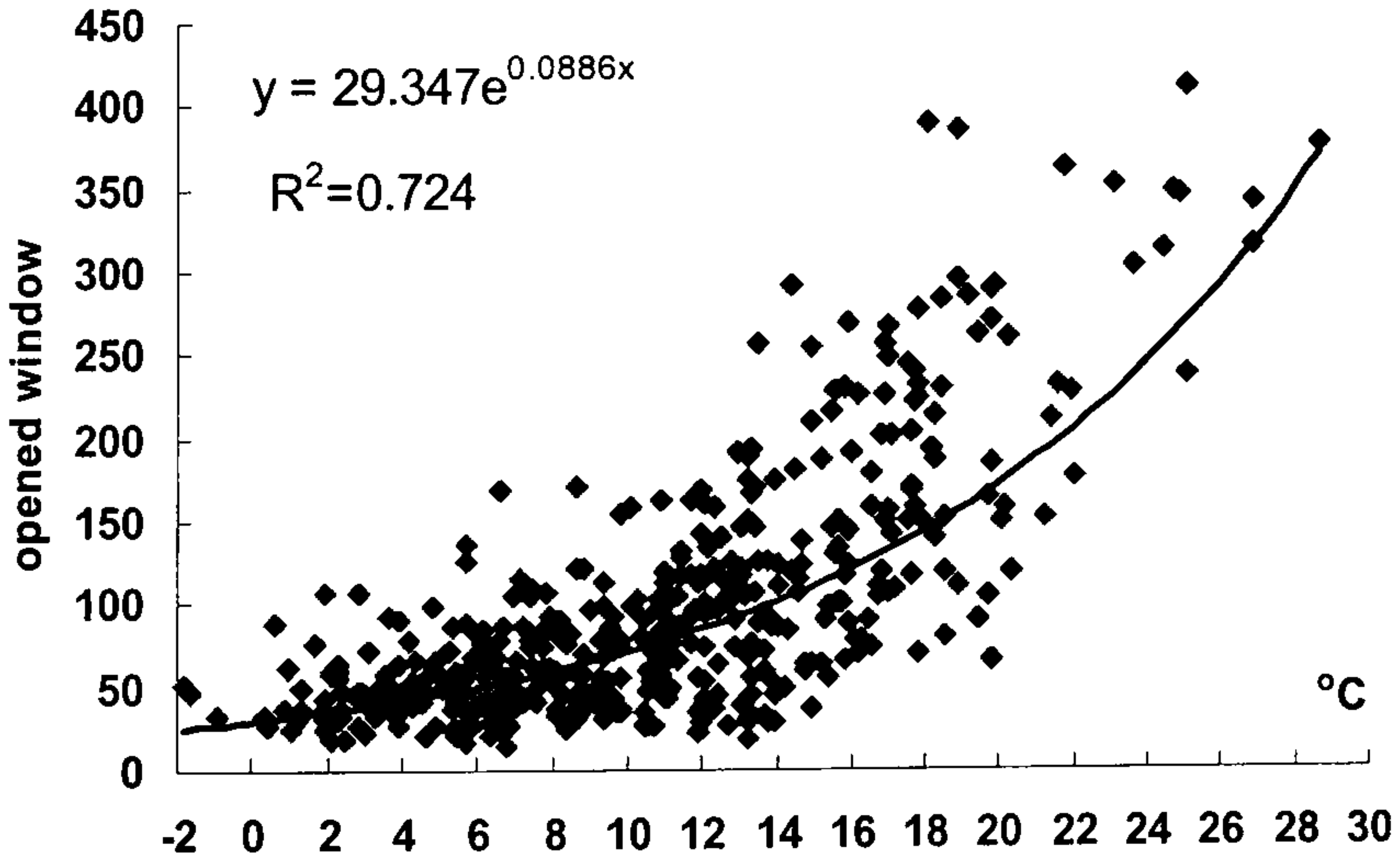


Figure 6.65 Correlation of the opened windows to outdoor temperature

The relationship between total opened windows and the outdoor temperature is analysed in greater detail in Figure 6.65. A strong accumulation of data points is found below 10°C. From 10 to 15°C, the impact of temperature on total opened windows becomes evident. A strong statistical spread is found from 15°C and at a temperature of 25°C, the highest value is reached. However, it must be noted that the results referring to the higher temperatures are observations specific to this study that cannot be generalised, since only a few days with average temperature over 22 °C.

Also it is found that wind speed, in this study is also related to the occupant's window control with the -0.279 R^2 value. High wind speed may results in lower opened windows value. At the same time, the high rise feature of this building strengths the negative impact of wind speed on the operation (Figure 6.66).

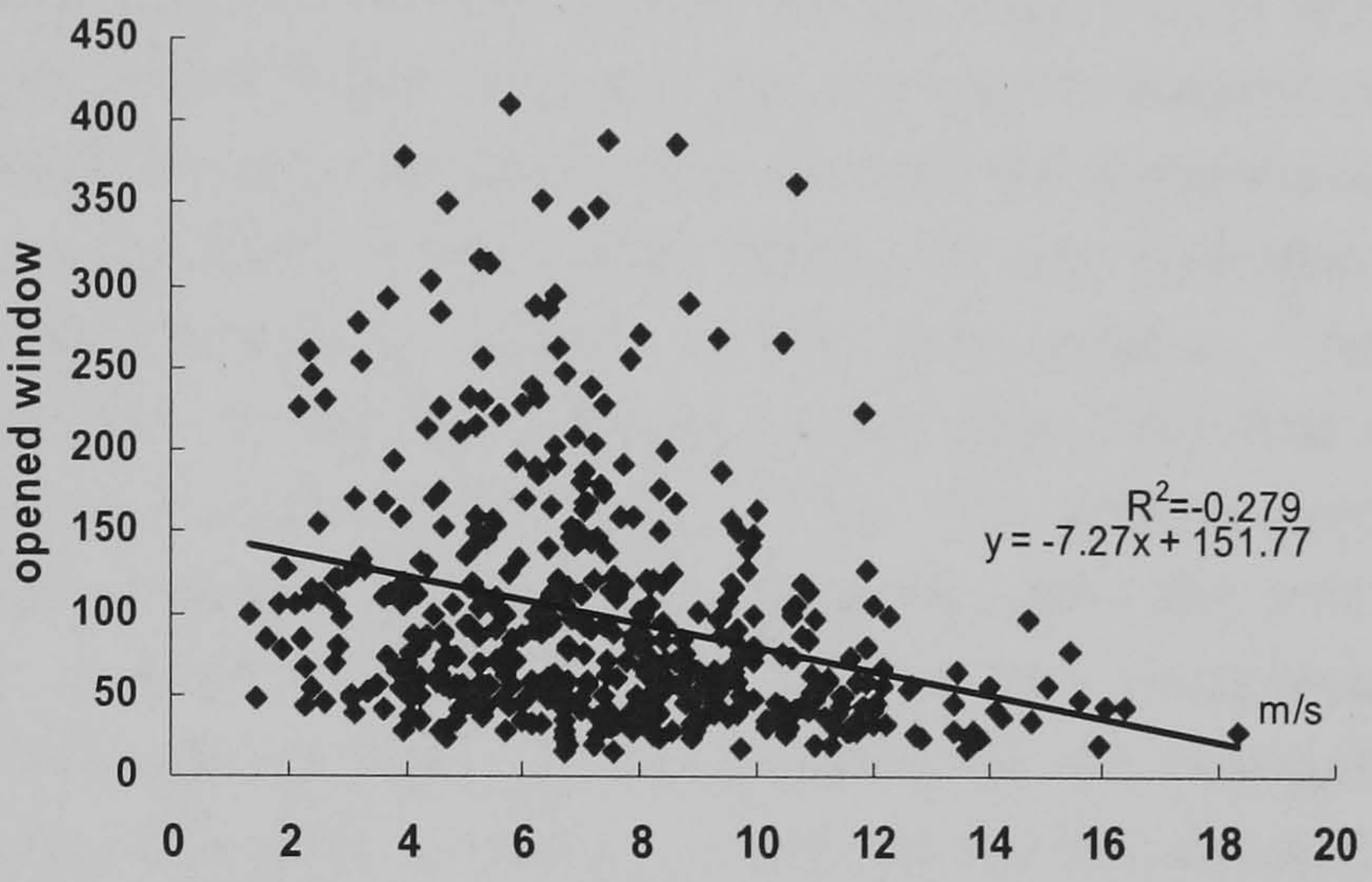


Figure 6.66 Correlation of the opened windows to wind speed

Blind operation with sunshine hours, solar angle and air temperature

From previous studies on occlusion by blinds, sky condition is the main issue acting as the motivating force for occupant control because when shading from the sun is required they are pulled down and the slats moved to the closed position and thus the average occlusion levels are increased in order to avoid sun glare and a very bright visual environment. In this section, although no specific sky illuminances are obtained from field measurement, sunshine hours, solar angle and air temperature are used because they are able to reflect the situation of sunlight and solar heat very well.

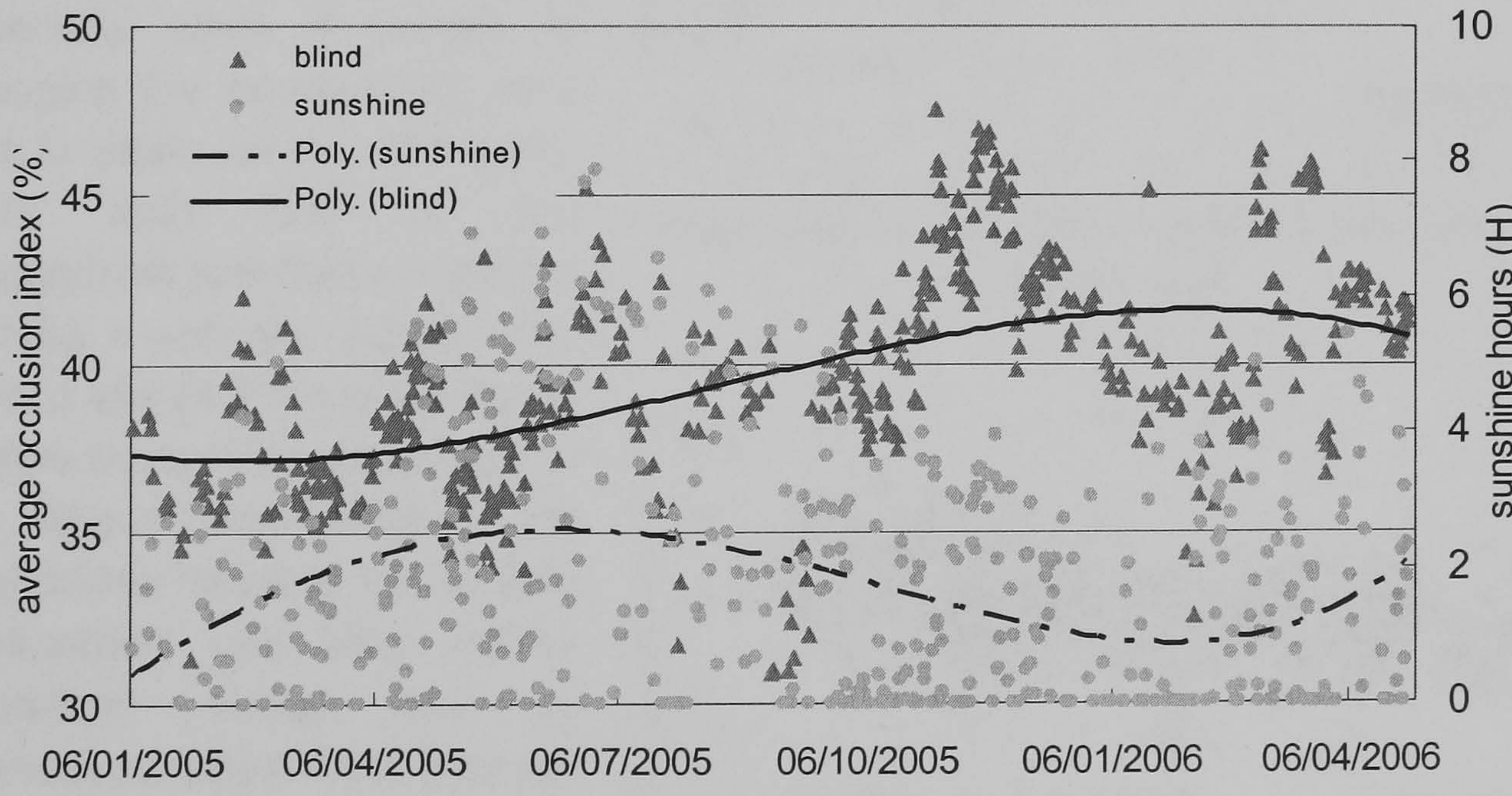


Figure 6.67 Total sunshine hours and average blind occlusion from Jan/05 to Apr/06

Figure 6.67 shows the relationship between total sunshine hours and average blind occlusion from Jan/05 to Apr/06. It can be seen that the blind is not used by occupants as actively as window and that the trendline doesn't follow an obvious rising and falling pattern. One of the reasons may be due to the features of weather as opposed to climate with respect to sky conditions like sunshine hours.

At between 30% and 55% of the maximum possible per year, the amount of sunshine in Sheffield is relatively low. During the survey period, Jan/06 was the cloudiest month with an average of only 1.2 hours per day in this month and May the sunniest (7.9hours) of the 16 months (see 5.2.2.1). However, when it comes to daily change, the sunshine is very unpredictable because the level of cloud cover, which affects the sky condition, changes very much all the time with regard to shape, density and position. The distribution of hours of sunshine, therefore, in the figure spreads everywhere from 0 to 7 hours with no strong accumulation in a particular period of time. This pattern also presented itself when sky illuminance changes dramatically during the same day from sunrise to sunset with clear sky conditions. Data analysis shows that occupants essentially ignore these changes because normally the blind position is not changed according to the illuminance of the sky. The blind operation, unlike the window, which is controlled based on the short-term fluctuations of air temperature, is based more on the occupants accurate long-term perception and experience of solar radiation.

Additionally, considering the internal blind is mainly looked at as a way of changing the visual environment, electrical lighting is an alternative that is both easier and quicker than using the blind, especially when it comes to changing the environment from dark to bright. On the other hand, more than half of the respondents feel that it is difficult to raise it up/down (32.6% very difficult and 24.9% a little difficult) (Figure 6.24). In this case both of the issues may weaken the relationship between the outside environment and blind control behaviour: during dark or overcast periods of time: they are not pulled up in a manner likely to optimise environmental control. Blinds are often still in the down position when there are few

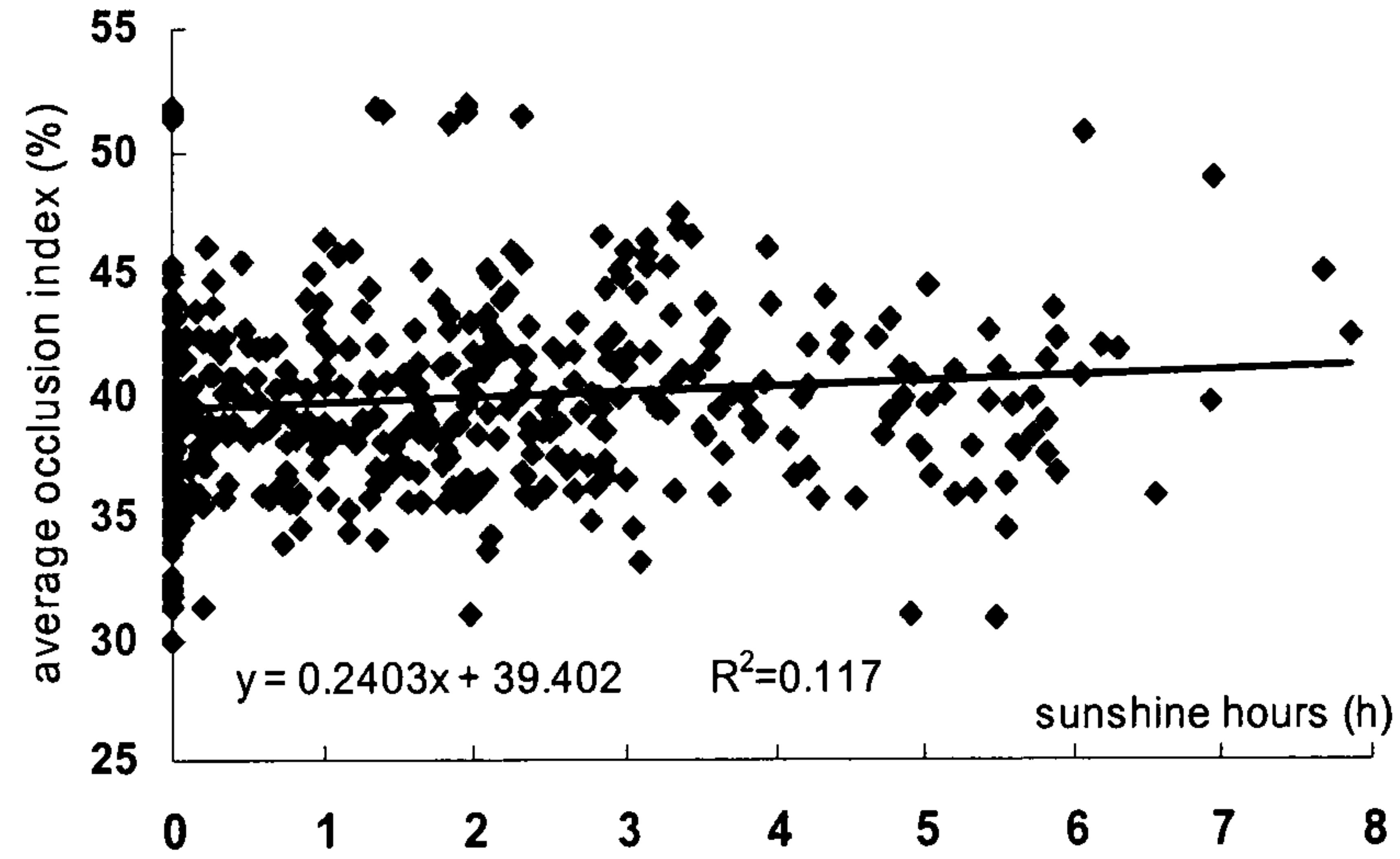


Figure 6.68 Correlation of the average occlusion index to sunshine hours

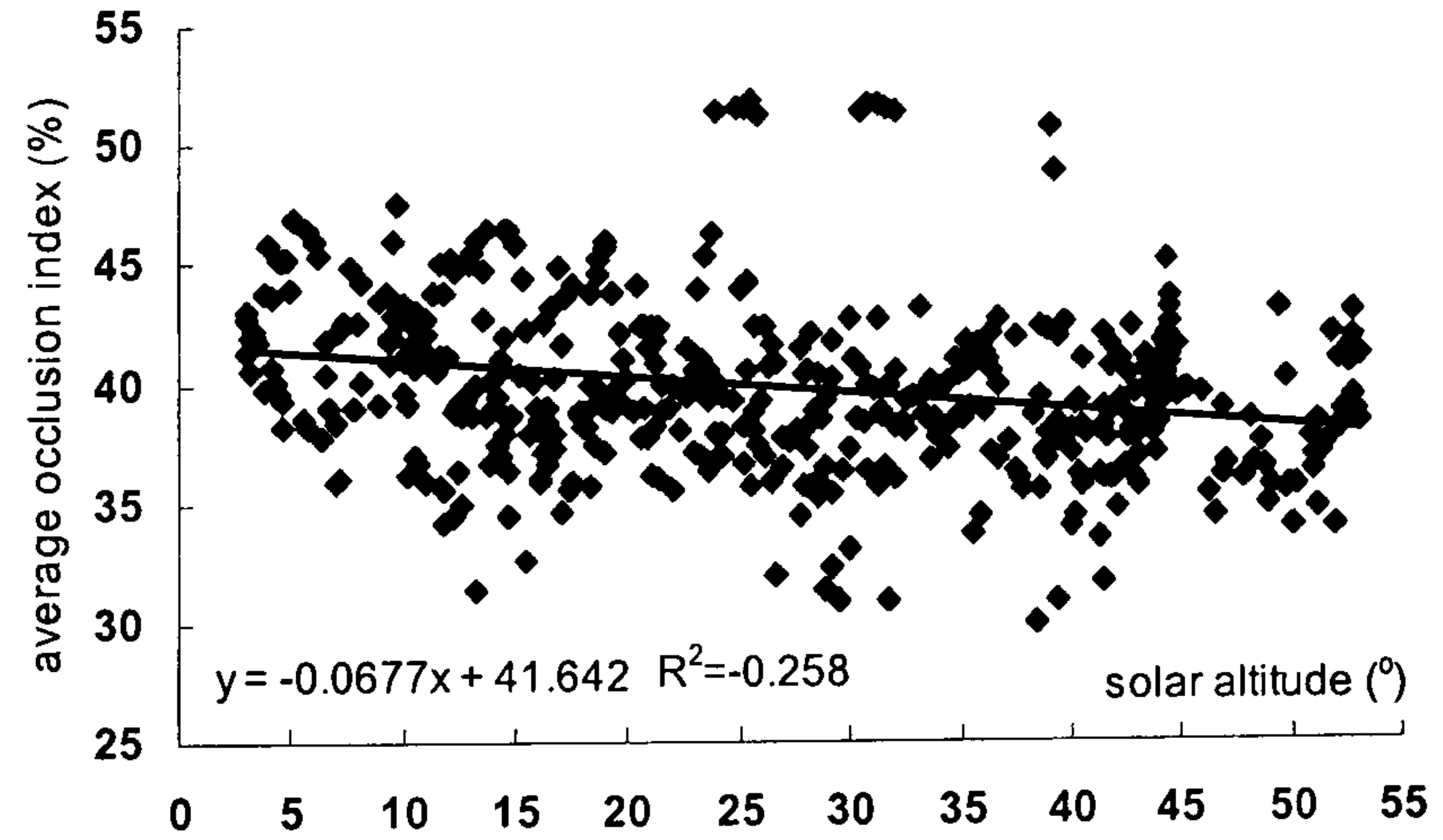


Figure 6.69 Correlation of the average occlusion index to solar altitude

hours of sunshine which leads to the fact that the gradient level is not as varied as expected. Thus, it is demonstrated that occupants may try to obtain as much light as possible but not through natural but artificial means. Therefore, although appropriate occupant blind use does not occur and much lower than unity for a perfect correlation coefficient in this case study, it is felt that the results obtained are reliable and indicative.

In general, there is a weak relationship between sunshine availability, solar altitude and blind occlusion level (Figure 6.68, 6.69). The results indicate that both the amount of sunshine and the position of the sun can lead to occlusion changing: more sunshine has higher blind occlusion in order to avoid direct and strong sunlight; a lower sun angle results in deeper penetration into the room, and then occupants are forced to manually pull blinds down. These two issues can affect occupant control at any time, for example long sunshine hours in hot seasons and low sun angles in cold seasons. Therefore, the regression line presents a flat increasing when sunshine hours increases in Figure 6.68 while a decreasing when solar angles increases in Figure 6.69.

	Winter I	**Spring I**	**Summer**	**Autumn**	**Winter II**	**Spring II**
Sunshine max. H	1.5	2.1	2.8	1.4	1.1	1.4
Sunshine min. H	0	0	0	0	0	0
Sunshine avg. H	1.5	2.1	2.8	1.4	1.1	1.4
Blind occlusion max.	42.0	43.2	45.2	47.5	45.1	46.3
Blind occlusion min.	31.3	34.0	31.8	29.9	32.6	36.8
Blind occlusion avg.	37.1	37.4	39.3	40.9	41.9	41.1
Correlation coefficient	0.287	0.237	0.263	0.242	0.259	0.229

Table 6.10 Some values of sunshine hours and average occlusion index in terms of seasonal change

Table 6.14 shows the variation more specifically. The average occlusion index in winter and spring is almost same (37.1% vs. 37.4%) although the average total sunshine hours increase dramatically from 62.7 in winter to 154.3 hours in the spring months (see Chapter Five). In summer, the blind underwent a slight rise (1.9%) compared with spring, then the average occlusion further increased by 1.6% (40.9%) with temperature and sunshine hours both going down in autumn. Sunshine hours, although less in autumn than in summer, were still long enough and coupled with the low angle of sunlight result in more blinds being drawn down. With the average sunlight angle further decreased in winter II, the blind occlusion curve reached its highest point (41.9%). However, when it came to spring II, the average sunshine hours increased and the angle of the sun increased as well, with the occlusion index finally dropping 0.8% from 41.9 to 41.1%, which demonstrated that the impact of the amount of sunshine and solar angle on blind use did in reality exist although the relationship was neither very clear nor dominant.

From the correlation comparison, it is noticeable that all the seasonal values are higher than average (0.117). This is due to the variations of sun angle and sunshine hours are more changeable over 16 months than 2-3 months. The annual correlation represents a balance of all the influencing issues, which are sometimes mutually reinforcing but at other times weaken each other. But the seasonal ones can reduce the interferences of the unstable issues (e.g. the sun angle) thus reinforcing the correlation. This feature can also be seen from the comparison between seasons: the values from the summer and the winter are higher than from the spring and the autumn because in the transition period, the weather is quite unpredictable and that fact potentially has a negative impact on the occupant's control of the blinds.

On the other hand, the impact of air temperature on blind control shows a weak relationship as well. In this case, higher temperature actually results in more blinds up (Figure 6.70). As mentioned at the beginning of Data Analysis II, although this part has concentrated on the operation of windows and blinds and its correlation with some basic weather parameters, this doesn't mean they are the only dominant issues. In fact, the individual occupant is far more sensitive than expected and many other complicating factors make a great contribution to behaviour aimed at controlling the environment.

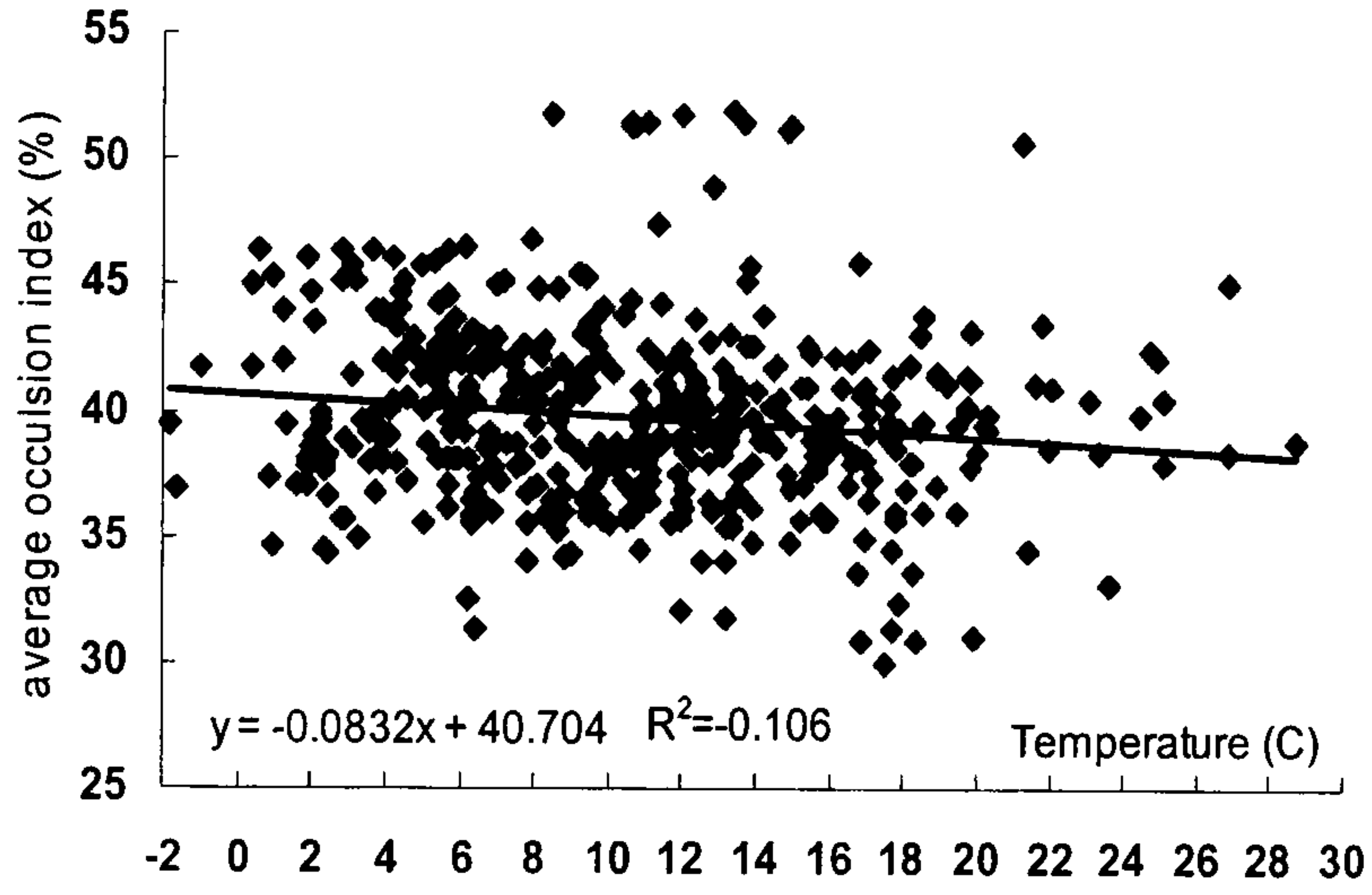


Figure 6.70 Correlation of the average occlusion index to solar altitude

The next part will focus on the nature of the rooms in the building as a primary factor possibly influencing user operation behaviour. To make the analysis easily controlled, it will only concentrate on the operation of windows and blinds and its correlation with outside temperatures and sunshine hours respectively in order to test the impact of the room usage, orientation and size on the user behaviour.

6.3.1.2 Operation Based on Room Usage

Occupancy	Office	Communication	Public study	Service
Cycle	Continuous	Intermittent	Continuous	Intermittent
Duration	Long	Short	Long	Short
Density	Low	High	Low/high	Low
User	Fixed	Floating	Floating	Floating

Table 6.11 Features of different room usage in the Arts Tower case

In this study the nature of the room occupation is of primary importance in considering operation behaviour. For the convenience of analysis, the rooms investigated in the Arts

Tower are grouped and processed in terms of four categories based on occupant activity. Chapter Five has mentioned the principles by which the rooms are organized into groups. In Table 6.11, features such as occupancy circle, time, density and type of user are further specified. Although this is still a broad pattern, within this framework there tends to be a constant and full-scale view in terms of space function.

Window operation with air temperature

The relationship between the window control behaviour and outdoor temperature when the users are in the different occupancy spaces can be seen in Figure 6.71. The opened window ratio is obtained by dividing opened windows by the total number of windows each category has and then multiplying the result by 100. The variation arises from day to day according to the room's functional arrangements but all of the trendlines tend to follow the temperature which indicates that the user behaviour changes along with the variations of the outdoor temperature. Yet a comparison of days in the same season reveals that the percentage of opened windows differs according to the room that users occupy as well. During winter time when the temperature was low, all the occupation rooms had a low ratio which was quite reasonable as it suggested that cold air from the outside was not being allowed into the room. Conversely, the ratios from each room space reached to their highest levels respectively during the summer time.

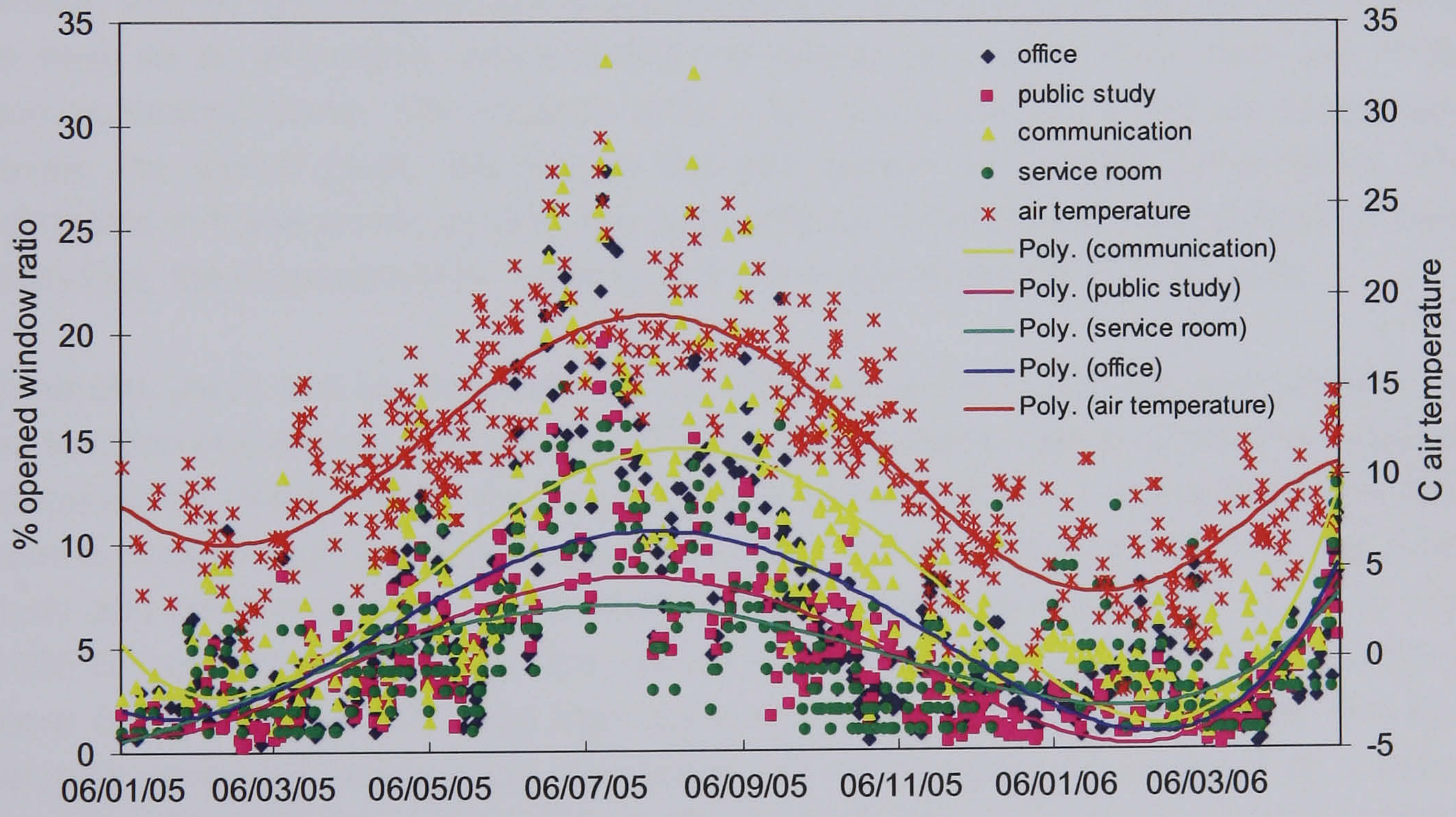


Figure 6.71 Mean percentage of opened windows based on room usage (occupancy)

However, the values of single data points assigned to certain temperatures deviate widely: the higher the temperature, the greater the variation. Rooms for communication show a strong statistical spread resulting in the biggest variation: roughly from 0 to 15%. This can be explained by the high density of occupation. The consequence of this is that heat gains from the occupants are quite significant. The impact of these people on the environment of a room is considerable and their heat output contributes greatly to the raising of internal air temperatures during the periods of occupation. Thus a high level of ventilation may be required even though the total period of occupation might last for less than three hours. And due to the communication functions of these rooms, opening the door to increase air velocity is not practical. Thus the requirement for ventilation is strengthened especially when the outside air temperature is high.

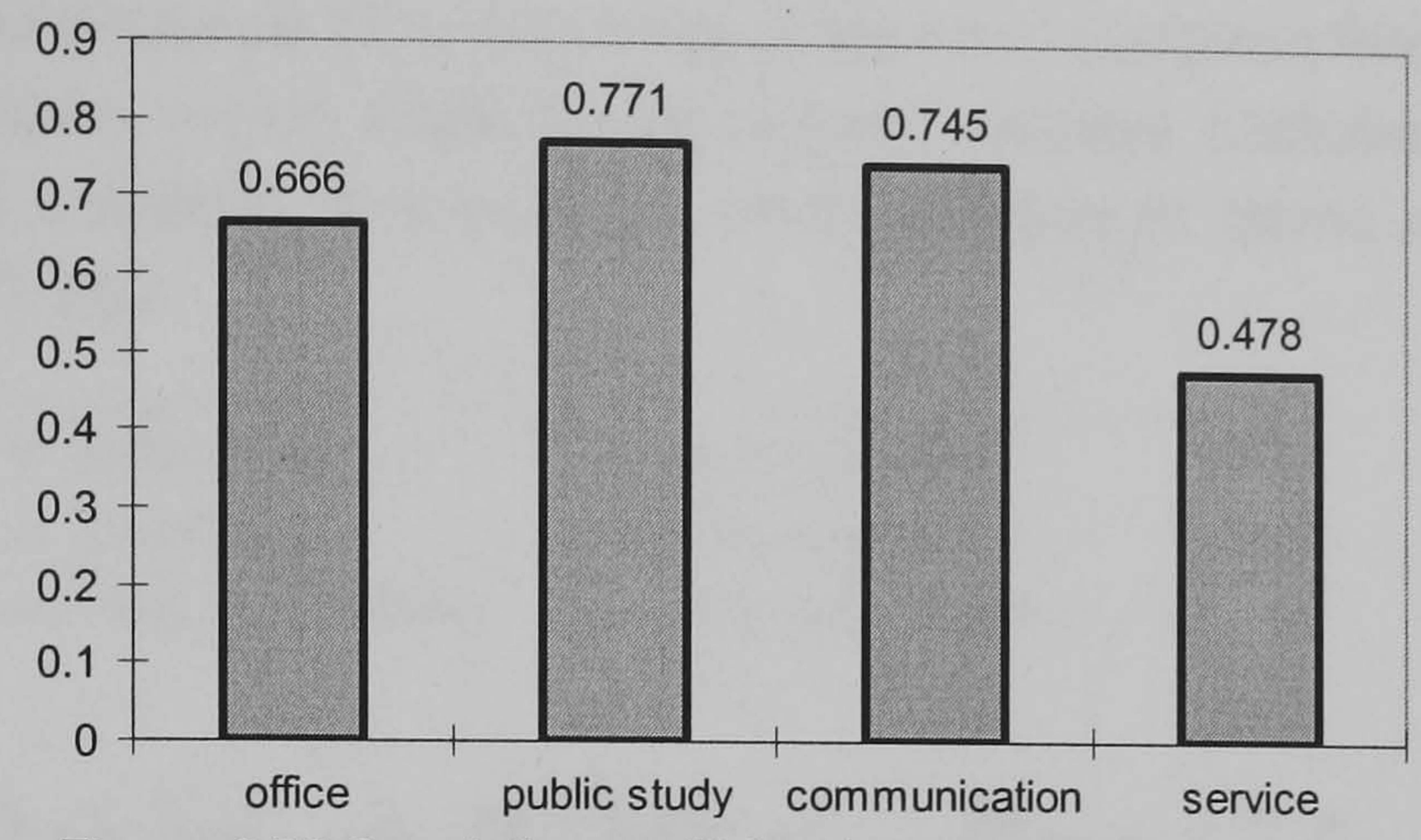


Figure 6.72 Correlation coefficient between air temperature and opened window based on room usage

The highest ratio point to the rooms used for offices and public study areas are around 5% lower than for communication. Usually these rooms do not have a high occupancy density as communication rooms, but they are occupied continuously for periods of up to more than 80% of working time. When ventilation is desired, opening the door is usually the first priority option as it is convenient and quick (see 6.2.1.7). Only when privacy, the fire door requirement and/or noise etc. are factored in can window opening be seen as an alternative, and it is this that makes its peak is lower than that of the 'communication' curve. The variation pattern for the service room, despite in this case having the lowest peak, still follows the line plotted for outside temperature. The occupants in these rooms usually stay intermittently for only very short periods of time. Therefore, the requirement for ventilation is not as great as in the other cases.

Generally, users can be characterized as 'active' in terms of window control whatever the function of the room they happen to be in. They show a high correlation with the air temperature. Among these, the percentage of opened windows in the communication room is most strongly linked to temperature: its R^2 value reaches up to 0.771. The public study and office rooms are in the second and third places with values of 0.745, and 0.666 R^2 respectively. Even for the service room, the R^2 value is still high enough to score 0.478 (Figure 6.72). The high correlation in each category indicates that in a naturally ventilated environment, the actual use of the operable window has a strong link with temperature but does not strictly correspond to the room's occupancy circle, time, density and user. It only makes a difference in terms of weakening the correlation when the occupancy is intermittent, of short duration and low density with floating users i.e. as in the case of service rooms.

Blind operation with sunshine hours

Comparing the occlusion variation of different occupied rooms reveals that although occupation circle, density and time are not significant, they do have some noticeable impact on the user's blind operation (Figure 6.73). The points of the blind occlusion from offices are in the upper accumulation, which leads to the highest average occlusion value (51.2%) and a very placid trendline. It shows the least variation in terms of maximum and minimum values (27.3%).

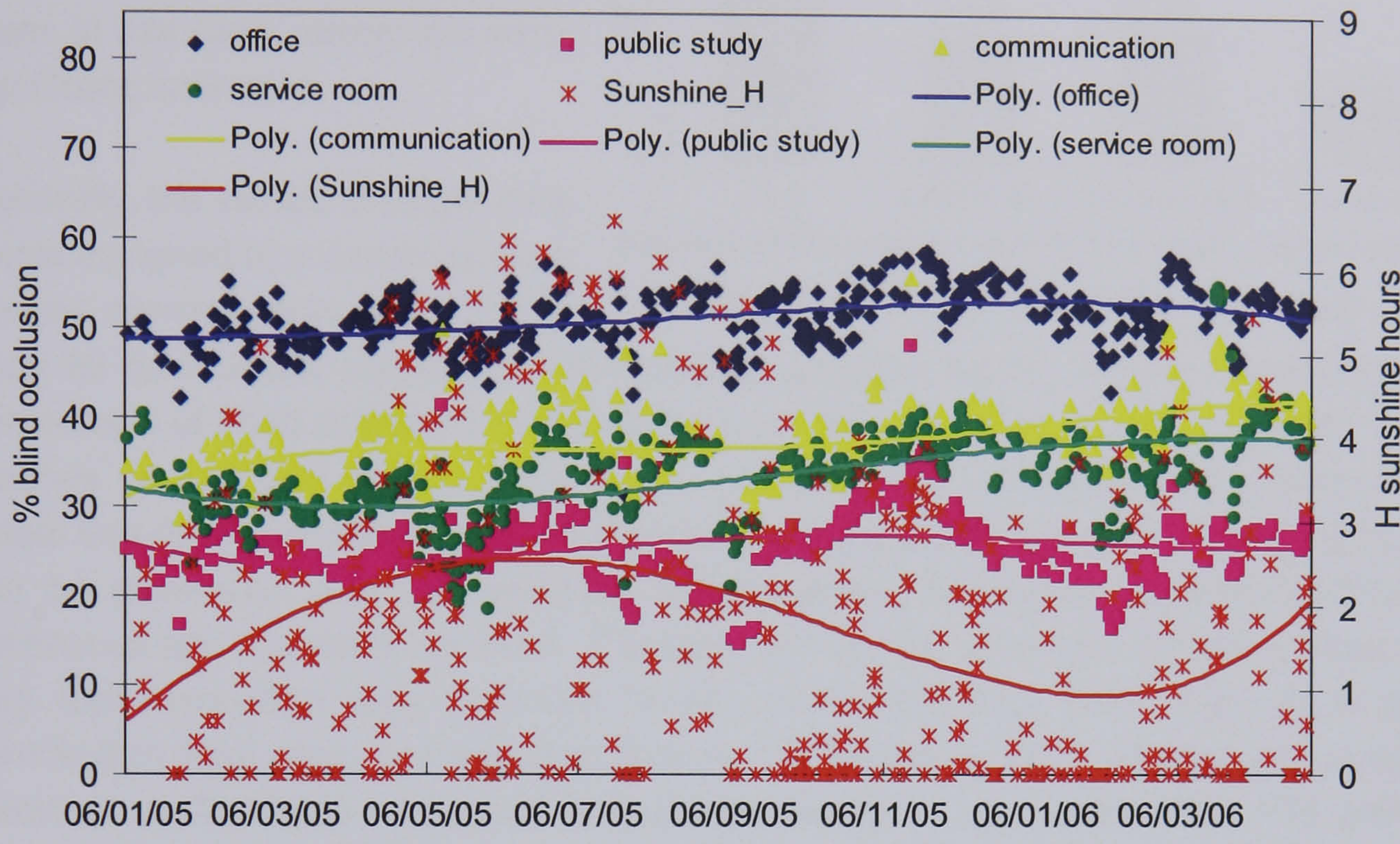


Figure 6.73 Mean percentage of blind occlusion based on room usage (occupancy)

This can be explained by the occupancy cycle and duration. Normally users are in these rooms with a relatively fixed working room/station for most of the week day and most of the time. They can build up considerable familiarity with the indoor environment of their rooms and are able to operate the primitive controls based on their own perceptions and experiences. By positioning different windows with proper occlusion blind, the users can ensure that their working planes have a sufficient degree of daylight penetration and/or a satisfactory view and in addition that glare disturbance is eliminated for most of the time. Once the blinds are positioned, occupants make little or no attempt to change them until a dramatic situation emerges. Therefore, it is reasonable to see that the most stable and flat trendline among these four categories is for the blind in the office.

On the other hand, public study room in this case, has the lowest accumulation with an average of 25.4% blind occlusion. The values for communication and service rooms are relatively close to each other with similar average occlusions - 37.6 and 33.6% respectively. But the service room shows the largest variation (36.7%) and its trendline presents a clear ascending inclination in comparison with the lines plotted for the others. The service room is not normally private and different people can come in and stay. People stay in these service rooms often intermittently and for a short period of time; therefore it is common for blinds that have been dropped for some reasons, such as to reduce the penetration of solar radiation, to be left there until the following day regardless of the daylight level from the start to the end of working day and that leads to the gradual increase of the overall level of window occlusion. This tendency profile, more or less, presents in all the categories. But the blind occlusion in the service room, in this case, shows the most significant inclination.

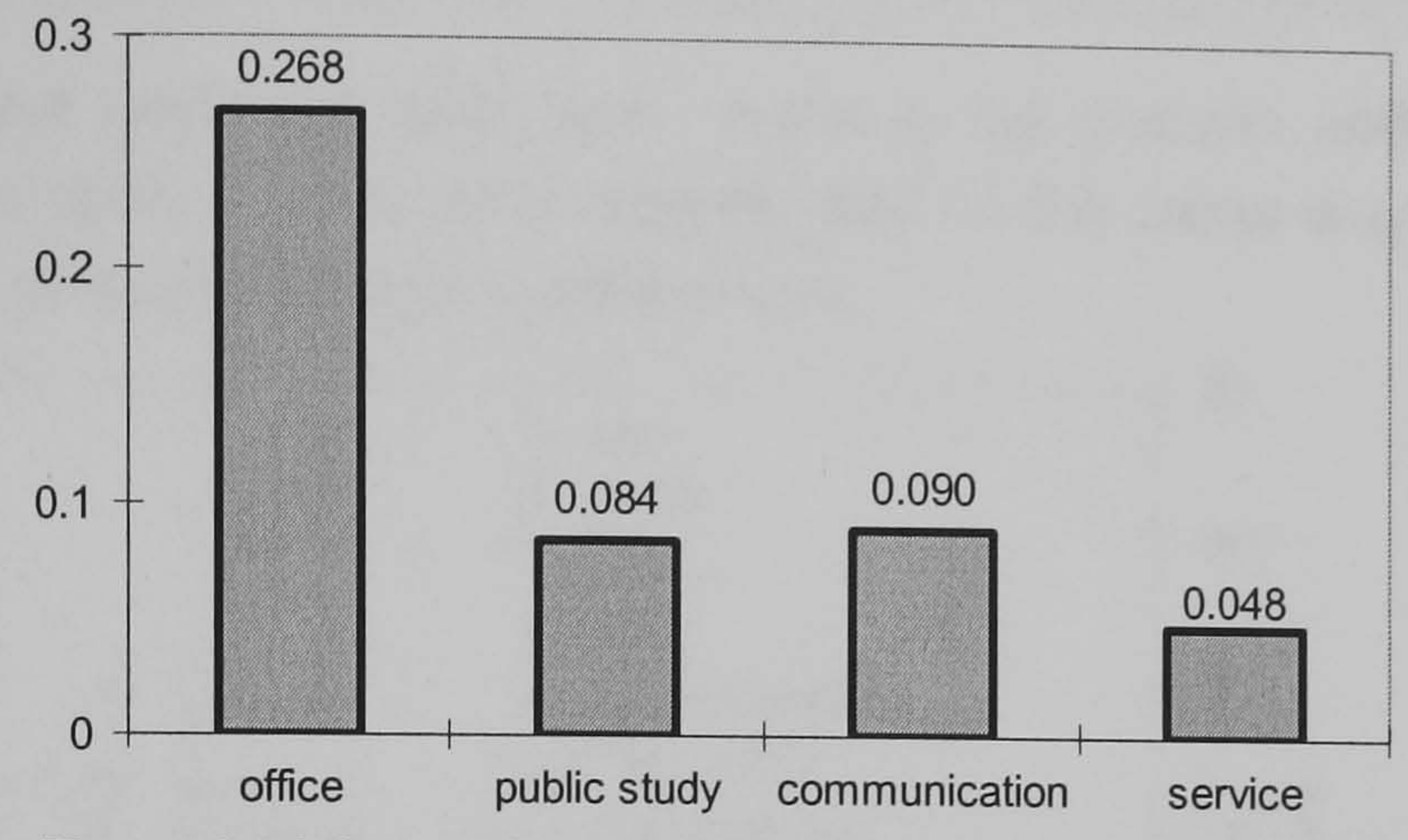


Figure 6.74 Correlation coefficient between sunshine hours and blind occlusion index based on room usage

Generally, the values of single data points assigned to a certain degree deviate narrowly and respectively. They all have a low correlation with outside sunshine hours. Among them, only the percentage of blind occlusion in the office room has a relative strong link: its R^2 value reaches up to 0.268 (Figure 6.74) which indicates that the relationship between the actual use of the venetian blind and the outside sky condition, such as sunshine hours, can be generated and corresponded loosely when the room's occupancy circle is continuous and the users are fixed. The other occupancy situations, however, present a very low correlation with sunshine hours, which indicates there may be a great contribution from other complicating factors. For example, as an institutional building, electrical audio-visual instruction is used frequently. A big screen can only present content clearly when the visual environment is dark enough to increase the contrast sensitivity, which means that no matter how dull or bright the outside is, the preference is for blinds to be in the down position in communication rooms.

6.3.1.3 Operation Based on Room Orientation

Direct solar radiation is a powerful determinant of the indoor environment the occupant experiences which is indissolubly linked with the actual use of the operable window and the venetian blind. Therefore, room orientation, in this case is considered to be an issue of primary importance in influencing user operation behaviour.

It has to be mentioned that due to the fact that all the corner rooms and some large area rooms are equipped with two, three or even four façade windows, although the analysis in this part is based on the room orientation, it is more accurate to refer to window orientation. Also, because the building axis is tilted 18°, the orientation of the building façade has to be more precisely described as being rotated 18° anti-clockwise. For example, the orientation of the south façade is actually 18° east of south.

Window operation with air temperature

Figure 6.75 is the comparison of the mean percentage of the opened windows to the outdoor temperature over 16 months based on window orientation. All of the trendlines have the same rising and falling pattern with air temperature. They drop to their lowest points in the winter and then gradually rise up when it comes to the spring. During the summer, each reaches to the highest point and falls down again in the autumn and reaches its lowest in the winter. This cycle continuously repeats itself in the same way as air temperature does, regardless of room orientation differences.

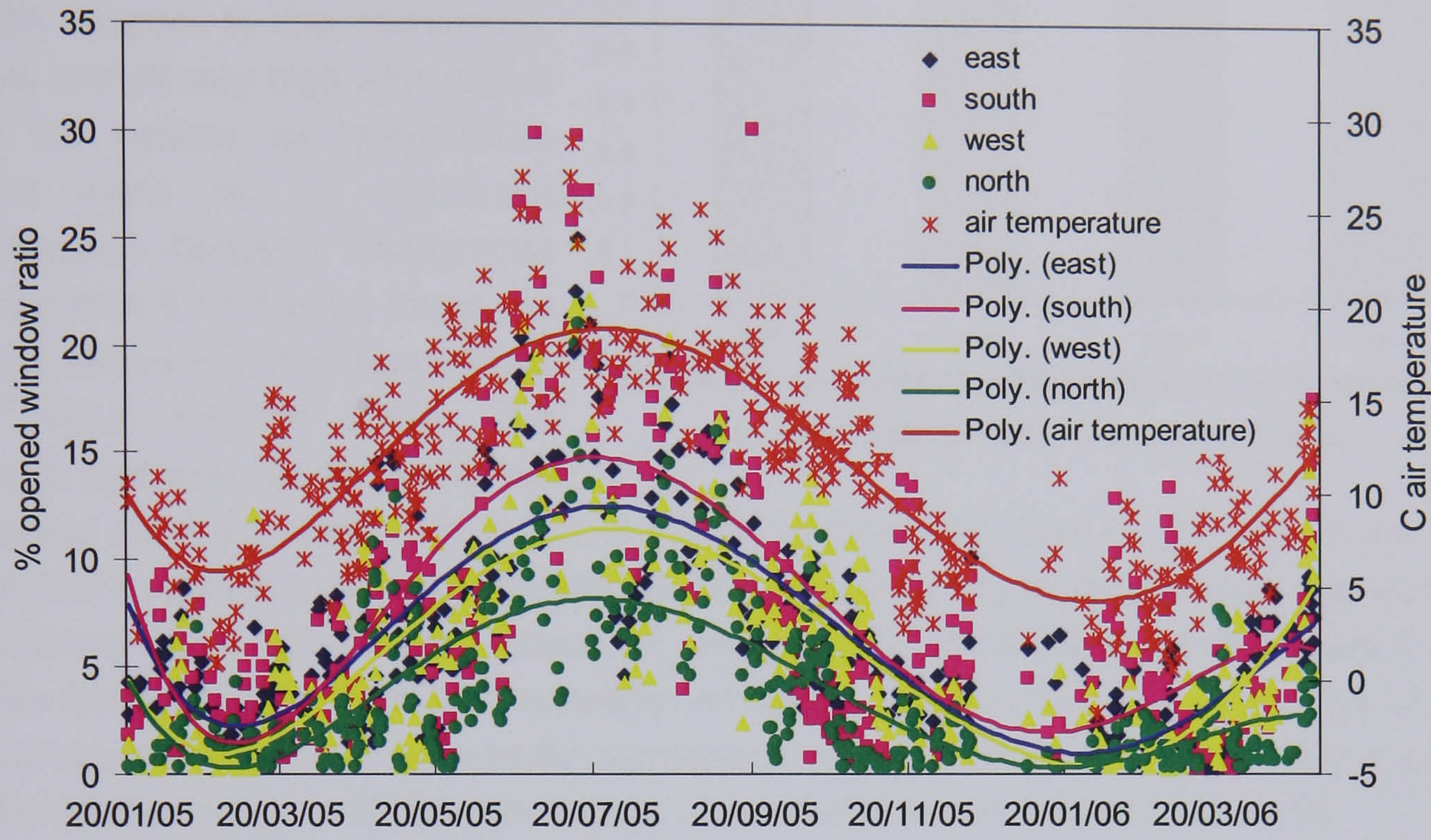


Figure 6.75 Mean percentage of opened windows based on room orientation (environment)

The four facades have a similar low ratio of opened window (around 0.2%) during the winter months. But the amplitude of fluctuation exhibits a discernable difference between the four room orientations. The ratio for the south façade shows the biggest fluctuation (29.9%) and the highest average ratio during the survey time with a figure of 7.3%. This is to be expected as the rooms towards the south receive the most solar radiation of all the different room orientations. The rooms are heat up quickly, especially during the summer time. Without air conditioning, natural ventilation to increase the air movement is the main option occupants have when it comes to eliminating the discomfort that arises from high temperature.

The trendlines for east and west are closely adjacent but their peak points are not as high as in the case of the south. The fluctuations from maximum to minimum are much the same: 24.7 and 24.6% with the average value just around 1% less than for the south with 6.3 and 5.6% respectively. Considering the east-west axis is 18° anti-clockwise due east, the two orientations cannot be treated as the same in terms of the global solar radiation received. The rooms towards the west experience stronger and more intense sunlight and sun heat than those towards the east. As a result, it is expected to see that the west and east ratios are close but that the former is a little higher (0.7% difference). The north rooms do not receive direct solar radiation for most of the time which means that the occupants' desire for higher levels of air movement due to overheating is not as frequent as the case for other room orientations. Therefore, it turns out that the ratio for the north has the lowest peak point with the smallest fluctuation (20.7%) and the lowest average ratio of opened windows (3.6).

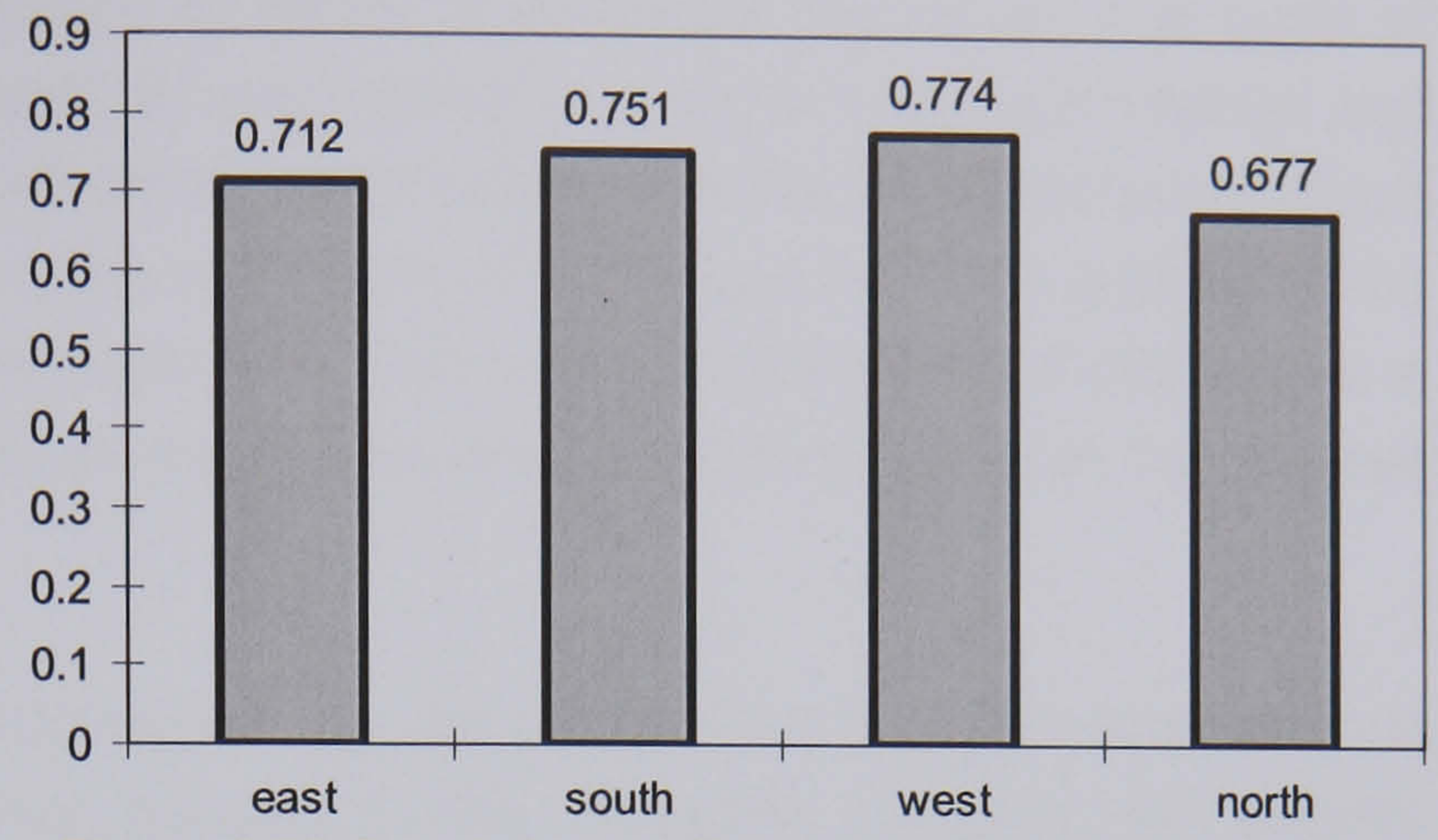


Figure 6.76 Correlation coefficient between air temperature and opened window based on room orientation

With respect to the correlation, they are all very high with regard to the outside air temperature and there is no significant difference between orientations (less than 0.1). Among them, the west shows the strongest link: its R^2 value reaches 0.774. The south and east rooms are in the second and third places with 0.751, 0.712 R^2 respectively. Even for the north room, the window operation to give high ventilation rate is expected to be less strongly related due to its low mean radiant temperature, its correlation R^2 still reaches 0.677 (Figure 6.76). The result indicates that in a naturally ventilated environment, the actual use of the operable window does not strictly correspond to the room's orientation. Only a small degradation occurs with the percentage of opened windows towards the north.

Blind operation with sunshine hours

Basically, the visual environment of the building room has different features in terms of orientation due to the amount of daylight which reaches the glazing is substantially affected by the solar azimuth and the angle of the sun path. Venetian blinds in the Arts Tower are the main way of adjusting daylight penetration into the room and its variation implies the occupants' own preferences with regard to the visual environment.

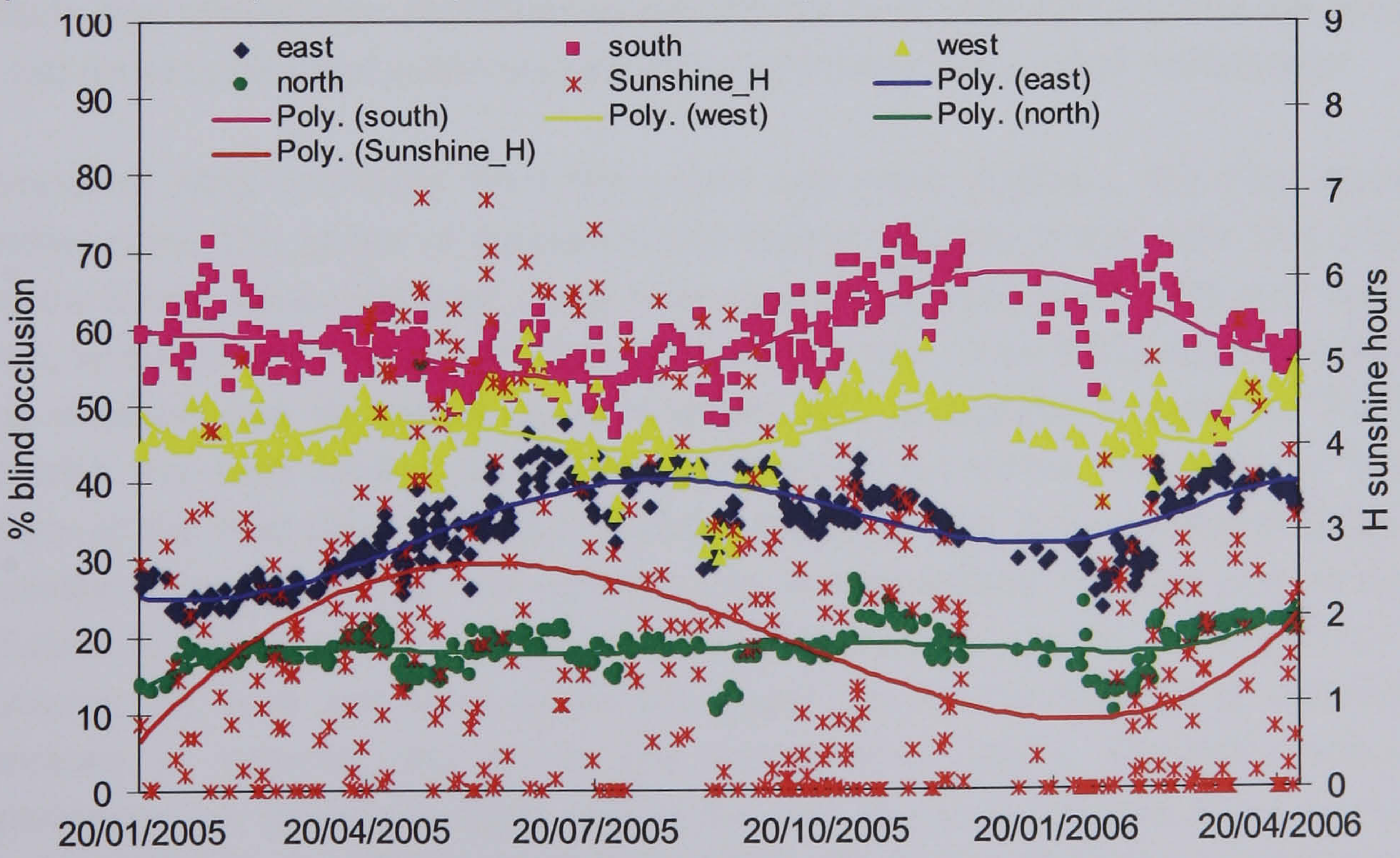


Figure 6.77 Mean percentage of blind occlusion based on room orientation (environment)

Figure 6.77 presents a clear difference in terms of occupant response. The point of single data with each orientation tends to accumulate in a certain occlusion range and separate in a quite notable way. Furthermore, compared with the blind occlusion which is grouped by the occupancy pattern, the amplitude of fluctuation for each oriented blind becomes more expanded except the north one. This indicates the effect of orientation is more significant than occupancy in terms of providing a motivating force for manual blind control.

Apart from the north curve, visible change in the user behaviour between summer and winter is found, although the curves respond to the changing seasons with varying sensitivities and patterns. Data analysis shows that the south curve is always located in the upper situation with a 58.9% average value. Strong and long-period direct solar radiation requires cooling or shading from the sun, thus the blinds are preferred to be pulled down or half down which leads to the highest occlusion among other orientated marks. Furthermore, the seasonal effect on blind operation for the south façade is very significant. It has the highest blind occlusion in winter and drops to its lowest in summer.

The curve for the west window blind has a similar pattern to that for the south, with the bends of hills and valleys appearing to happen almost synchronously. But its curve is lower than the south which can be explained by the shorter period of direct solar exposure. The average blind occlusion index maintains at 46.9% with 12.0% less than the south which means comparing with the south façade window, the west one has a higher glazing area ratio (area with no occlusion / total glazing area) to receive the solar radiation (heat and light) without blind blocking. Also its amplitude of fluctuation is not as sensitive as the south. This is perhaps because the west room can only receive the low altitude and strong solar radiations in the afternoon all year around, and the occupants do not experience great extremes like those inhabiting the southern orientation.

Comparing blind operation from the south and west windows, the east curve tells another story. The bends of fluctuation are clearly opposite to the other two orientated window blinds. When the east curve rises up gradually, the south and west ones drop down, while when it drops down the others start to rise. Thus the blind occlusion for the east windows has its lowest point in winter and its highest in summer. The result indicates that solar heat is a powerful determinant of internal conditions for occupant control of the east blind. During the winter months when low sun angles allow direct insolation deep into rooms, the resulting rise in temperature from warm morning solar radiation is often seen as providing a welcome bonus without causing overheating problems, so more and more blinds are raised up. As the strength of radiation gets increases in summer, the blinds are pulled down again. Generally although it experiences low altitude sunlight, just as the west does, its intensity is not as strong in the morning as in the afternoon, and, therefore, the average occlusion is lower than for the west at 34.5% or 12.4% less.

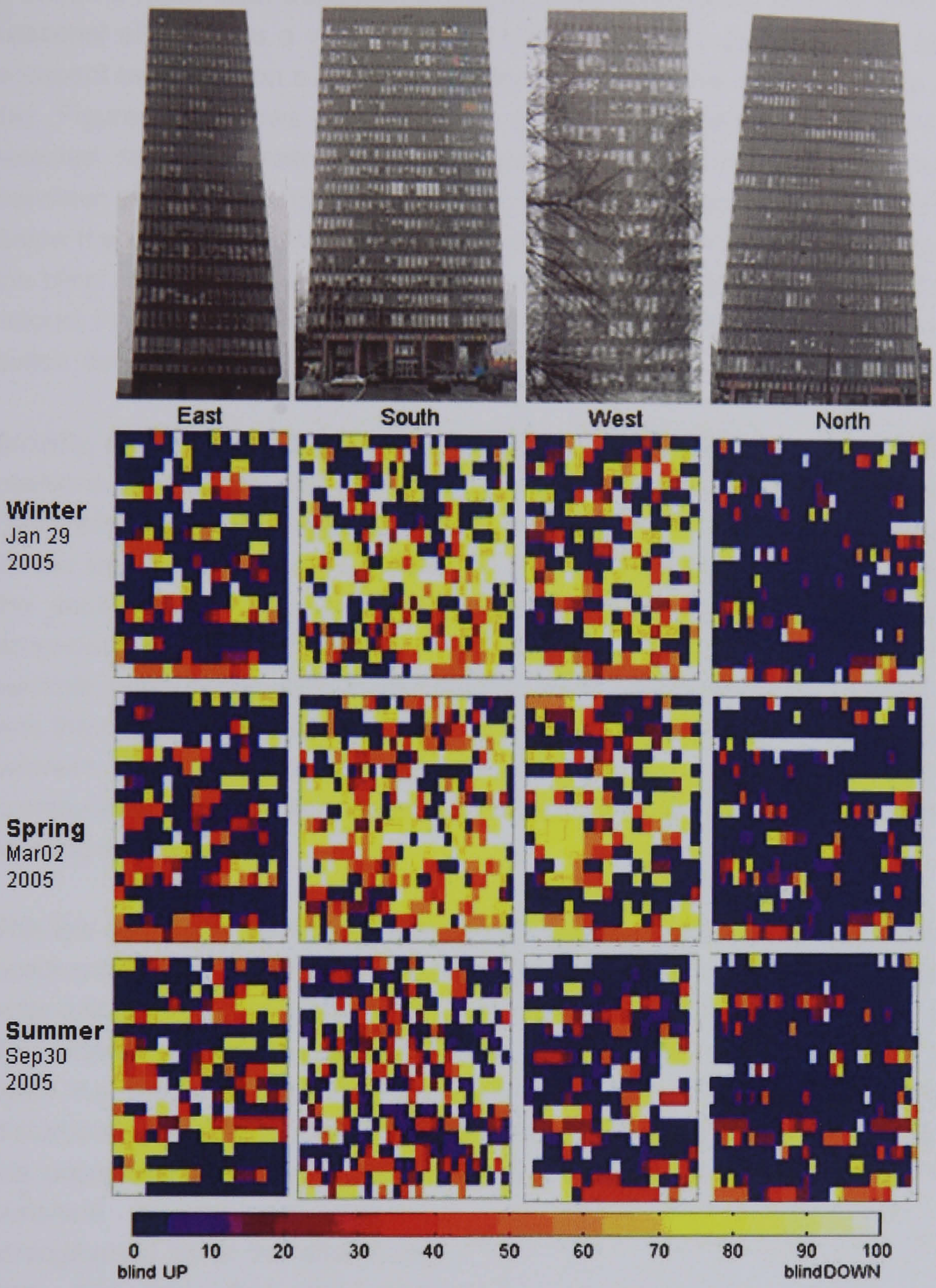


Figure 6.78 Blind position on three typical seasonal days

The north curve, in this case is the only one doesn't show a significant variation and fluctuation. This is quite acceptable as the north rooms, although experiencing relatively low strength illuminance, have the most constant and uniform daylight. Thus they seldom have problems with glare disturbance and overheating discomfort, with the result that the trendline presents an almost flat curve without drops or/and hikes. And its average occlusion is always kept at the lowest level with just 18.4%.

Generally the analysis of the proportion of fenestration occlusion against orientation provides a more clear indication of the motivating forces for manual blind control. The seasonal effect plays a very important role. Even if the sunshine hour are the same, occupant behaviour on a hot summer day differs from that taking place on a cold winter day. Figure 6.78 shows this feature in a more direct and vivid way. Three days are selected randomly from winter, summer and spring, which present hot, cold and transition periods respectively. In the plot, the first row is the appearance of four facades. Below the photo, one little square represents one window blind and its colour represents the blind occlusion. Thus all the blind positions in one day are illustrated into different colours from blue which means completely pulled 'up' to white which means completely pulled 'down'.

Broadly, on the winter day the south had the most blinds in the 'down' and 'half down' positions. As time passed, more and more blinds were pulled up. On the summer day, a clear reduction of down-position blinds was presented. The same situation happened for the west facades, but its number of down-position blinds didn't as great as that for the south facade. The east one, however, displayed a different tendency. Their down-position blinds were clearly less than the west ones in winter. But when it came to summer, many blinds were pulled down to avoid strong radiation. The north one, which was the only façade, with most blind in the 'up' position did not show a clear difference between each season. The variations indicate that occupant operation behaviour corresponds with the season and their own experiences of solar radiation in their working environments.

The low altitude of winter sunlight can be a serious and annoying problem and drive occupants to pull the blind down in a room towards the south. But in summer, as the solar altitude becomes higher, even with increasing solar gain more blinds are pulled up. This doesn't exclude the possibility that people raise the blind because they want to open the window easily to reduce overheating. But it still indicates that the glare disturbance is not as much as in winter. This picture and explanation can be extended to the occupants of the west but not the east rooms. One reason is that the morning sunshine is not as intensely strengthened as in the afternoons and the fact that the east orientation is actually east of north further reduces the sun's penetration during this period of time. All these issues result in the occupants of the east rooms preferring the winter sun light penetration.

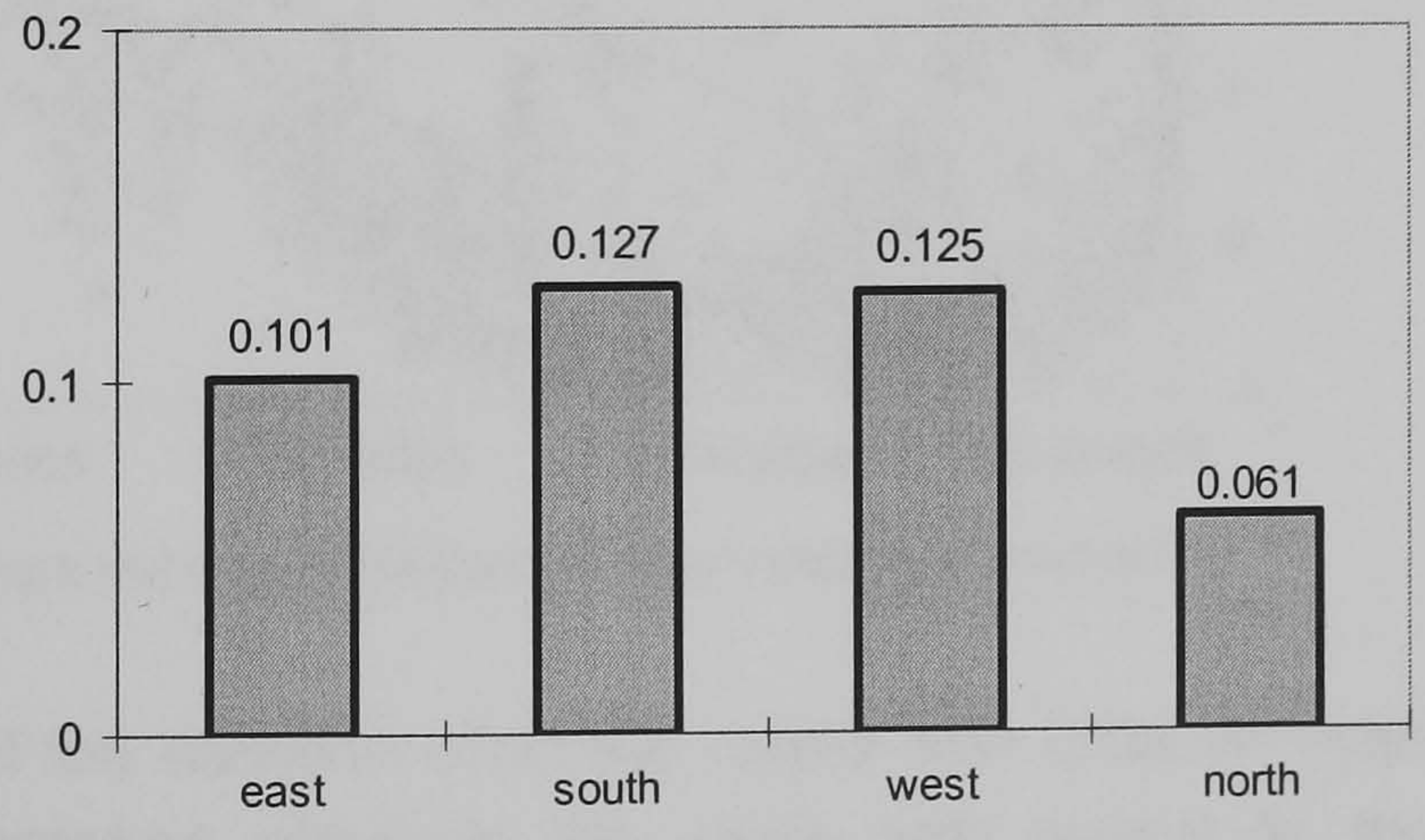


Figure 6.79 Correlation coefficient between sunshine hours and blind occlusion index based on room orientation

Roughly more sunshine hours can

be loosely correlated with higher blind occlusion. Among them, the percentages for blind occlusion for the south rooms show the strongest link: here R^2 value reaches 0.127. The one for the west is only slightly lower at 0.125. The east and north are in the third and fourth places with 0.101 and 0.061 R^2 respectively (Figure 6.79). From the general analysis in this part, it appears that not only sunshine hours but also the solar altitude and solar radiation intensity have a great impact on blind operation for the different window orientations. Further analysis is needed to test and confirm this hypnosis in future studies.

6.3.1.4 Operation Based on Room Size

Room size is one of the important parameters not only in determining the air exchange rate in terms of indoor air quality requirements, especially given the room height but also the daylight distribution of the building room with respect to the internal surface to the volume ratio [20]. Therefore, room size, although not mentioned in any previous related work, may affect the occupant's behaviour and motivation to control the comfort level. For convenience of the analysis, the rooms investigated are grouped and processed in terms of four categories based on room area – small (<20m^2), medium (20 m^2> and <40 m^2), large (>40 m^2 and <70 m^2) and superlarge (>70 m^2). Chapter Five mentioned in detail the principle by which the rooms were organized.

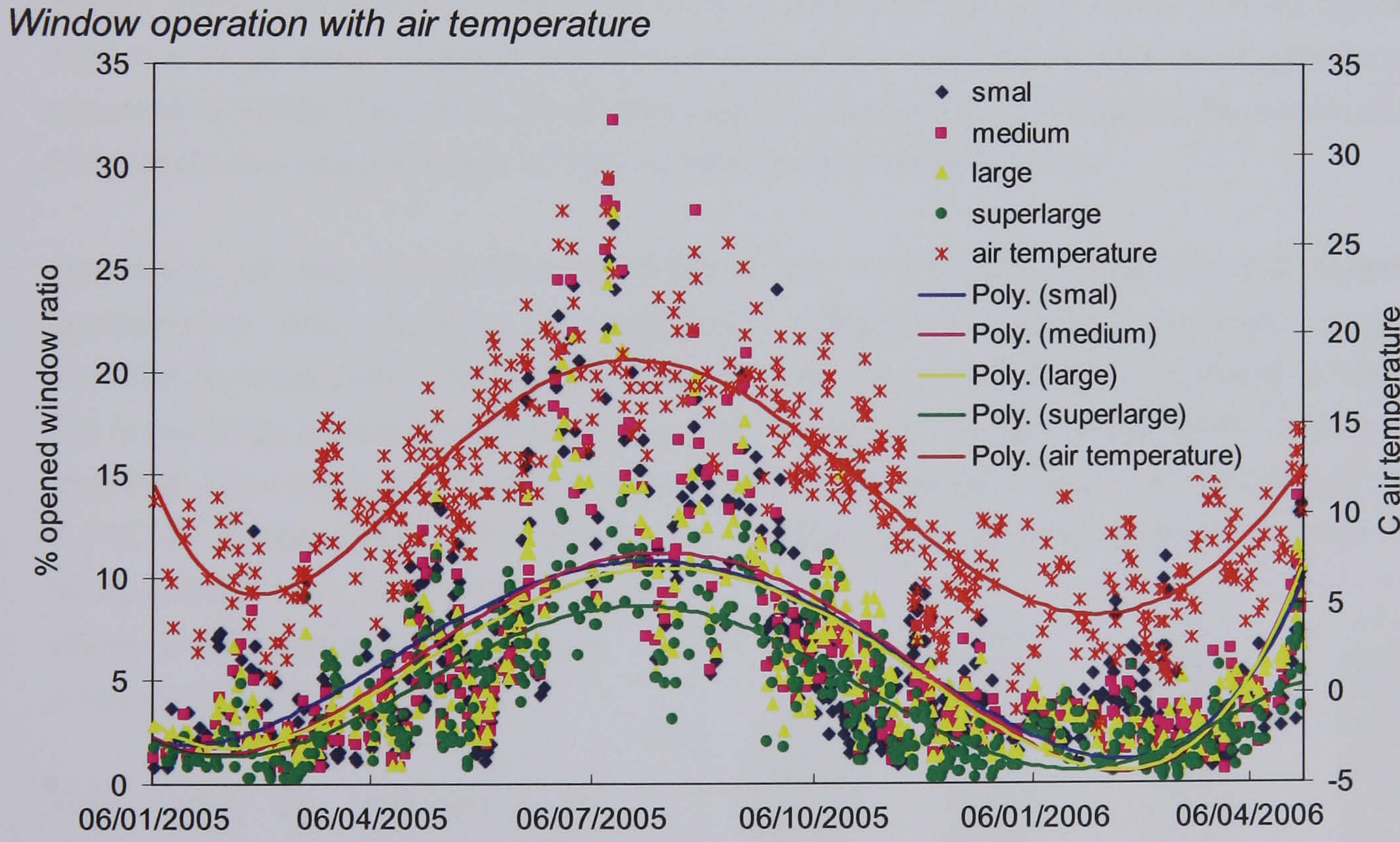


Figure 6.80 Mean percentage of opened windows based on room size (architecture)

It can be seen from Figure 6.80 that the variation of all the rooms with different sizes follows the fluctuation of air temperature which is the same with regard to the occupation and orientation situations. When the temperature is low, the bends of four curves drop to the bottom of a 'valley', which means that the number of opened windows is clearly reduced during the winter time, while during the hot summer time, more and more windows are opened with the result that the bends reach to the top of the 'hill'. Spring and autumn in this case, are two transition periods of time that connect the 'hills' and 'valleys'. This cycle of variation continuously repeats itself over the following year, just like the outside air temperature.

Data analysis shows that a strong accumulation of data points are found in winter, spring and autumn. As a result, the curves which present the four room sizes are much closer to each other, especially in winter. They all fall down to the same level with a very low opened-window ratio value. However, the values for data points assigned to the summer months deviate a little wider. The ratio from small, medium and large are still very close with only the superlarge one accumulated at a slightly lower level than the rest of them. Consequently the peak for the super-large curve is lower than the other ones as well.

This may be explained by the ventilation features of these rooms. Normally the small, medium and large rooms only have single-side windows (except the corner rooms), while all the superlarge rooms have at least two orientated windows. Therefore, in terms of efficiency to increase the air velocity inside the room, the superlarge one, although poorly supplied with fresh air because of its big volume has more advantages than the rest of them due to the fact that it is able to take advantage of cross natural ventilation. And the large area coupled with low resistance to air flow further strengthens the air movement inside the room. Thus, the opening ratio does not have to be same as it can still satisfy the requirements of the ventilation rate when it is hot.

Generally, all the correlation coefficients are strong with regard to the outside air temperature and there is no significant difference between medium, large and superlarge ones (less than 0.04). Among them, the percentage of opened windows for the superlarge rooms shows the strongest link with air temperature: its R^2 value reaches to 0.758. The large and medium rooms are in the second and third places with 0.741, 0.715 R^2 respectively. The small one, in this case is less strongly related to the temperature but its correlation value is still high enough to have a value of 0.608 (Figure 6.81).

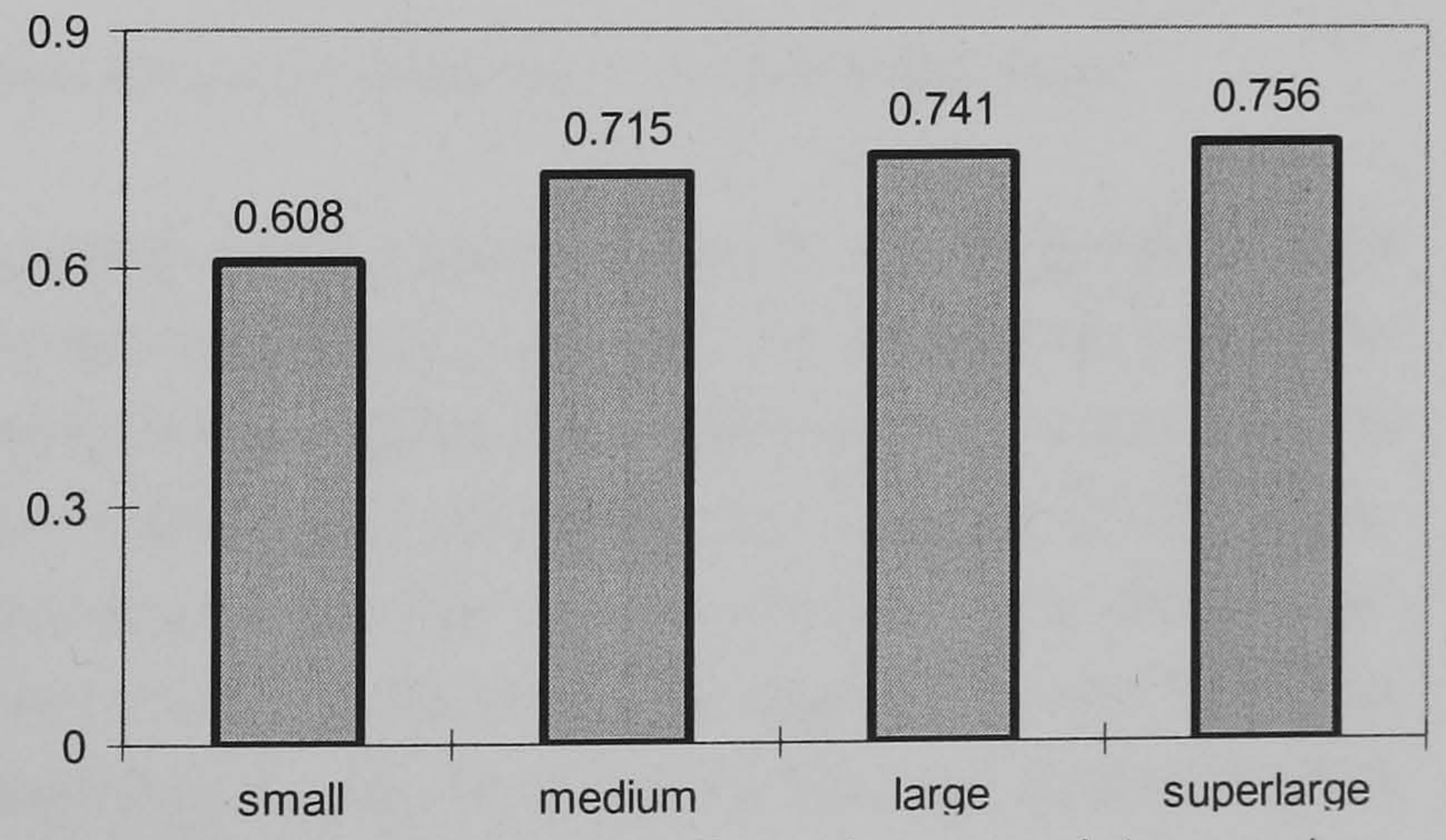


Figure 6.81 Correlation coefficient between air temperature and opened window based on room size

This may be explained by another option for increasing the air velocity: door opening. For an occupant in a room with a small area, the effect of door opening on increasing the ventilation rate is often convenient and efficient compared with opening the windows. But in a room with a large area, normally what the door can do is limited, especially during the hot summer months. Thus, the fact that door opening may weaken the correlation between window opening and temperature when it comes to the small rooms, it does not influence the medium, large and superlarge sized rooms very much.

Blind operation with sunshine hours

In a small room, the walls have very much more area than the ceiling, and, thus, they are more significant in terms of their reflectance's effect on lighting quantity. Conversely, in a superlarge studio, the ceiling is visually much more significant than the walls in affecting the overall space illuminance level, with the exception of places near the wall. Thus, it is not surprising to see in situations with the same sky conditions and orientations, that the small room has a higher average daylight factor than a superlarge room. Different position of blind, here, can play a very important role in adjusting the visual environment.

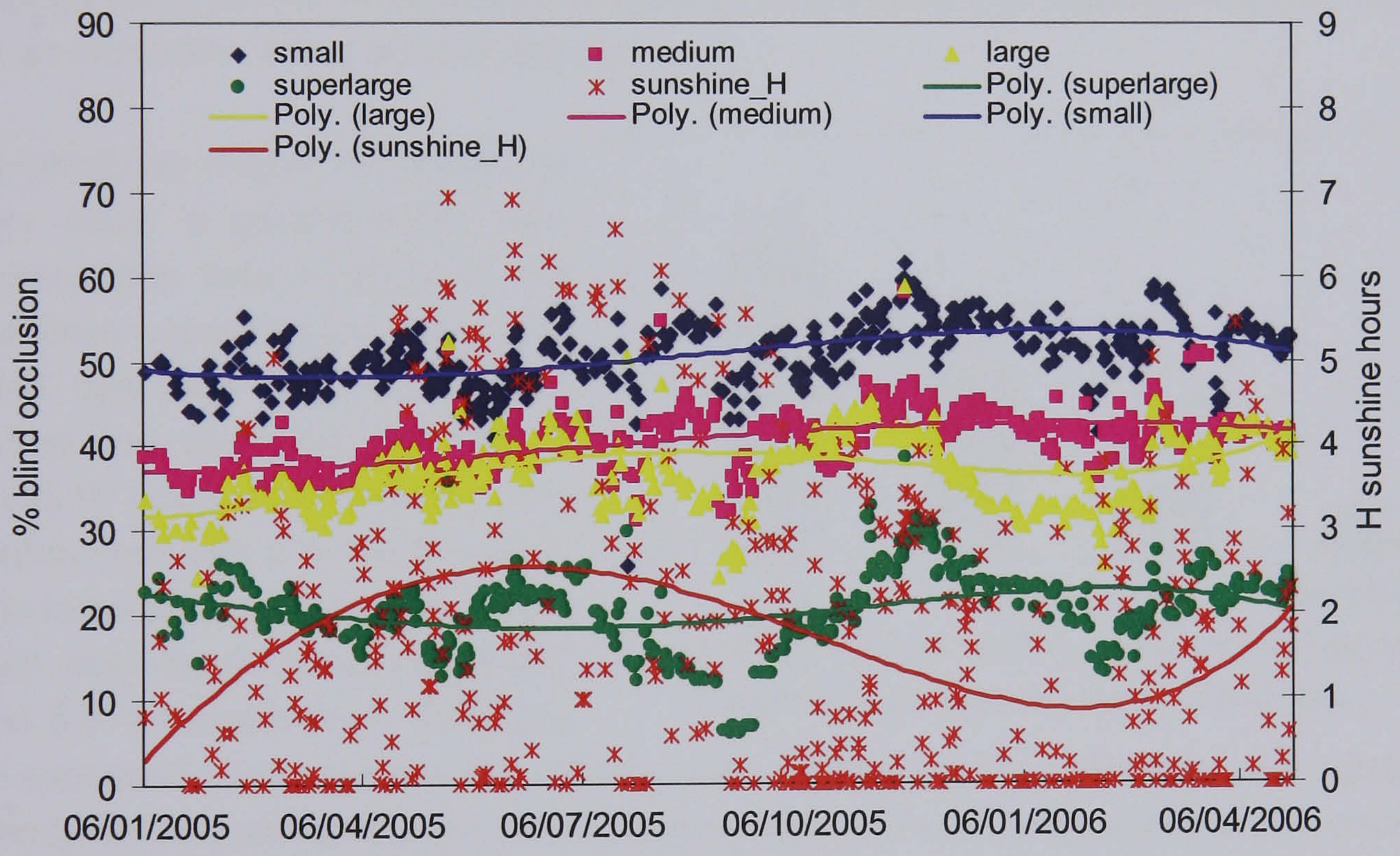


Figure 6.82 Mean percentage of blind occlusion based on room size (architecture)

Although the visual environment between each sized rooms is quite different with respect to daylight received and reflected, the results present only a slight distinction in terms of environmental response by occupants between the various room sizes (Figure 6.82. The blinds from small and medium rooms are both varied in a specific small range. Accordingly, the two curves they represent are very flat without obvious 'hills' or 'valleys'. Graphically, the two curves follow a very similar pattern: gently ascending and they run almost parallel with each other. The average occlusion index for the two rooms is 50.9 and 40.7% respectively with a difference of 10.2%.

The points of average occlusion values for the large rooms although are accumulated closely with those for the medium room, its amplitude of fluctuation is wider than the medium with average blind occlusion maintained at 37.2%. The widest fluctuation occurs in the superlarge room but still they are all in a very low position which means compared with the situation for blinds in the other sized rooms, the superlarge one has the least occlusion and most of the blinds are in the 'up' or nearly 'up' positions. As a result its average value is the lowest with an occlusion index of just 20.6%.

Although the values for large rooms also presented an upward swing, the points of average occlusion value dropped down in summer from Jul to Aug and in winter from Jan to Feb, which meant many blind were pulled up when the strength of solar radiation was at its strongest and the angle of solar altitude was the lowest of the year. The variation in blind occlusion from the superlarge room also exhibited the biggest fluctuation, especially from Sep/05 to Dec/05, which was exactly the period of autumn semester of the university. A firm connection cannot be established to explain why they happen but a further investigation is planned to consider the occupant specific activity as an interactive effect on user operation.

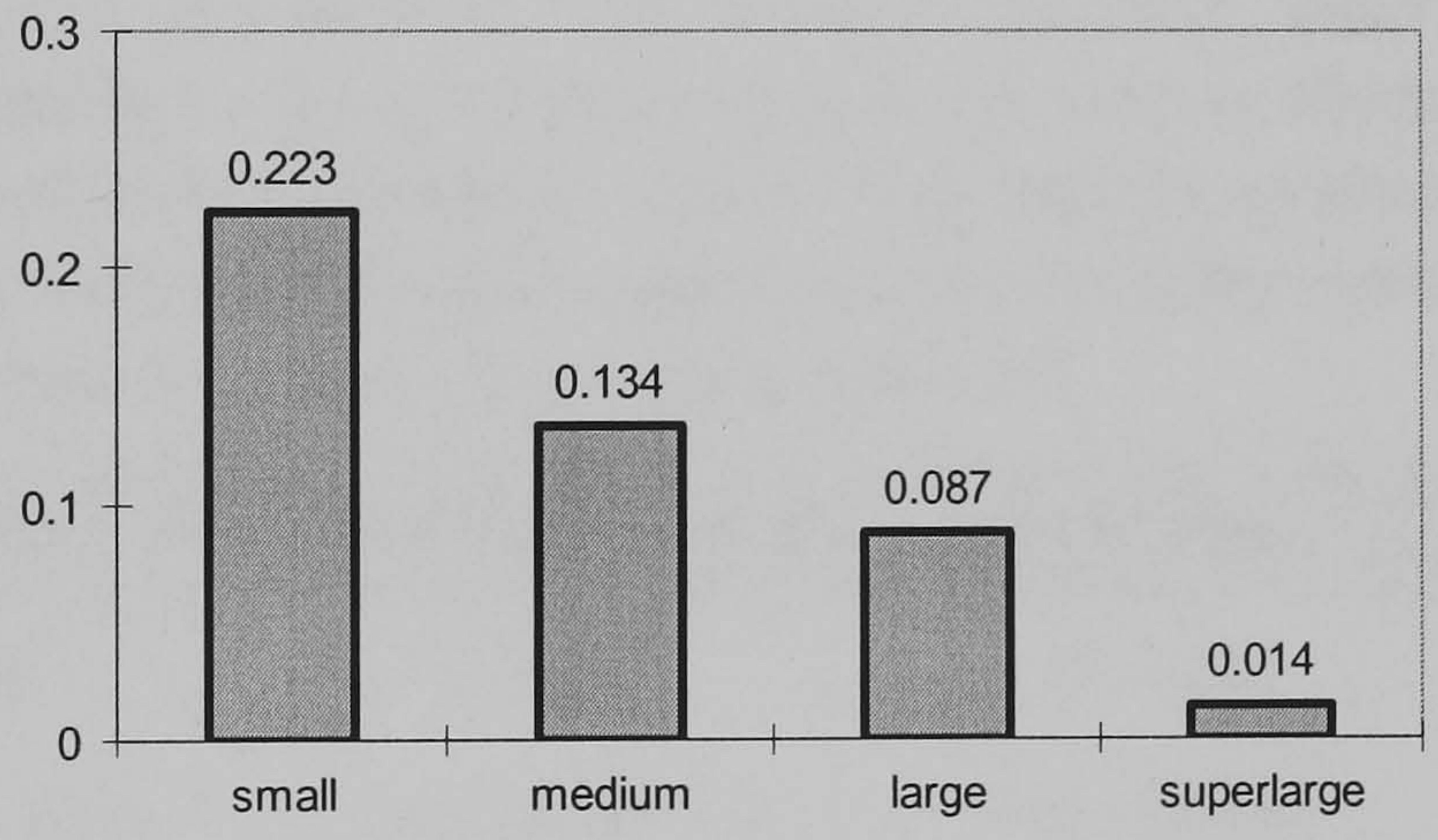


Figure 6.83 Correlation coefficient between sunshine hours and blind occlusion index based on room size

Generally an inverse relationship is very clear: a greater room area corresponds less strongly to the sunshine hours (Figure 6.83). The blind operation in a small room shows the strongest link with a 0.223 R^2 value. The medium one is slightly less with a 0.134 R^2 value. The large and superlarge are in the third and fourth positions (0.087 and 0.014 respectively). This may be explained by the occupants' preference for a good visual environment with relatively evenly distributed illuminance. The daylight factor reduces very rapidly with increasing plan depth from the side window and the large area unavoidably leads to the fact that the reflection from wall can do little to help. Moreover, the variously oriented glazed areas can further intensify the uneven distribution. Under such circumstances electrical lighting is normally switched on to make up for the disadvantage of the daylight impact when the room is occupied, which also means the electric lighting may, in turn, reduce occupant control of blind as a way of adjusting the visual environment.

The impact of three aspects (main effects) on occupant operation behaviour is summarized in Tables 6.12 and 6.13 for comparison purposes. Table 6.12 peration is found to be strongly related to the weather condition: the outside air temperature is an important variable accounting for 0.724 of the correlation coefficient. The percentage of opened window drops to a minimum during the cold winter time but rises to a maximum during the hot summer time. Among them, the value for the west room shows the highest correlation (0.774) while the room for service use has the lowest (0.478), which indicates that the occupant normally has the window opened or closed based on the temperature, and the room function, orientation and area does not change the impact significantly except in the case of those rooms whose occupancy is intermittent, short and low density and composed of floating users, such as the case with service rooms.

R^2 with air temp.	Room usage	Room orientation	Room size
All 0.705	Office 0.666	East 0.712	Small 0.608
Redefined 0.724 (without weekend & holiday)	Communication 0.771	South 0.751	Medium 0.715
	Public study 0.745	West *0.774*	Large 0.741
	Service *0.478*	North 0.677	Superlarge 0.756

Table 6.12 Correlation coefficient between window operation and air temperature

Compared with window operation, blind operation is much more complicated, which shows that the factors that may contribute to occupant positioning of the window blinds may include solar intensity, solar altitude and sunshine hours etc. Their impacts on blind operation are constantly changing as time goes by daily, seasonally and annually. Here the sunshine hours are measured to test the relation to the blind operation.

R^2 with sunshine hour	Room usage	Room orientation	Room size
All 0.097	Office *0.268*	East 0.101	Small 0.223
Redefined 0.117 (without weekend & holiday)	Communication 0.084	South 0.127	Medium 0.134
	Public study 0.090	West 0.125	Large 0.087
	Service 0.048	North 0.061	Superlarge *0.014*

Table 6.13 Correlation coefficient between blind occlusion and sunshine hour

Table 6.13 shows there is some link between the period of sunshine and blind use with a correlation coefficient of 0.117. As time passes, the fluctuation of blind occlusion only deviates within a limited scope and gradually rises up, which means many blinds once pulled down are not usually put up again no matter what outside sky condition is. Only in the case of the office room, which differs from other occupancy patterns, can a connection be established between blind use and sunshine hours. It also has the highest correlation with 0.268. But the variously orientated rooms can all be related to sunshine hours according to the order south, west, east and north. This order is strongly related to the sun path which has a significant impact on the specific range the blinds are positioned in. When it comes to differently sized rooms, only in the case of the small and medium rooms is the correlation with sunshine hours more than 0.1, with figures of 0.223 and 0.134 respectively.

6.3.1.5 Operation Based on the Interactions between Variables

In the preceding part, the variables considered are all discussed separately and analyzed in a situation that ignore the other two impacts. In this part the study considers the effect of the interactions between these variables. Due to time and human resource limitations, which have been mentioned before, only the office room is discussed with respect to the various room orientations and sizes. Other occupation patterns have to be omitted and can only be analyzed in future studies.

One reason is that the office is shown to be statistically significant in terms of blind operation. It has the highest correlation with sunshine hours when compared with the other occupancy patterns and the opened window ratio also has a high (although not the highest) R^2 value with air temperature. Also, it is important that almost respondents of the questionnaire survey in the Arts Tower were occupants who had a fixed study and/or working office room. Therefore, a comparative study can also be done in order to have a clear view of the differences between the answered and actual operation of the windows and blinds by occupants. Before the survey was finished, in total 223 rooms were for office use in the Arts Tower. The south occupied 66.4% of the total number of office rooms. And the rest of them (33.6%) were then broadly evenly distributed in the east, west and north (Figure 6.84). Similarly, the office windows also followed the similar distribution with the office rooms based on orientation (Figure 6.85)

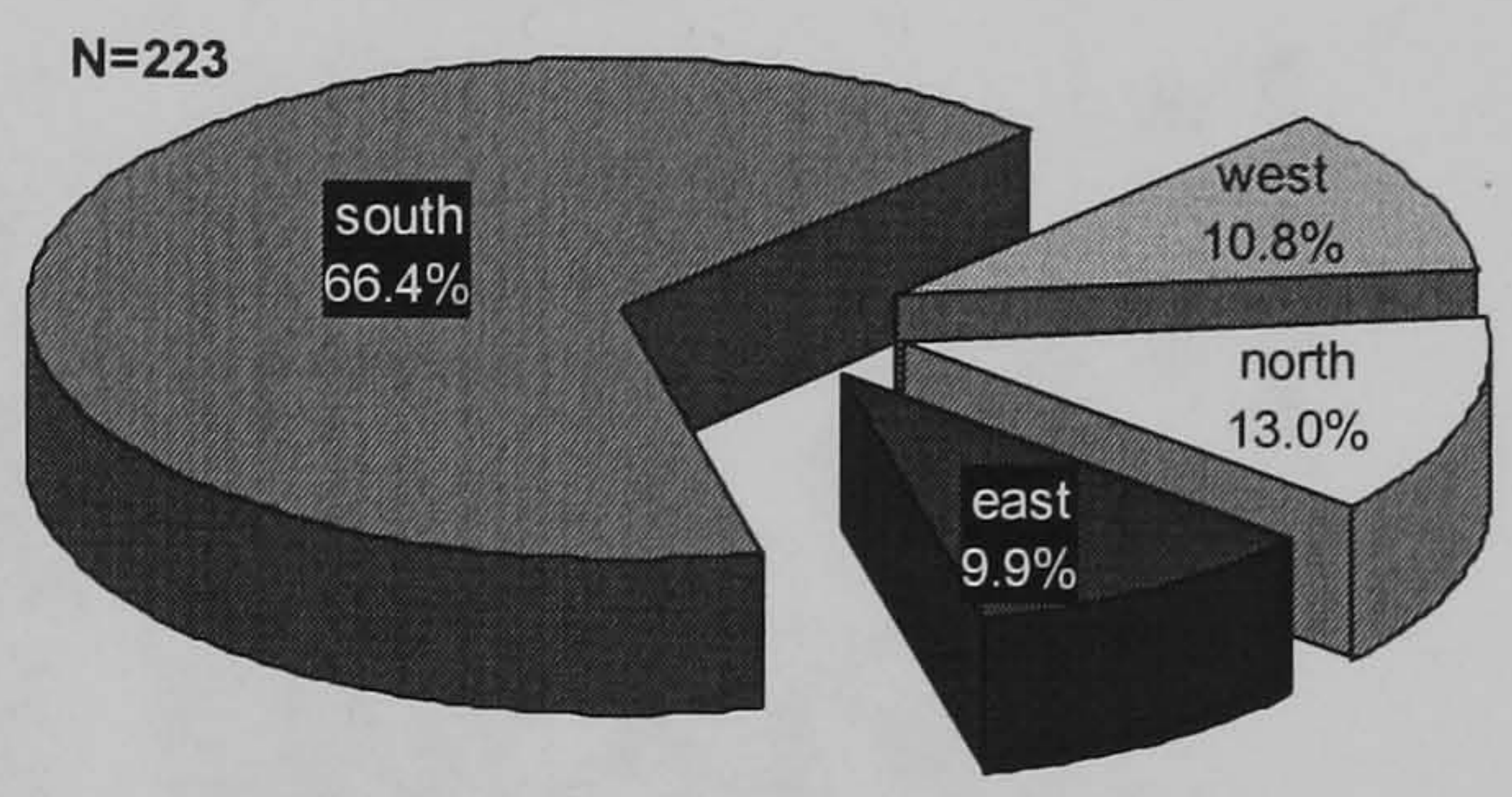


Figure 6.85 Breakdown of the offices based on orientation

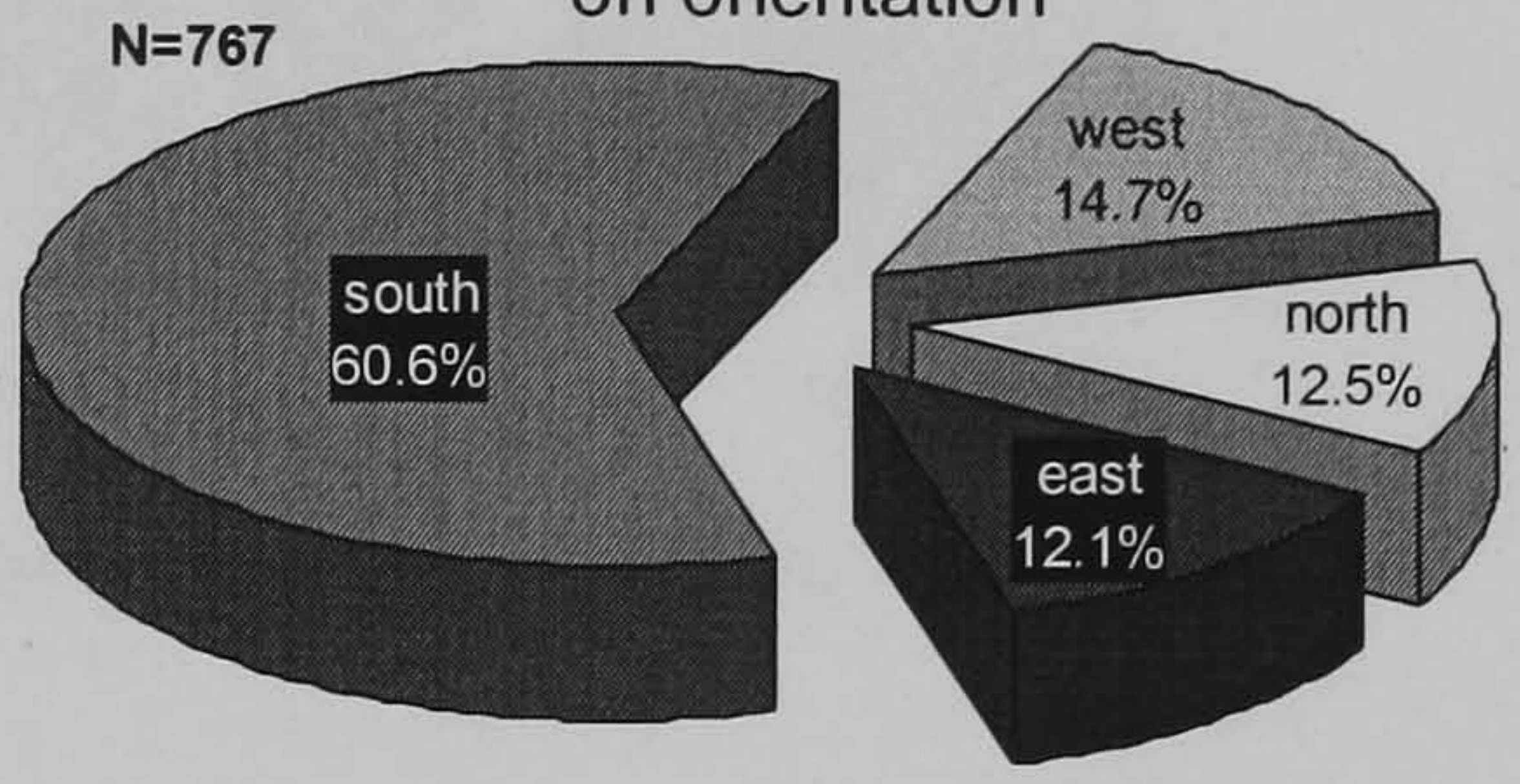


Figure 6.84 Breakdown of the offices windows based on orientation

Window operation with air temperature based on the orientations of the offices

Generally, there is not much difference when the office windows are filtered from the whole building (Figure 6.86). The peaks of the opened window ratio for all the oriented office windows still follow the fluctuations of air temperature. Orientation does not have a significant impact on the change of the trend.

However, the orientation does affect the amplitude of the variation, especially when it comes to the summer and autumn months. Data analysis indicates the occupants in the south office are active in window opening. Its curve line always stays in the upper position and this becomes more and more evident, moving from the winter to the summer. The north and east curves are close but slightly lower than the one for the south. The points for the values from the west office in this case are kept in the low accumulation, which is plotted apart from the alternatively orientated office rooms. The average ratio also confirms the impact of orientation on window operation. The windows in the south office have the highest value with a 9.8% opened ratio. The north and east ones are in the second and third positions with 8.6 and 7.2% respectively. The west one, in this case, has the lowest (3.8%).

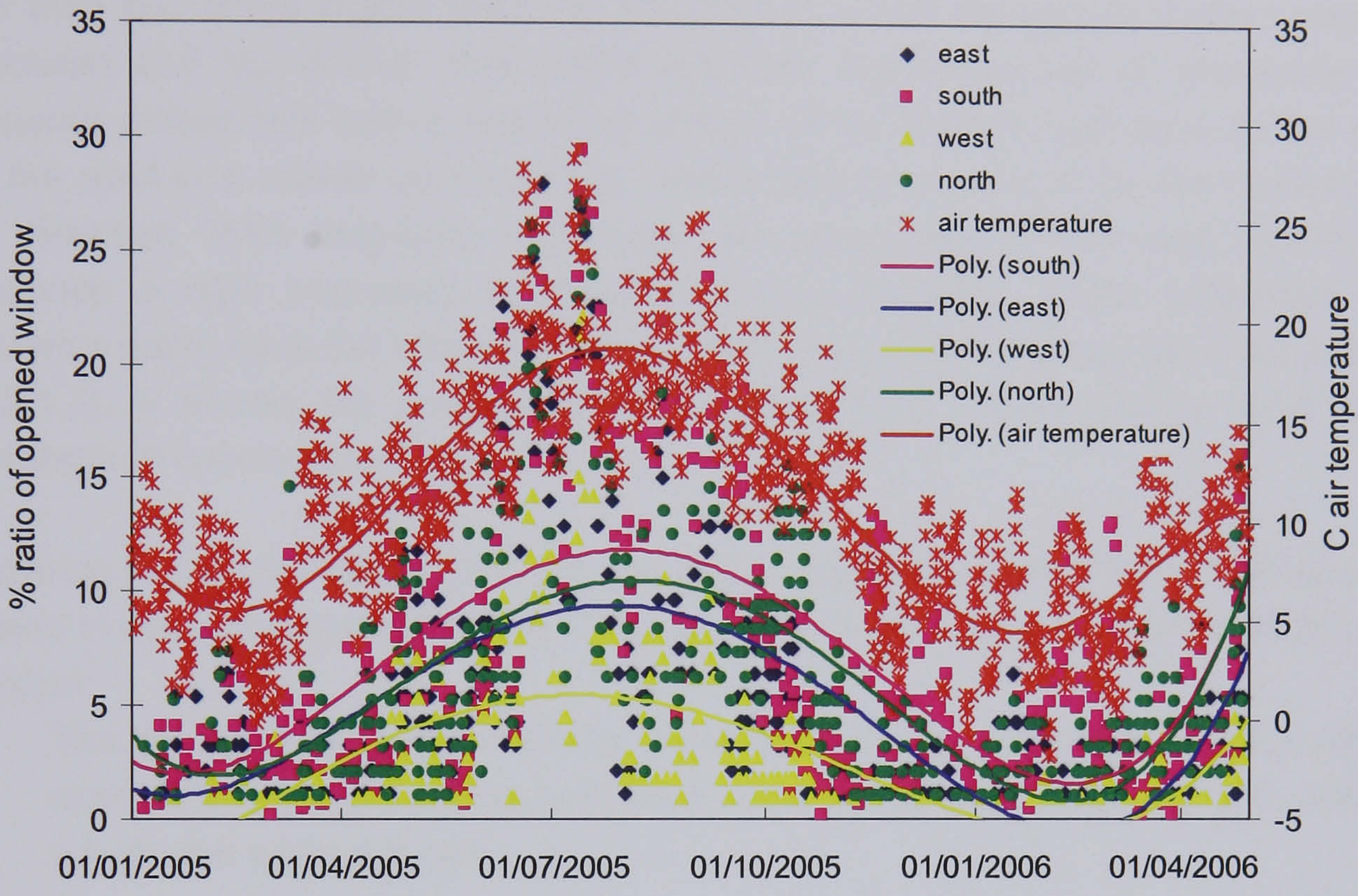


Figure 6.86 Mean percentage of opened window based on the orientations of the offices

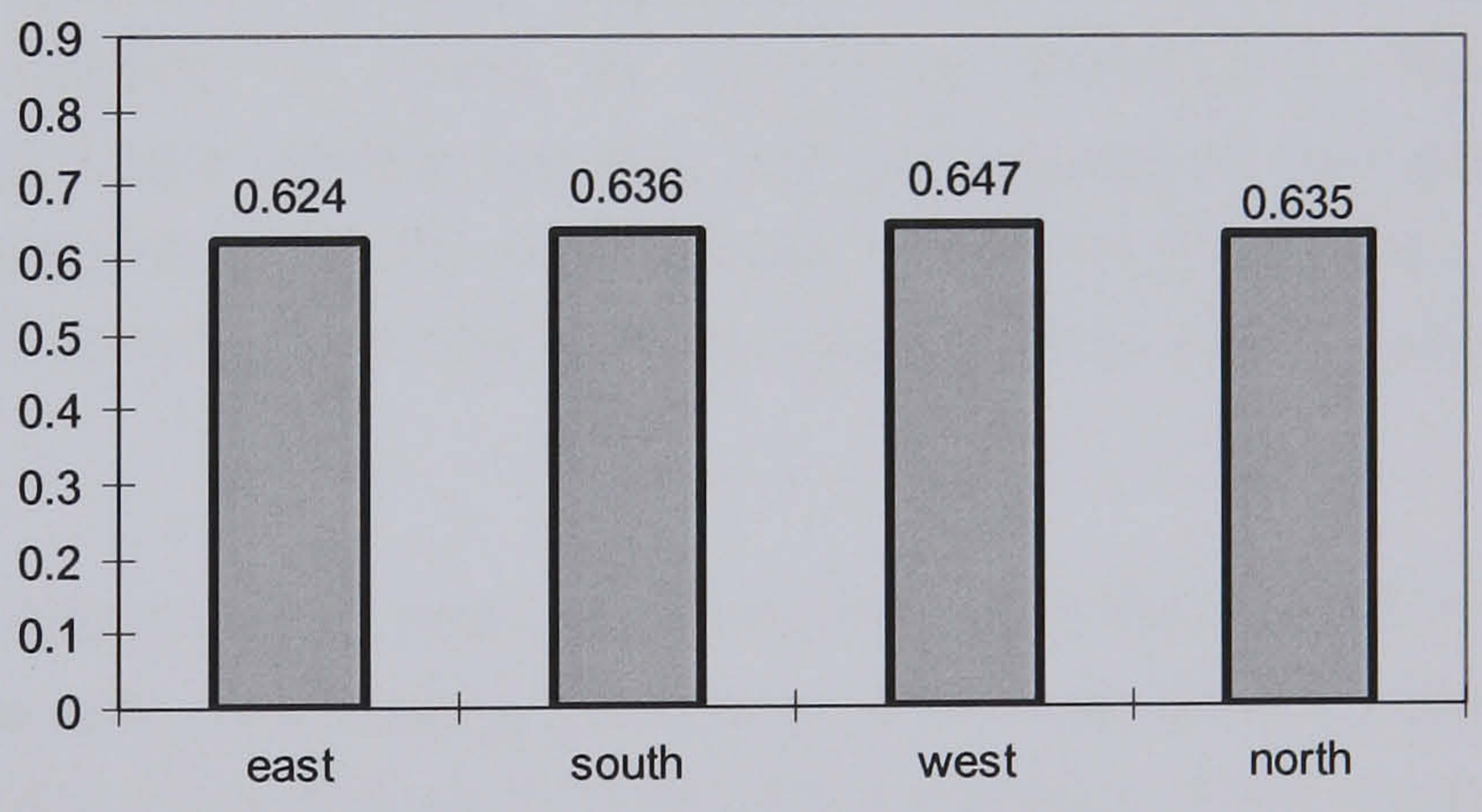


Figure 6.87 Correlation coefficient between air temperature and opened window based on the orientations of the offices

Generally, in terms of air temperature correspondence, all the correlation values for the office room grouped by orientation are slightly lower than the ones without orientation considerations (0.666). But there is no difference between each orientated window, which means that no matter in which orientated office room occupants stay, their window opening behaviour tightly corresponds with the outside air temperature. It can be seen that they are almost the same with only 0.02 more from maximum to minimum R^2 (Figure 6.87). Comparing the R^2 value with the whole building (0.724), the office occupancy pattern (continuous and long-term occupants with fixed users) weakens the window operation with the air temperature. This may be explained by the fact that these occupants in such a working environment prefer door opening - a more convenient and quicker alternative. This tendency can be seen also from Data Analysis I when comparing the operation of doors and windows under various weather conditions (6.2.1.7).

Comparing the average opened ratio without considering the occupation pattern, all the ratios of the variously oriented office rooms are slightly higher except for the west one. This is especially true when it comes to the north orientated office. Its average value is more than two times higher than the situation in which occupancy pattern was not considered (3.6 vs. 8.6%). This result indicates the interaction of orientation and occupancy pattern has both a promoting impact on the window operation. In this case, only the west one makes an exception, which may be explained by the predominant wind direction. With long-term occupancy, the occupants of the west rooms may experience a high frequency of discomfort from draughts, which influences their preference not to have the window opened. This is also indicated from the Data Analysis I (6.2.1.7). It shows the occupants of the west office rooms always have a low percentage of opened windows.

Comparing the results which show the occupant's actual control in Figure 6.86 and their answers in the questionnaire survey in Figure 6.30, there are three main conclusions to be drawn:

- The two figures present a similar trend in which temperature affects the window operation very much. They both have a low percentage ratio when it is cold and a high one when it is hot.

- Broadly, although the overcast cold (sunny hot) weather cannot absolutely refer to the winter (summer) days, they roughly represent most of the weather situations in these two seasons. In terms of orientation distribution, the occupants from south office rooms always have a high percentage of opened windows while there is a low one from the west rooms in both of the figures. From this point of view, the results from the questionnaire survey seem quite reliable in practice.

- When the occupants feel it necessary to open windows, not all of them but only some are operated. For example, statistically, there are 148 offices towards the south with 397 windows in total. From Figure 6.30, 90.8% occupants of the south offices select their windows 'opened' when the weather is sunny and hot. These 90.8% occupants are from 118 office rooms with 376 windows. However, in reality even in a hottest day with the longest sunshine hours, the opened window ratio is still less than 30%, which is shown in Figure 6.86. This indicates that only a small proportion of the windows are actively controlled by occupants in the south office rooms. If this extends to the other orientated office rooms, the result also matches.

Blind operation with sunshine hours based on the orientations of the offices

The value of blind occlusion for just the office rooms does show some noticeable difference with the situation in which all of the building rooms were grouped according to their various orientations. However, the values for each orientated blinds occlusion still do not present a better distribution in terms of following the pattern of sunshine hours (Figure 6.88).

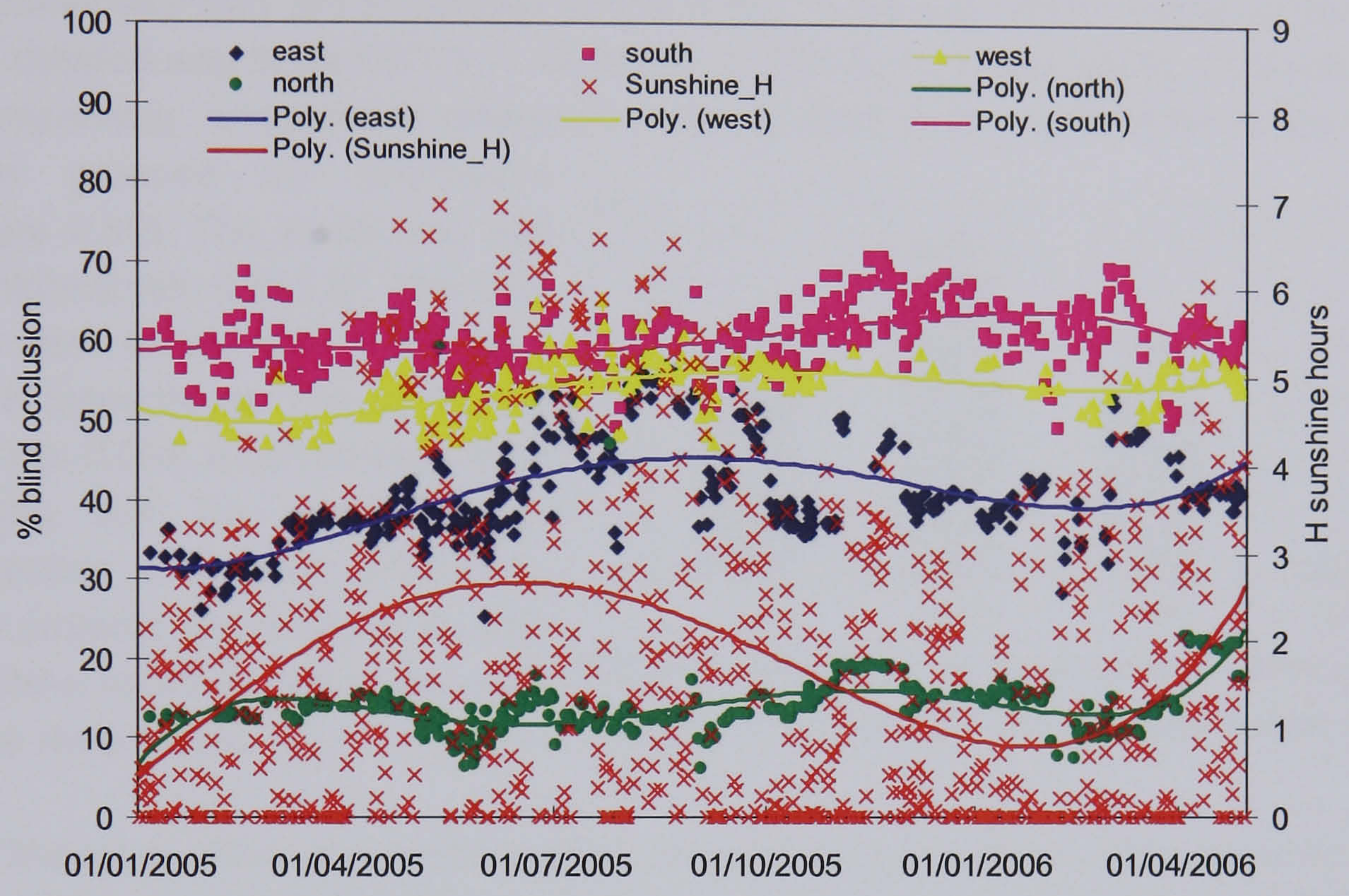


Figure 6.88 Mean percentage of blind occlusion based on the orientations of the offices

Although the occlusion values for each oriented blind are separated from top to bottom in an obvious order: south, west, east and north like the situation in Figure 6.77, it presents a more stable fluctuation, especially from the south and west curves. Therefore it is not the blind for the office but for other room usages that drives the curve's decrease during the summer months as the south office curve is very flat from the very beginning to the late autumn, while it partly contributes to the increasing curve line during the winter months: it rises up slightly but does not fluctuate as much as the result shown in Figure 6.77. On the other hand, the west line for the office room is placid when compared with the two figures. It also indicates that the occupants in rooms with other usages are more active than those in the office, and this makes sure that the west orientation experiences a very varied fluctuation.

Of all the four oriented curve lines, there is not a discernable ascending trend except for the east one. This presents the biggest variation and shares a similar pattern of fluctuation with the one in Figure 6.77. From the middle of spring in Apr. the curve line gradually rises up and reaches the highest point in the late summer. After that the curve drops but it can be seen that not all the blinds in the office are pulled up as a result, the line has a clear increasing trend, which makes the valley of the curve in winter II is a little higher than in winter I. Therefore, the east office blind also makes a contribution to the whole façade's variation. The north curve is the same, as expected, without obvious rises and falls. It maintains the lowest blind occlusion level.

The values of these four orientated points generally are assigned in an order that is same as the general situation and without the consideration to occupation. Fundamentally they are influenced by the angle of the sun, which was discussed in a very detailed way in part 6.1.1.1. Generally, in terms of corresponding sunshine hours corresponding, a significant difference presents itself in the case of the office rooms when grouped by orientation (Figure 6.89). The south one has the highest with 0.323 R^2. The east and west follow with 0.227 and 0.215 respectively. The north one only has 0.003. It can be seen after filtering that the interaction of orientation and office occupancy both promote the relationship with sunshine hours except in the case of the north blinds.

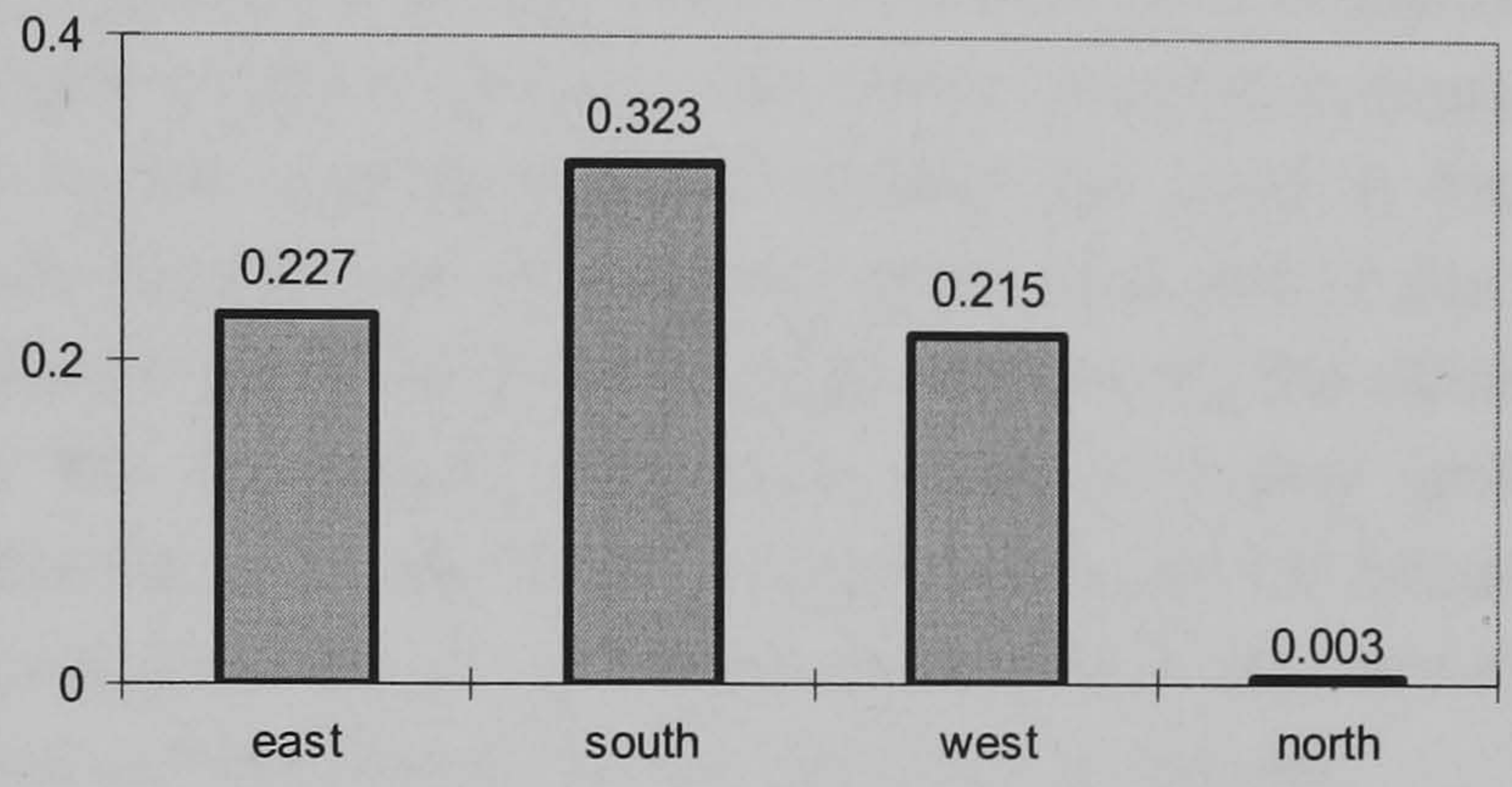


Figure 6.89 Correlation coefficient between sunshine hours and blind occlusion based on the orientations of the offices

The impact of office occupation pattern on blind operation does make for some other differences. Except the north one, the accumulation of each oriented point is slightly higher when compared with Figure 6.77. This is not discernable for the south as the average value is only 0.6% – an increase from 58.9% to 59.5% for south office rooms only. But both the west and the east show an obvious increase: the west goes from 46.9 to 54.1% (a 7.2% increase); the east from 34.5 to 41.6% (a 7.1% increase) which leads to the trendlines being much closer to the one for the south. On the other hand, the north accumulation presents a decreasing trend from 18.4 to 13.8%. This result indicates the interaction of orientation and fixed user with long time occupation both has a promoting impact on blind operation, requiring more occlusion, especially for the east and west façade office rooms. Conversely, the occupants in the north office room prefer larger areas of glazing penetration than in the rooms with other usages.

Compared with the results that show the occupant's actual control in Figure 6.88 and their answers to the questionnaire survey in Figure 6.32, there are four main conclusions to be drawn from the results:

- The figures drawn from the questionnaire survey show a trend in which the sky condition continues to be the dominating factor, although its impact is not as dramatic as expected. From the figure for site observation, it doesn't show an evident relation with sunshine hours. But from the statistical correlation calculation, the sunshine hours and blind operation corresponded but not in a very strong way.

- Whatever the weather situation, the respondents in the north office room do not bother with blind control. The result very much matches what actually happens and a very stable trendline is exhibited. The values for single data points assigned to a certain occlusion deviate very narrowly. As a result the trendline's amplitude of fluctuation is very small and without a clear variation.

- The respondents in the south office room always have the lowest ratio of blinds in the 'up' positions and the highest ratio of those in the 'down' position in every weather situation considered in the questionnaire. Naturally, the blind in the office rooms towards the south façade has the highest blind occlusion index. The figure of actual control also presents the highest occlusion among the other blind orientations. However, the significant difference between sunny and overcast in the result of questionnaire survey doesn't reflect the figure for actual control. It indicates that the occupants are not as active as they think they are in making adjustments to the blind position based on the condition of the sky.

- The occlusion index for the offices in the west and the east is between south and north, which indicates both in the questionnaire survey and actual observation. However, from the result of questionnaire, it is indicated that the blinds in the west are often kept in the 'up' position with a higher ratio than those in the east. But this does not make the blind occlusion level lower than that in the east. By contrast, in reality, the occupants in the west office rooms always keep more blinds in the 'down' or 'half down' position than do those in the east office rooms.

Window operation in the south office rooms with air temperature based on room size
Among the four orientations the south one always displays a high correlation with the weather situation in terms of occupant control of windows and blinds. Therefore, in this case the windows and blinds from the south façade are further filtered from other orientations. Furthermore, there is another reason to pay attention to the south office room only.

Office space, as one of the typical occupancy patterns in the Arts Tower occupies 41.1% of the total investigated area with 223 rooms and 3318.0m^2 (Figure 5.22). Among these rooms, 66.4%, almost two thirds, of them are distributed towards the south façade (Figure 6.84). Therefore, the occupant behaviour from the south office room can also display a typical and representative pattern in terms of the whole building. They are used to test how and on what level room size affects the occupant behaviour when the occupancy pattern (office) and orientation (south) are both the same. The other orientations, although also important, can only be discussed in future studies. It has to be mentioned that in reality there are no large and superlarge office rooms towards the south, so the figure can only present the situation with regard to small and medium office rooms (Figure 6.90).

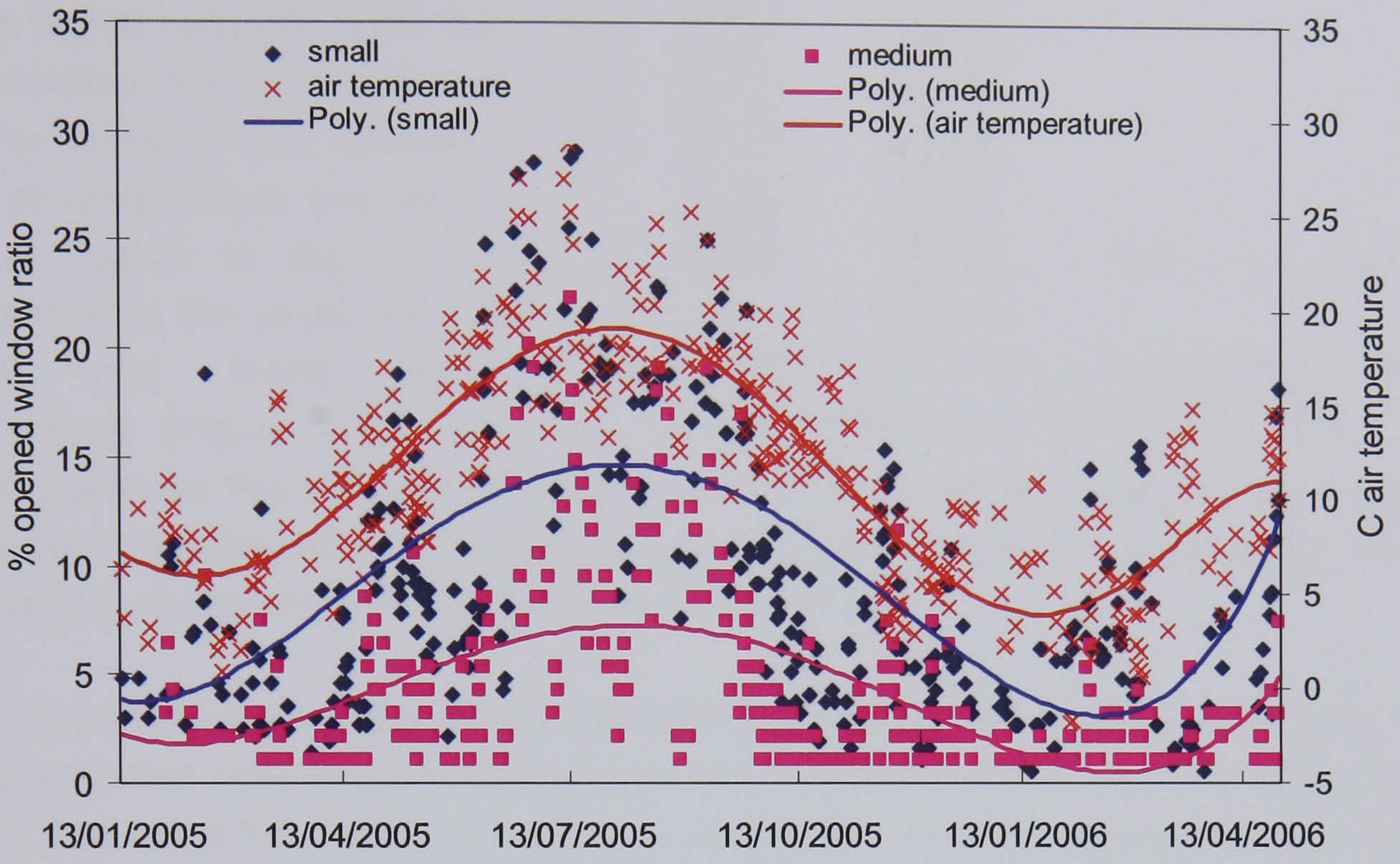


Figure 6.90 Mean percentage of opened window based on the sizes of the offices towards the south

Data analysis shows the points of value accumulated still follow the variations in air temperature. The interaction of room usage (office), orientation (south) and size (small, medium) doesn't affect the strong relationship between temperature and window opening control. But from the figure it can be seen that most of the lower accumulation is accounted for by the medium room while the upper one represents the small one. This feature is maintained noticeably even during the winter months, and it becomes more and more obvious in the summer months. As a result the amplitude of fluctuation for the medium room is much smaller and its position is below the small curve from which it is clearly separated.

This may be explained by the combination of several factors. One, which was demonstrated earlier, is that only a small number of windows are actively controlled by occupants. The others are normally kept closed all the year round. Compared with the total number of each of the variously sized office rooms, the small offices are over 12 times than the medium ones (137 vs 11), which unavoidably leads to a higher ratio for opened windows. On the other hand, 63.6% of medium office rooms are intended for multiple occupancy use, while 78.8% of small office rooms are for the use of a single person. Therefore, individuals in a multiple occupancy office room may not feel as empowered as they would do in a personal office when it comes to altering the window. Especially during the summer time, the occupant of a small room is able to manipulate the primitive controls at will more freely than in a medium-sized public office.

From the view of the average ratio of opened window, as expected the small office room has a higher ratio with 9.4% than the medium office room (4.3%). But in terms of the correlation with air temperature, the value is slightly higher in the medium office than in the small one with 0.615 and 0.598 figures respectively (Figure 6.91). The main reason for this can be explained by the fact that widow opening is more efficient than door opening in a room with a large volume in terms of increasing the air movement, especially on hot summer days (see 6.3.1.4).

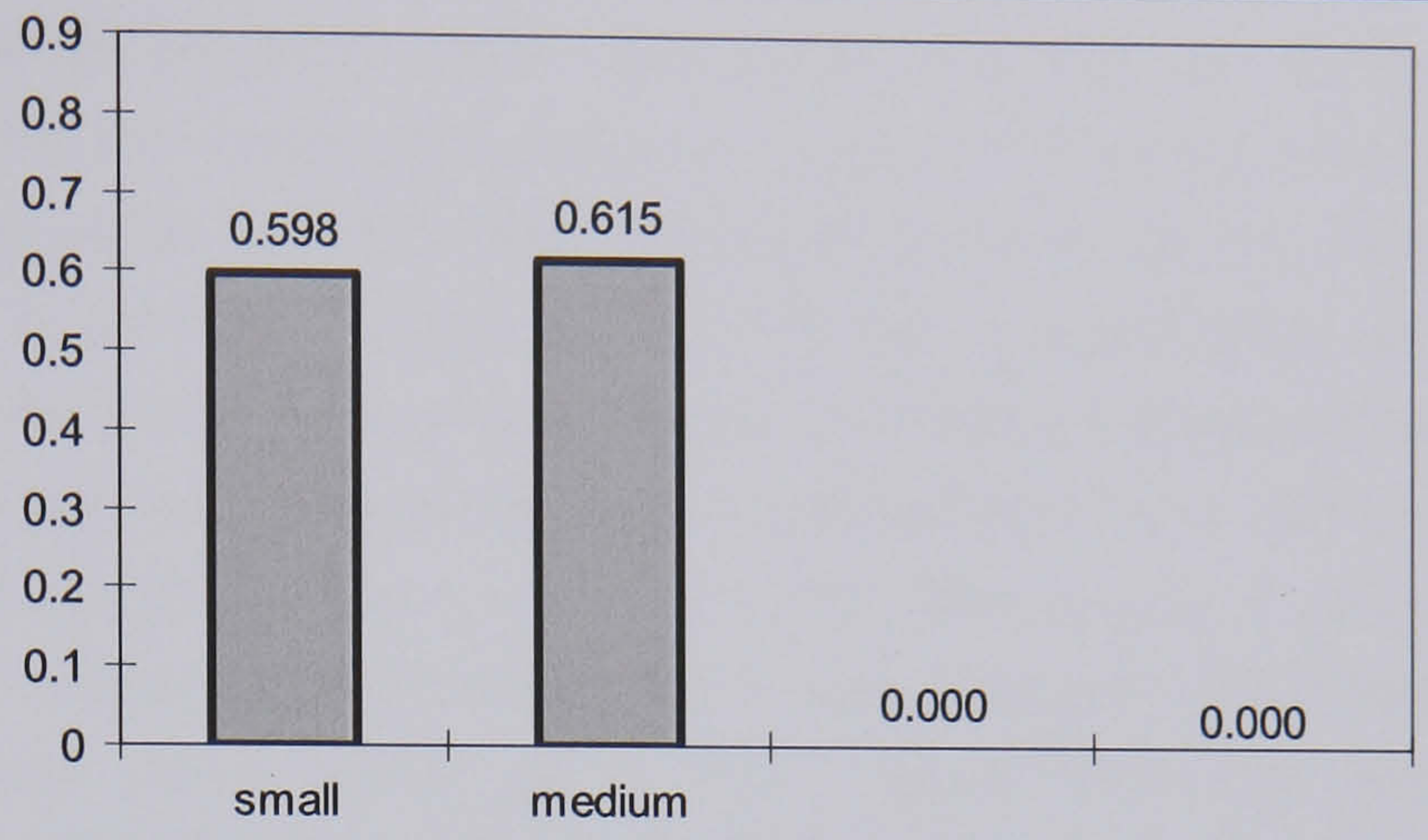


Figure 6.91 Correlation between air temperature and opened window based on the sizes of the south offices

Blind operation in the south office rooms with sunshine hours based on room size

Blind operation between each office room size displays a similar kind of pattern (Figure 6.92). The value for single data points is distributed across a narrow occlusion range. Consequently, the trendlines are very flat without obvious increases and decreases. Comparing the results with a stable curve that has a slight winter increase in Figure 6.88, two factors for manual blind control may be indicated. The stable condition without a discernable fluctuation from the beginning of the year to the late autumn is a result of data relating to both of the room sizes. But the increasing level of occlusion during the winter months is mainly as a result of data relating to the blinds in small sized offices.

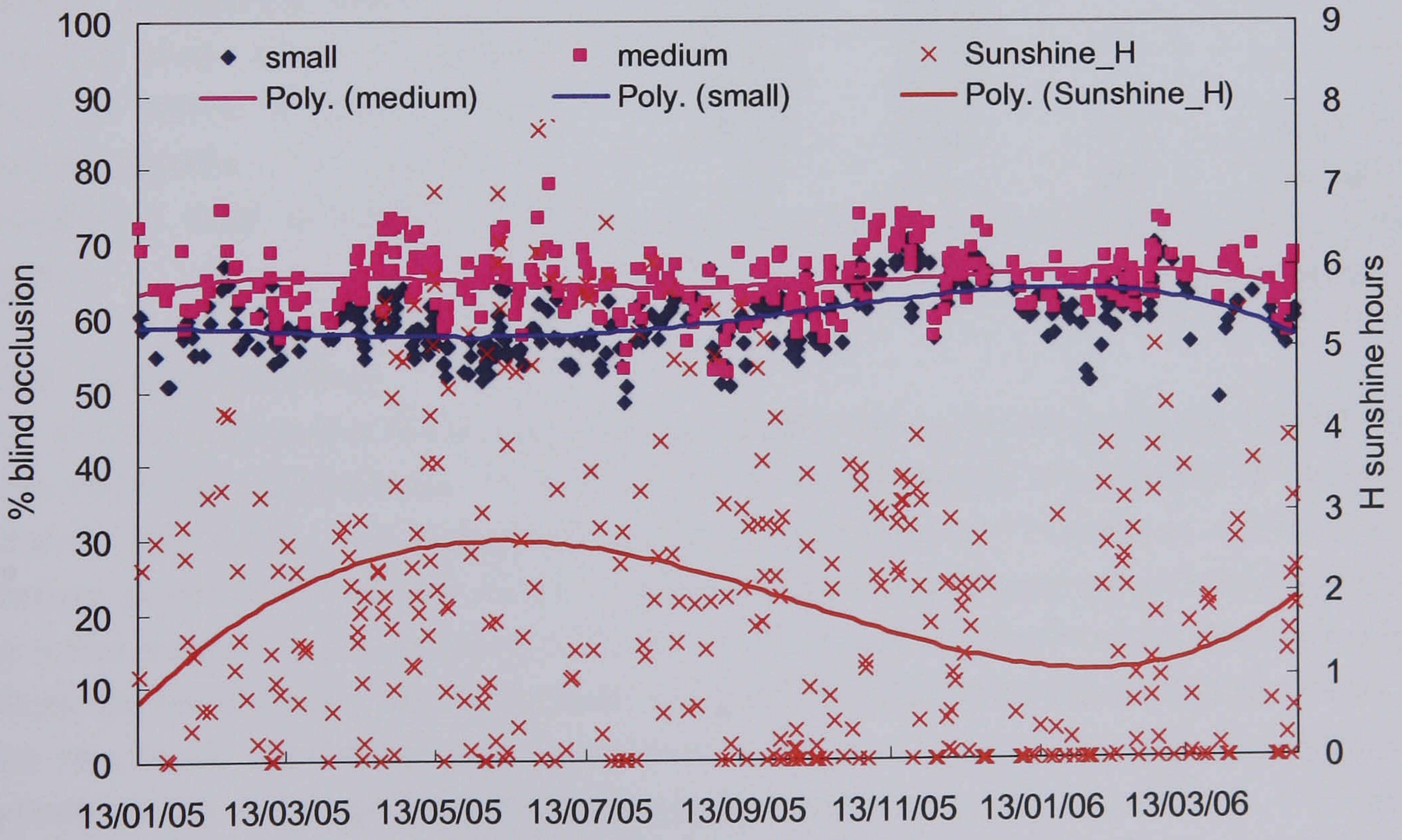


Figure 6.92 Mean percentage of blind occlusion based on the sizes of the offices towards the south

From the observation, the curve for the medium office room stays relatively flat during the winter II period while the one for the small office has an upward tendency, which means that more blinds in the small south office rooms are pulled down in winter. This may be explained by the layout of a particular office. In a room with a small area the visual display terminals may not be as freely arranged as those in a medium sized office, which means that in winter with low sun altitudes glare occurs unavoidably if the blind is not pulled down and the slat is not closed. On the other hand, the points of each occlusion value are distributed very closely to each other. As a result the two trendlines are located very near the medium office curve at a level higher than the line representing the small one. Compared with the average value for the whole building (39.8%), the south office has a very high level of average occlusion with 64.9% for medium and 59.8% for small. It seems the occupants prefer to use artificial lighting as the main lighting source and the function of glazing is more important in terms of the view than for daylighting, as around 60% of the glazed area is occluded by the blind.

However, further data filtering of the south office blinds in terms of different sizes strengthens the correspondence with sunshine hours. The blind for the medium sized south office has the highest correlation: 0.449. It even reaches to the highest level among all the main effects and interactions considered in this study. The small one, although lower than the medium one, is still as high as 0.336 (Figure 6.93). This result is not expected, because from the analysis of window operation, individuals may not feel as empowered to alter the blinds in multiple occupancy office rooms, and this may have a negative effect in terms of blind control. Further studies are needed to establish a clear principle in this respect.

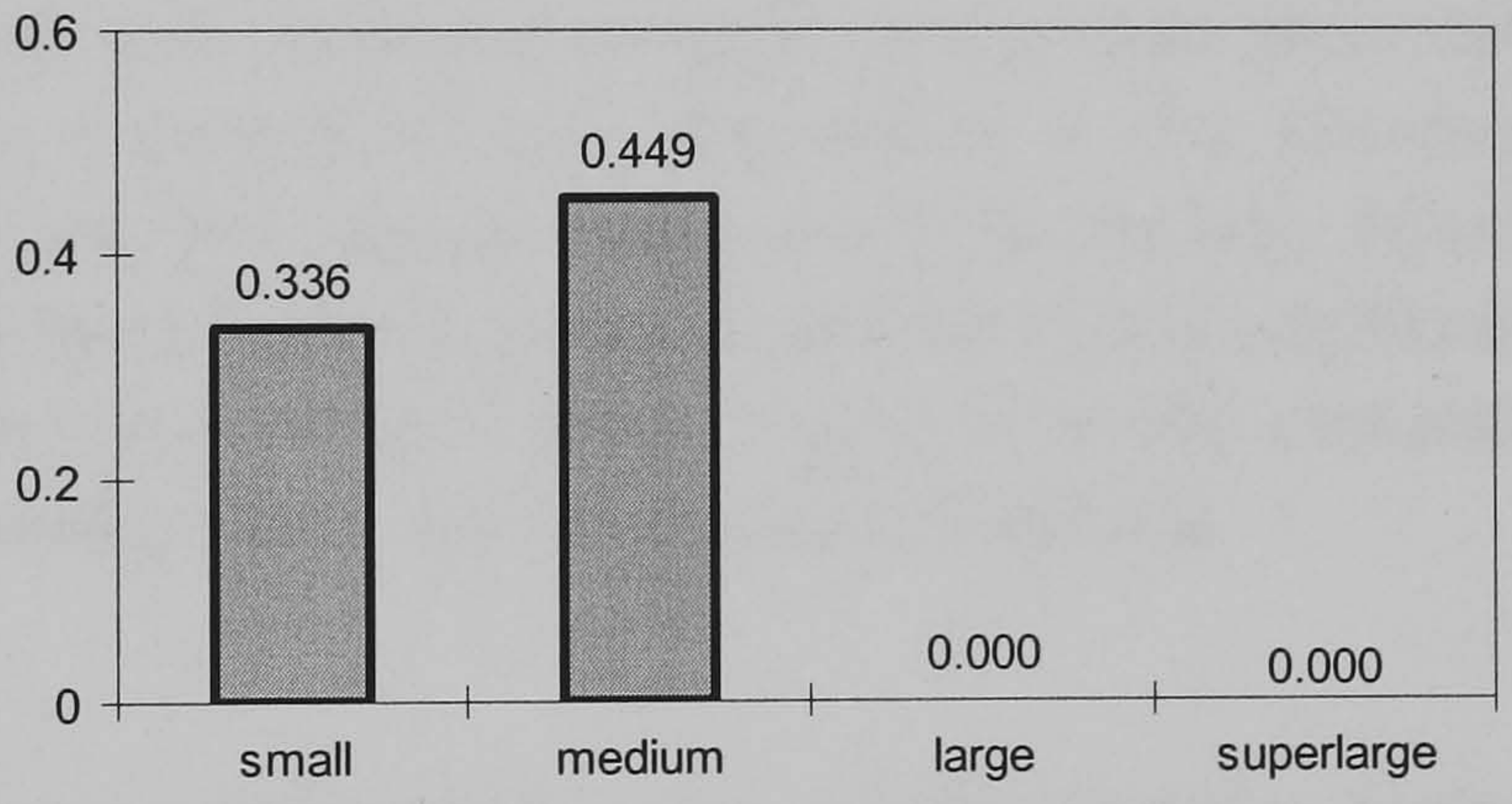


Figure 6.93 Correlation coefficient between sunshine hours and blind occlusion based on the sizes of the south offices

6.3.2 ICOSS Building

The investigation in the ICOSS Building included three multiple-occupancy rooms and three open-plan laboratories, as these are the working areas where most of the daily activities take place. The occupancy pattern is office use and it involves rooms of two different sizes (174.4 m^2 and 42.0m^2). All the multiple-occupancy offices are located in the same position on three floors from 2nd to 4th toward northwest while the open-plan offices are beside them with both south and north facing windows (see Chapter Five). It also has to be mentioned that the ICOSS has an advanced Building Management System (BMS). Although this part discusses how occupants use the windows, it is more accurate to refer to the results as a combination of both occupant manual control and building operation by BMS.

Due to its distinct features, the rooms are not grouped into occupancy, orientation and size as in the case of the Arts Tower study. However, the air temperature and sunshine hours are still two main weather parameters considered to affect the occupant control of windows and shading rolls. The correlation coefficient is used to validate the relationship between them as well. In this part seasonal effect is firstly discussed to see the impact of the time of year on occupant manual operation. Two variables are then added to identify their influential effects.

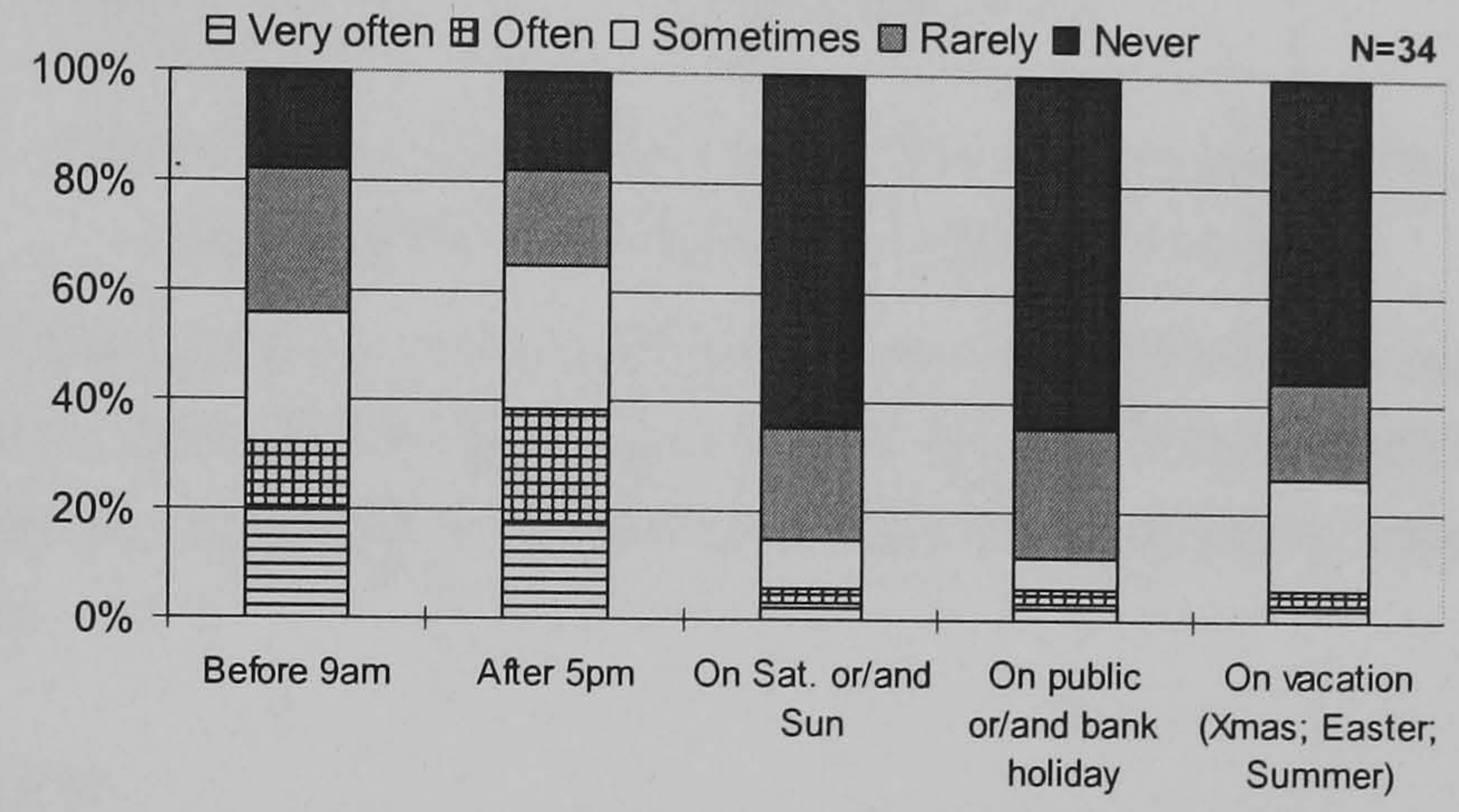


Figure 6.94 Occupancy situation with regard to the non-standard semester time and day (ICOSS Building)

For the ICOSS investigation, the record of window and blind positions towards the south was available from Mar/05 to Apr/06 and for the north from Jul/05 to Apr/06. The small window towards the west with 1.8m^2 area in each multiple-occupancy office has not been included in this study. When it comes to occupancy density, because the ICOSS Building is a research centre comprising mainly management and technical staff and research students, the working schedule is very predictable in the standard workweek (see 5.4.5), With regard to the non-standard semester time and day, Figure 6.94 shows on weekends (Sat and/or Sun), holidays (public and/or bank) and vacations, over half of the percentage users are 'rarely' and/or 'never' presented which indicates during these periods of time, the building has a very low occupancy density.

Data filtering

The data for window and blind positions obtained from the ICOSS Building is also examined in order to filter the days when it has a low occupancy density, in this case weekends and holidays. Figure 6.95 compares the results in a time series order from Jul/05 to Apr/06. The correlation coefficients (R^2) in each chart above are corresponded with the windows opened and the average outside temperatures while the charts below are the average occlusion index and its R^2 value with the sunshine hours. Both of the values are higher in the sampled data set than in the complete one which means due to filtering the situation with low occupancy density of the building, the strength between the two variables is improved. Therefore, the data abstracted from observation are redefined without weekend and holiday records. They are used in order to do the further analysis.

6.3.2.1 Seasonal Effects

The ICOSS Building has a well-designed layout for each working station in the office space (see Chapter Five). The arrangement of the station near south façade is placed 5 meters away from the glazing which efficiently avoids the dramatic change of illuminance from daylight and the asymmetry of thermal radiation, both of a solar and cooling radiation. A relatively stable environment may weaken the seasonal effects on occupant control of windows and blinds. In addition, this building was original designed for over one hundred researchers, but up until the end of the survey period in April 2006, there were only about 45 occupants working in the ICOSS Building. The new building with its low density of occupancy may further weaken the seasonal effects.

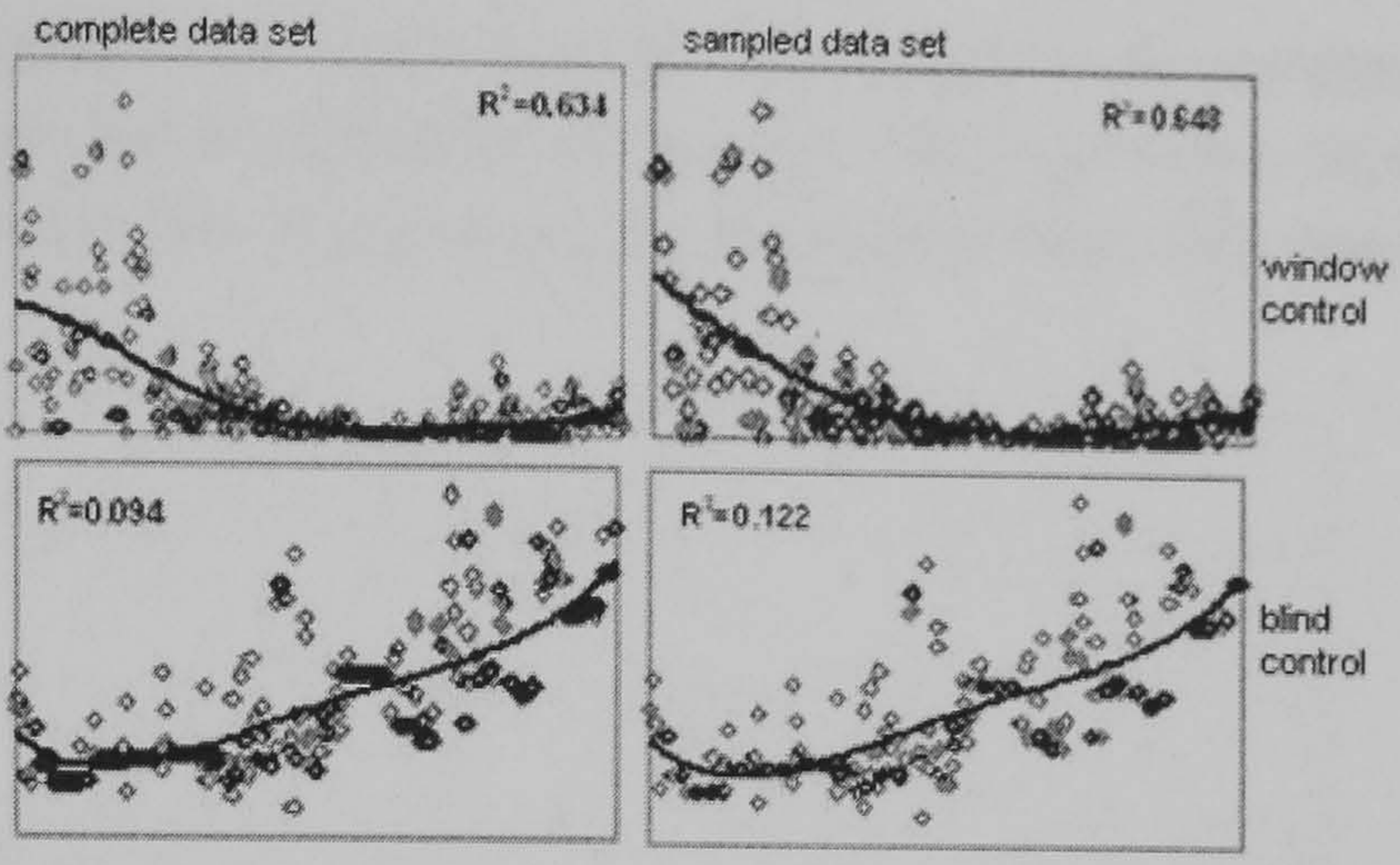


Figure 6.95 Comparison of the statistical results between the complete set and the sampled set (ICOSS Building)

Seasonal effects on window operation

In the ICOSS Building, the windows towards the south are sealed with only 12 remaining openable, all of which are located on the 5th clerestory floor. They are used mainly to provide additional top floor ventilation. Generally, once operated, they are open and/or closed all together by BMS with no single opened and closed situations (Figure 6.96). Figure 6.97 shows how many days per month they are opened from Mar/05 to Apr/06. It can be seen that the frequency of opening is very low. Over 14 months observation, 10 months (71.4% of the total time) had no days at all when windows were open, and this means they were always in the 'closed' position. Only in the summer time and early autumn from Jun to Sep were these windows recorded as having been opened.

This may be explained by the advanced ventilation system that utilises the stack effect for this building. The louvered termination on the top floor is designed to provide a means of enhancing airflows to all floors when necessary. The control of this louver system can satisfy the need for air movement most of the time over the whole year, while the main function of clerestory windows in this case offers further openings to vent the warm air out of the building when it comes to very warm days. Therefore, it is to be expected that they are operated only for a very limited period of time. However,

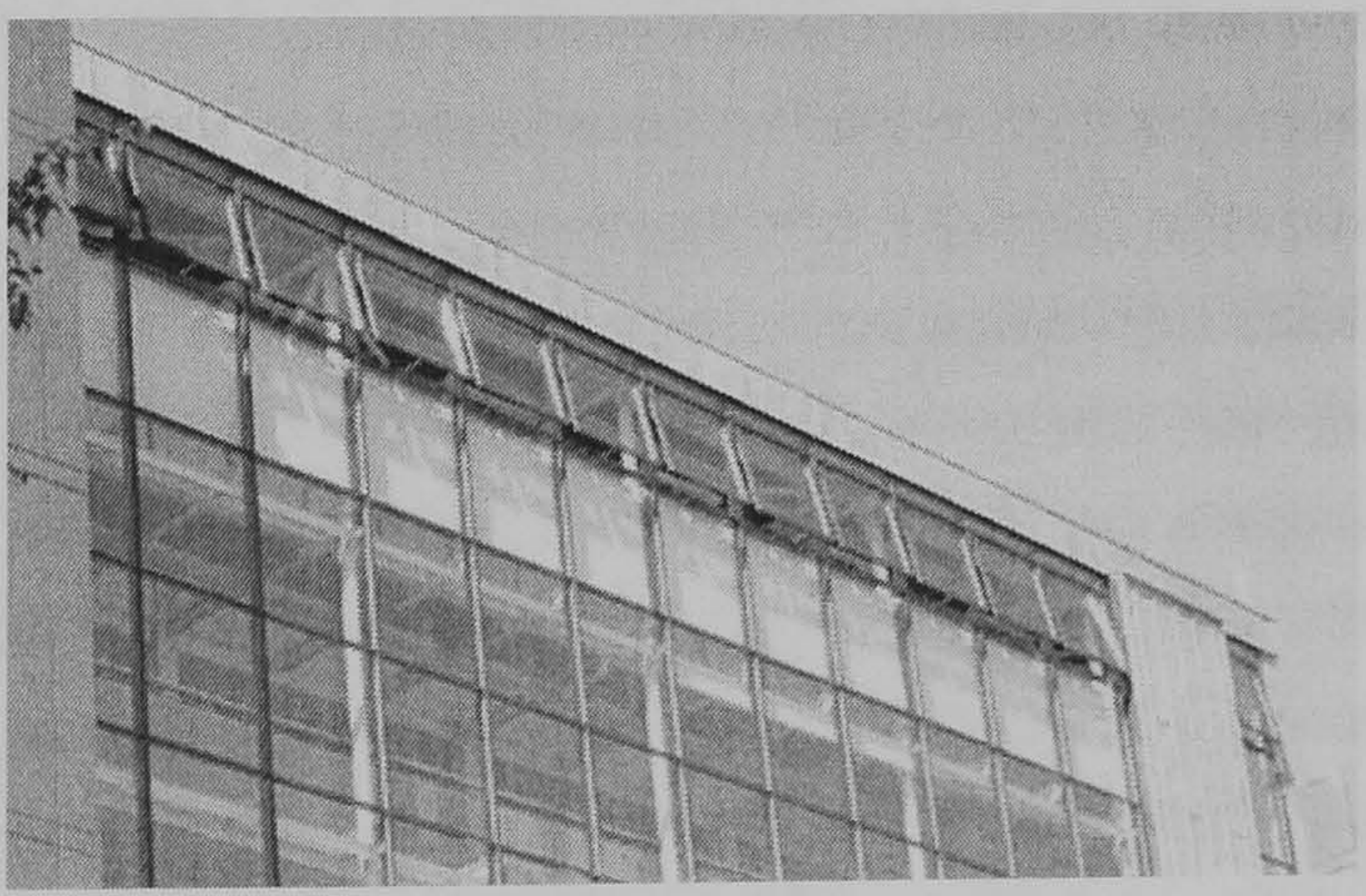


Figure 6.96 One day when the windows towards the south opened

because these windows are not located in the working area, the occupants do not play an active role to operate them. From the temperature measured, July had more days with high temperatures than June but in fact it was June that had more days with open windows.

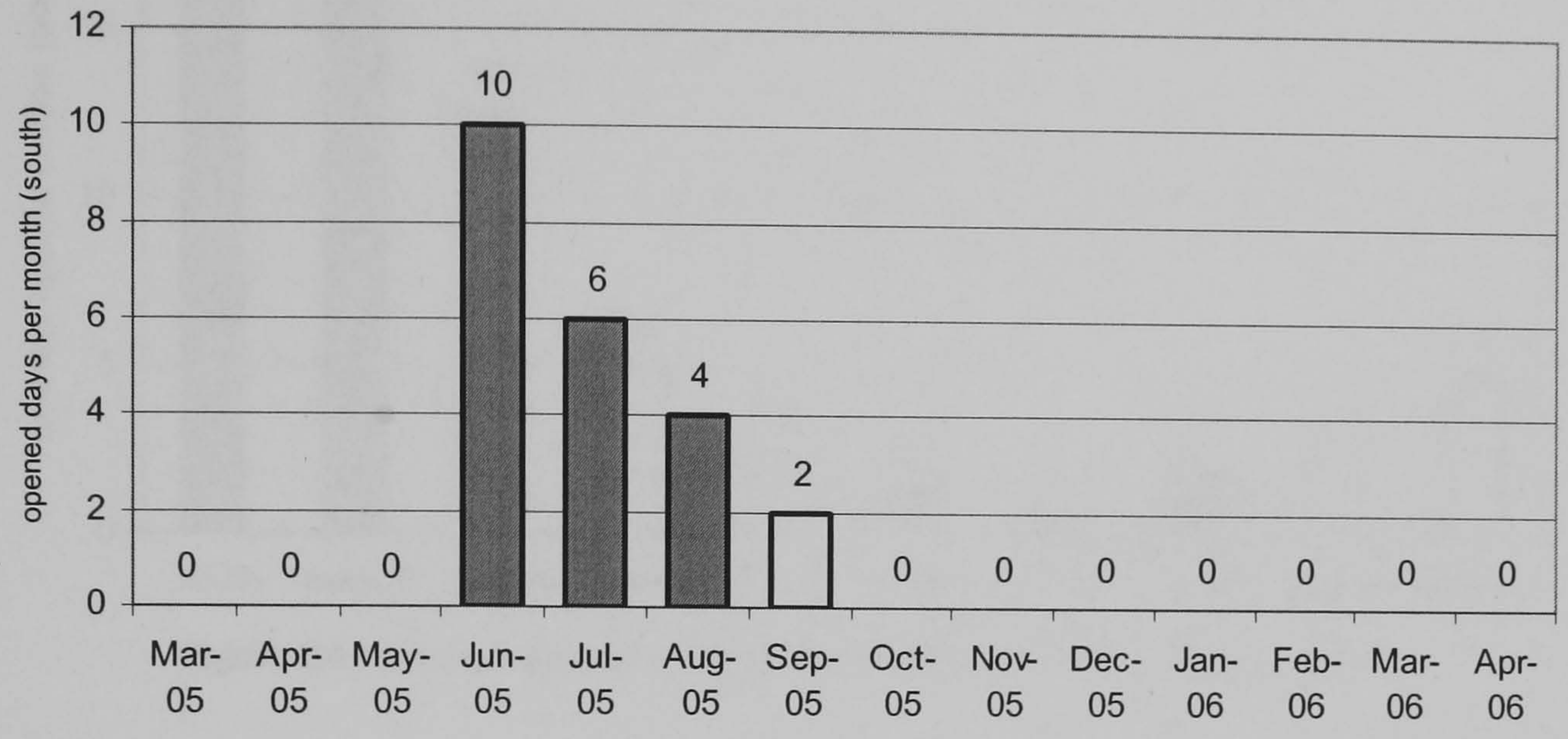


Figure 6.97 Amount of days that south windows opened from Mar/05 to Apr/06

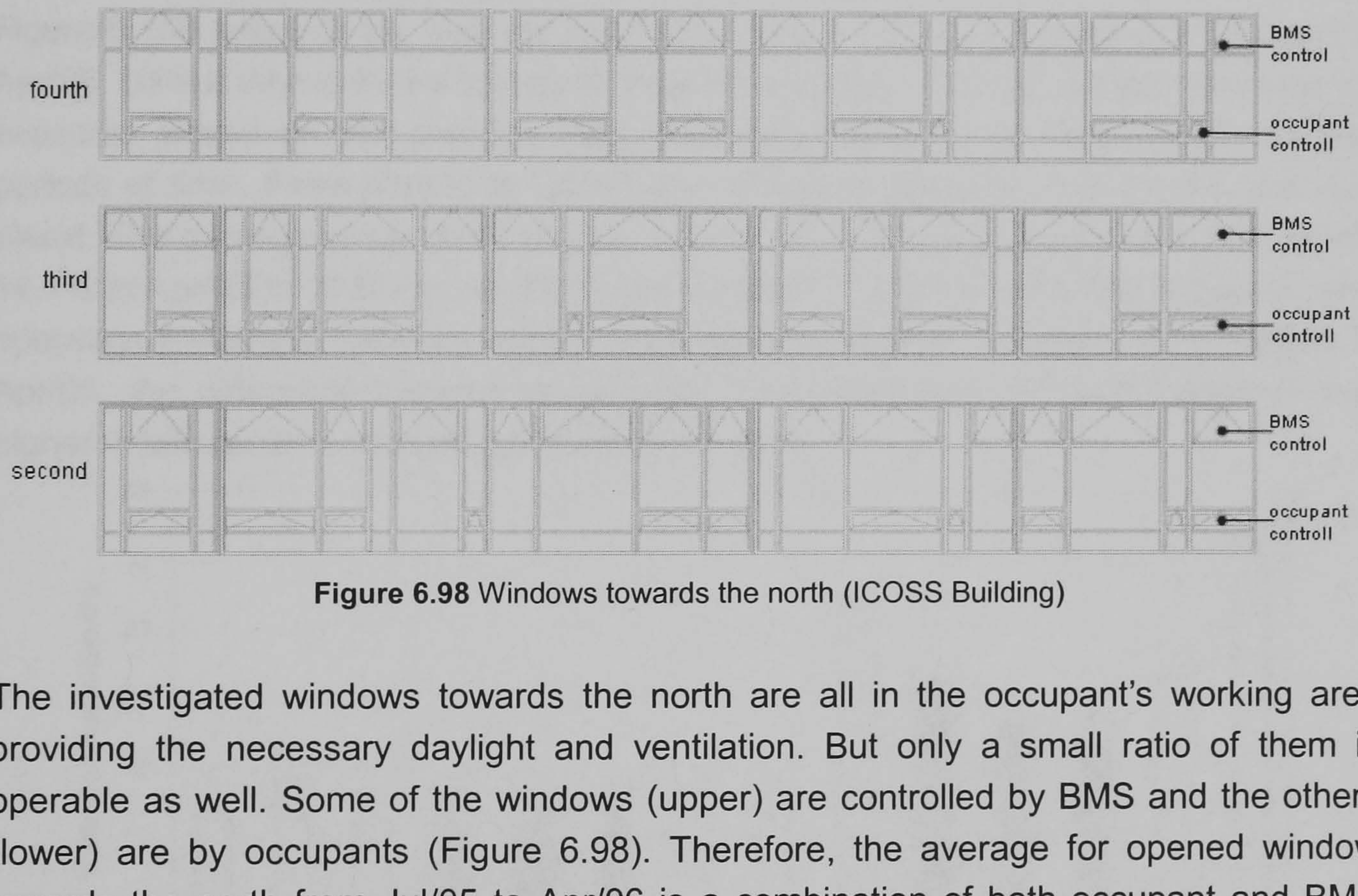


Figure 6.98 Windows towards the north (ICOSS Building)

The investigated windows towards the north are all in the occupant's working area providing the necessary daylight and ventilation. But only a small ratio of them is operable as well. Some of the windows (upper) are controlled by BMS and the others (lower) are by occupants (Figure 6.98). Therefore, the average for opened window towards the north from Jul/05 to Apr/06 is a combination of both occupant and BMS control (Figure 6.99). Furthermore, a large change between the four seasons can be observed. In summer, the average for opened window reaches the highest level while in winter it drops to its lowest point. Of the 10 months, Jul and Aug/05 has the most opened windows with averages of 18.6 and 17.7 respectively. From Dec/05 to Feb/06 the number of opened windows is greatly reduced with the least 0.7 in Jan/06. As expected during the spring and the autumn, the value is between the maximum and the minimum, as this is a transition period of time. The result indicates occupants respond very well to changing weather conditions between the seasons.

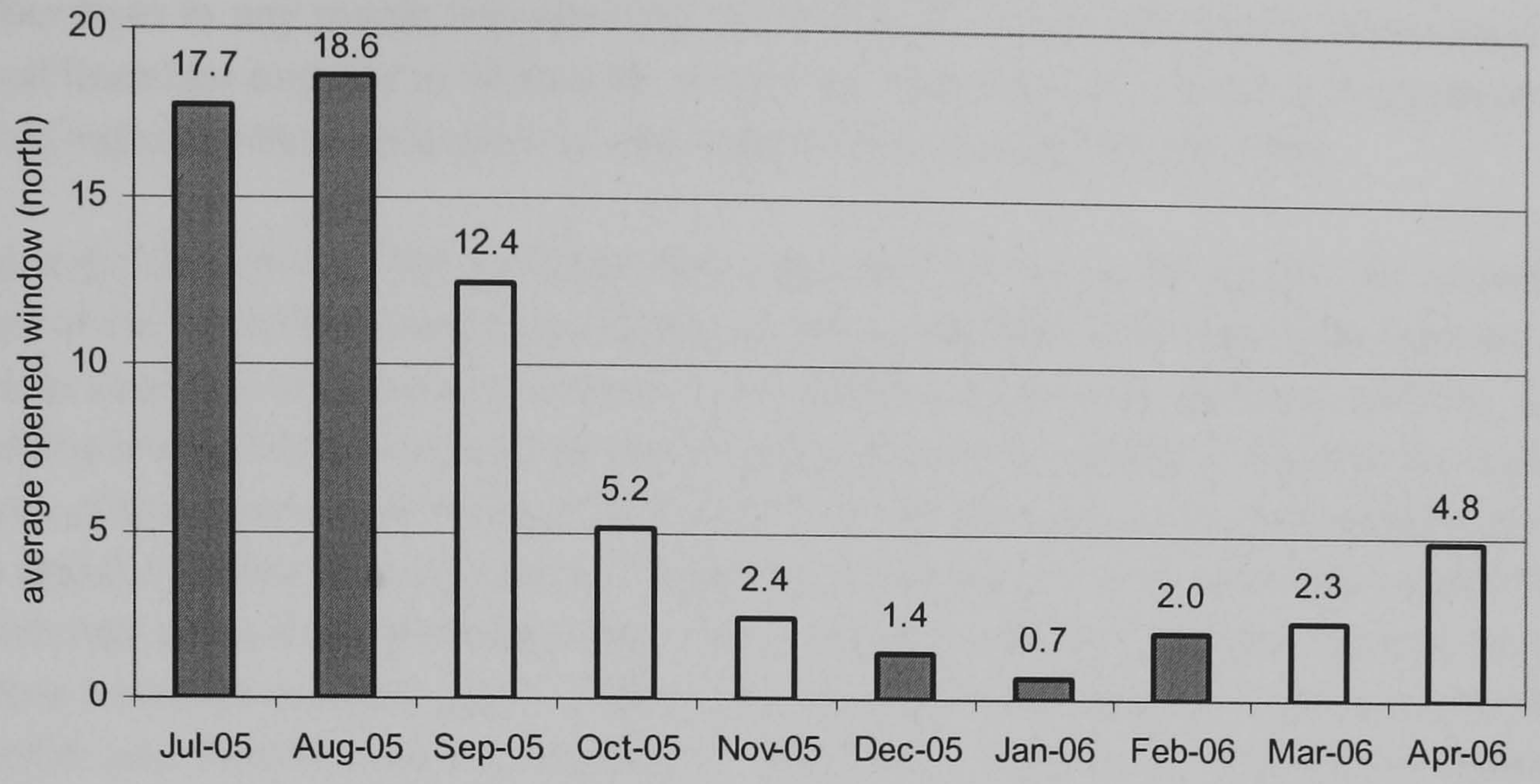


Figure 6.99 Average opened windows towards the north from Jul/05 to Apr/06

Seasonal effects on blind operation

Figure 6.100 presents the average blind occlusion on the south façade from Mar/05 to Apr/06. Data analysis shows it doesn't present an obvious case of variation between the seasons. Based on the average blind occlusion value, it can be grouped into two periods of time. From Mar/05 to Oct/05 the fluctuation between the months was very placid. The average value didn't change very much in these 8 months from a maximum 14.4% in Apr/05 to 10.8% in Jun/05 (3.6% variation). This indicated little impact on user operation behaviour between spring, summer and autumn. However, from Nov/05 to Apr/06, the difference became discernable. The percentage of blind occlusion was higher in late autumn and spring II than in Winter II.

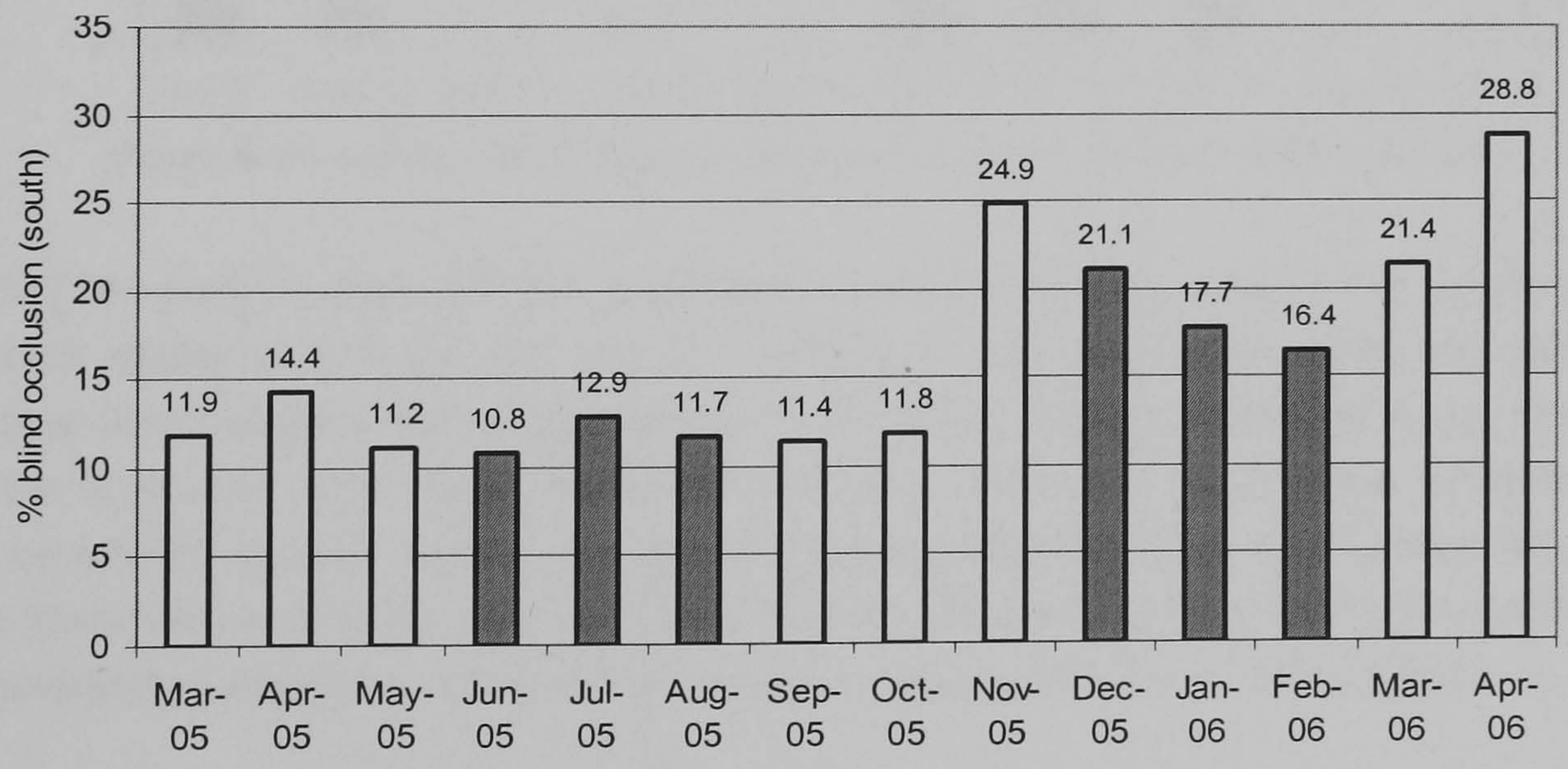


Figure 6.100 Average blind occlusion index towards the south from Mar/05 to Apr/06

However, there was a dramatic increase from Nov/05. The average blind occlusion was more than two times higher in this month than in Oct/05 (24.9% vs. 11.8%). After that, although in the period of winter II, the average value gradually decreased but was still higher than in any month between Mar/05 to Oct/05. It was interesting to compare the result from Mar and Apr in 05 and 06, where the latter showed a distinct rising tendency which indicated that more glazing was occluded by shading rolls in 2006.

Figure 6.101 presents the average blind occlusion for the north façade. As expected, most of the north blinds were maintained in the 'up' position over the whole year without a clear seasonal difference, especially from summer to autumn (Jul/05 to Nov/05). After that, the level of occlusion started to rise gradually and in Feb/06, it reached the highest levels of the other months (14.9%). In Mar and Apr the values dropped slightly at only 1.5 and 0.4 % less than in Feb/06. The situation was the same for the north façade blind, which had a low blind occlusion index with a stable fluctuation that lasts several months before a distinct rise took place. But in the case of the north façade, it occurred between Dec/05 and Feb/06 with an increase of more than three times but without dramatic effect as Jan appeared to be a transition period with 1.6 times more than in Dec and 2.1 times less than in Feb.

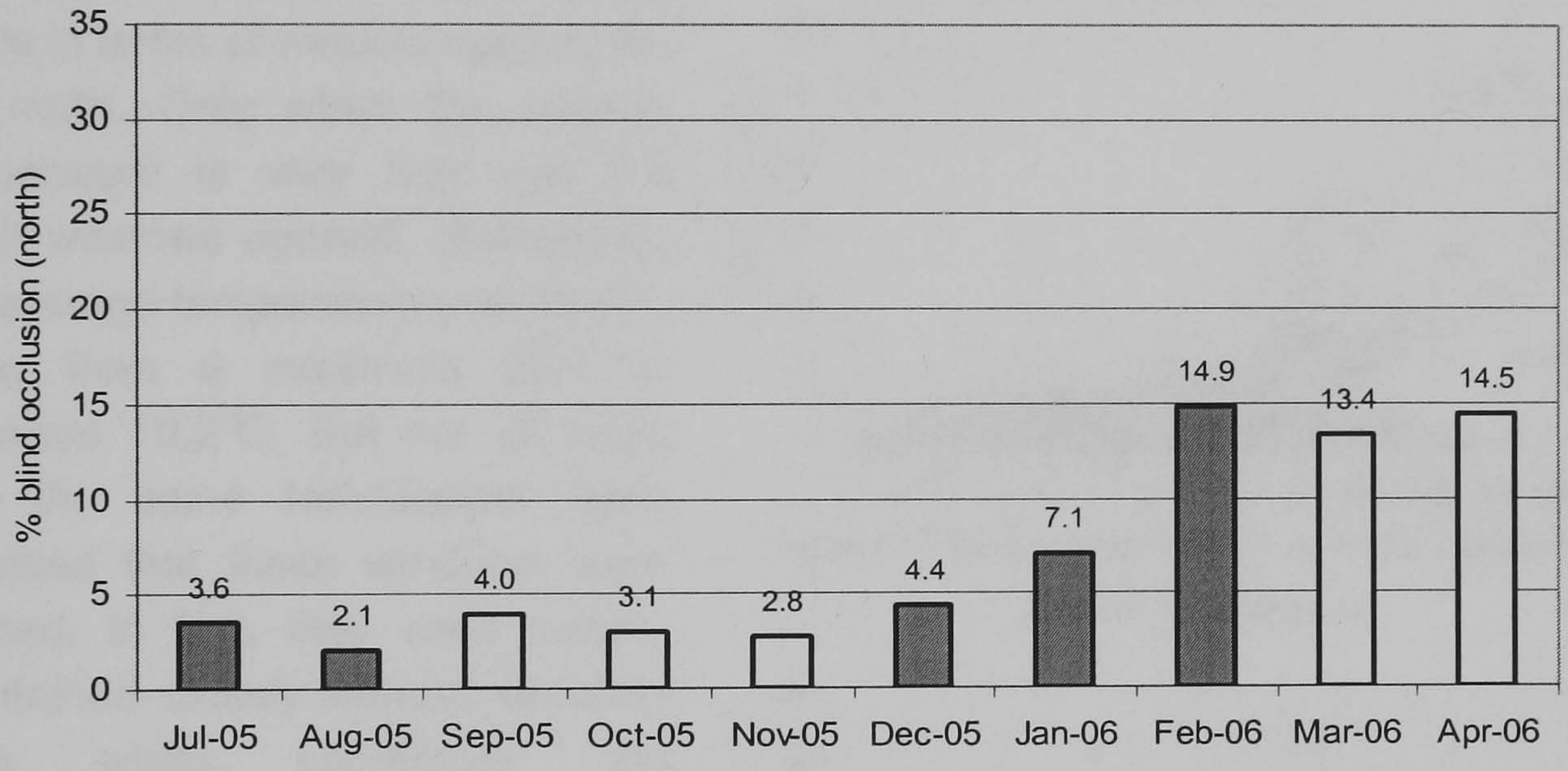


Figure 6.101 Average blind occlusion index towards the north from Jul/05 to Apr/06

It is still too early to draw definite explanations about why the case of the south façade presents placid picture for the first 8 months but then suddenly rises and why the increase also happens with regard to the north blind, although here it must be stressed that the time is not coincident with the south one. There are many other variables that may be related to blind control, such as occupancy density and/or occupant activity etc. More tests will have to be conducted and further evidence gathered before establishing any underlying principles concerning occupant blind operation in this building.

6.3.2.2 Window Control with Weather Parameters

Because the operable windows in the south and north façade are quite different from each other in terms of location and function, they are plotted separately at the initial stage (Figure 6.102).

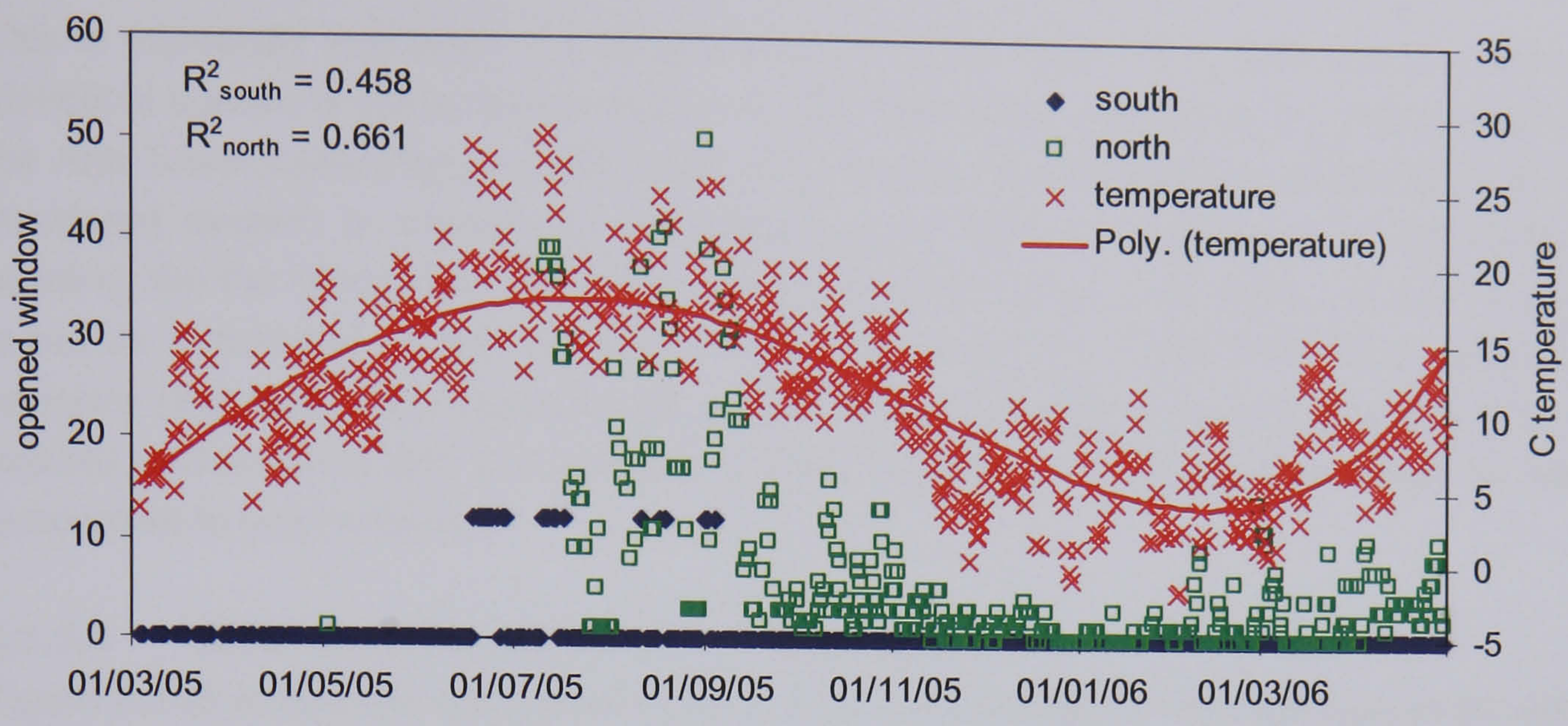


Figure 6.102 Amount of opened windows based on orientation (ICOSS Building)

Comparing the opened windows of two façades, the south one is not as active in terms of window opening as the north. Only when the outside temperature is very high are the south windows opened. Statistically, the average temperature was 24.4°C, going from a maximum 28.7 to minimum 19.2°C. But not all days with the same temperature were recorded that these windows were opened. In fact, they were usually maintained closely without variation even when sometimes the temperature reached to 28°C. However, the value of single data points for the north window is quite different. The points of opened windows deviate in a wide range in the summer months. When the temperature becomes cold from the autumn, they accumulate at the lower level and arrive at their lowest in Jan and Feb, which experience the coldest days of the whole year. After that, they rise again when air temperature increases. Generally the user behaviour (including the BMS operation) changes roughly in accordance with the variations of outdoor air temperature.

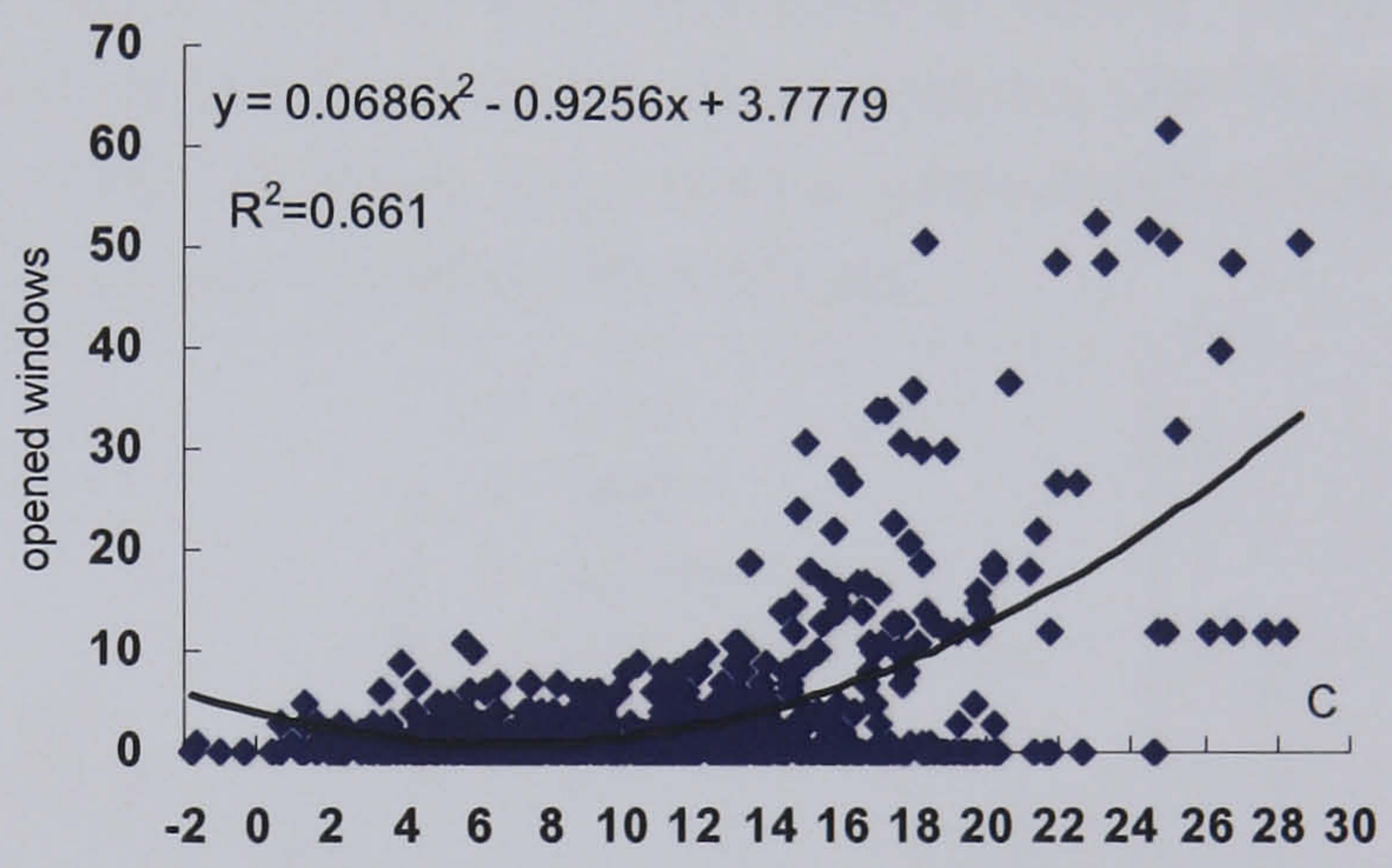


Figure 6.103 Correlation of the opened windows to outdoor temperature

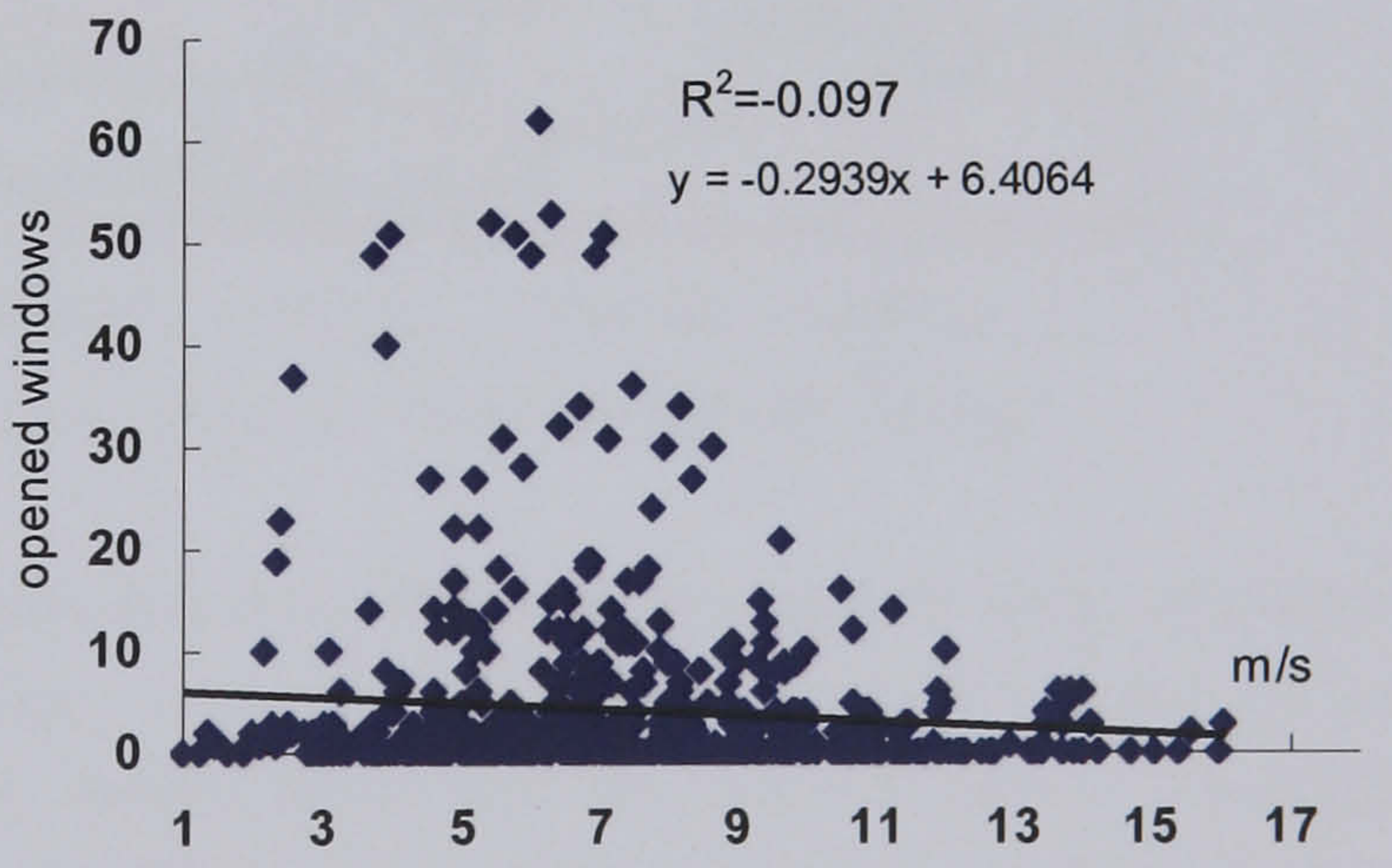


Figure 6.104 Correlation of the opened windows to wind speed

This is especially true when the temperature is higher than 15°C, because an evident statistical spread is presented in Figure 6.103. This figure is around 5°C higher than in the Arts Tower case (Figure 6.65) which may further indicate that the advanced natural ventilated system is capable of providing appropriate air movement in the ICOSS building. On the other hand, the impact of the wind speed on occupant's window control is not as noticeable as it in the Arts Tower, accounting for -0.097 R^2 of the observed variance (Figure 6.104). Again its advanced natural ventilation system provides a very reliable performance and enables the external façade to be sealed thus leads to less susceptive to wind effects.

6.3.2.3 Blind Control with Weather Parameters

Figure 6.105 shows the comparison of the mean percentage of the occlusion index with sunshine hours for over 13 months when it comes to the different blind orientations. It has to be mentioned that from the site observation, the south blinds on the 5th floor (clerestory windows) are always in the 'down' position with only several days in which they are pulled up or half down. Therefore, in the figure below, the situations with those single data points that deviate less than 10% (including 10%) can be considered as fully exposed glazing in the working area without any occlusion from blinds.

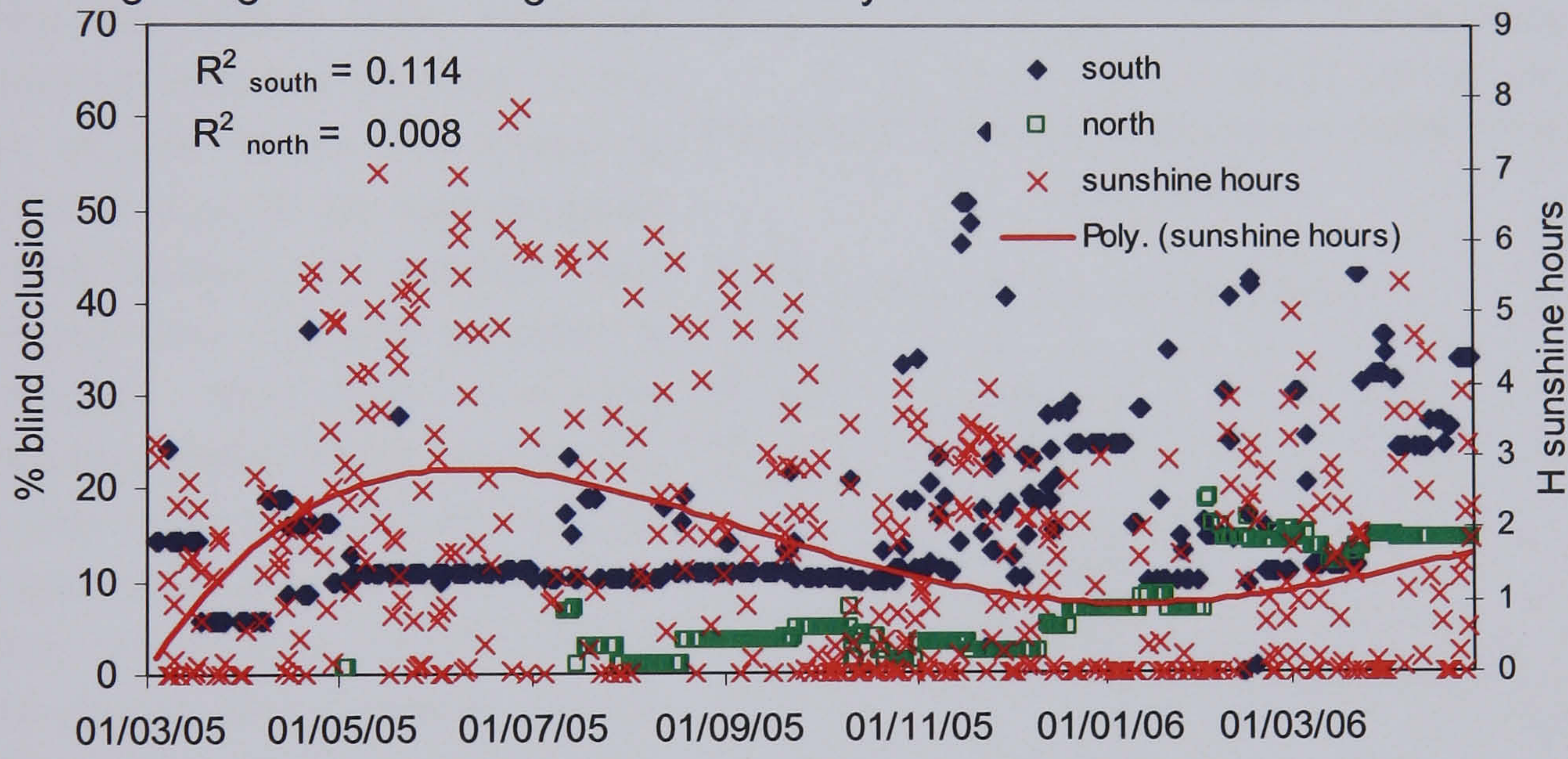


Figure 6.105 Average blind occlusion based on orientation (ICOSS Building)

It can be seen there is a very noticeable feature with regard to south blind variation. From May to Oct/05, the average blind occlusion index maintained a very stable tendency without much fluctuation no matter how the sunshine situation changed outside. However, before May and after Oct/05, the distribution of value points suddenly spread widely. This observation indicates that the blinds are always up from May to Oct/05. The windows are primarily seen as providing daylighting and glare does not to be a major problem. This can be attributed to the fact that the solar angle during this period is high and at about 5m from the façade the penetration of sunlight is minimal. However, apart from that period of time, the solar angle is much lower, which means more penetration occurs and blinds on the south façade has to be used to prevent the glare problem. So the blinds are put up and down much more frequently and diversely in order to accommodate the needs of the occupants.

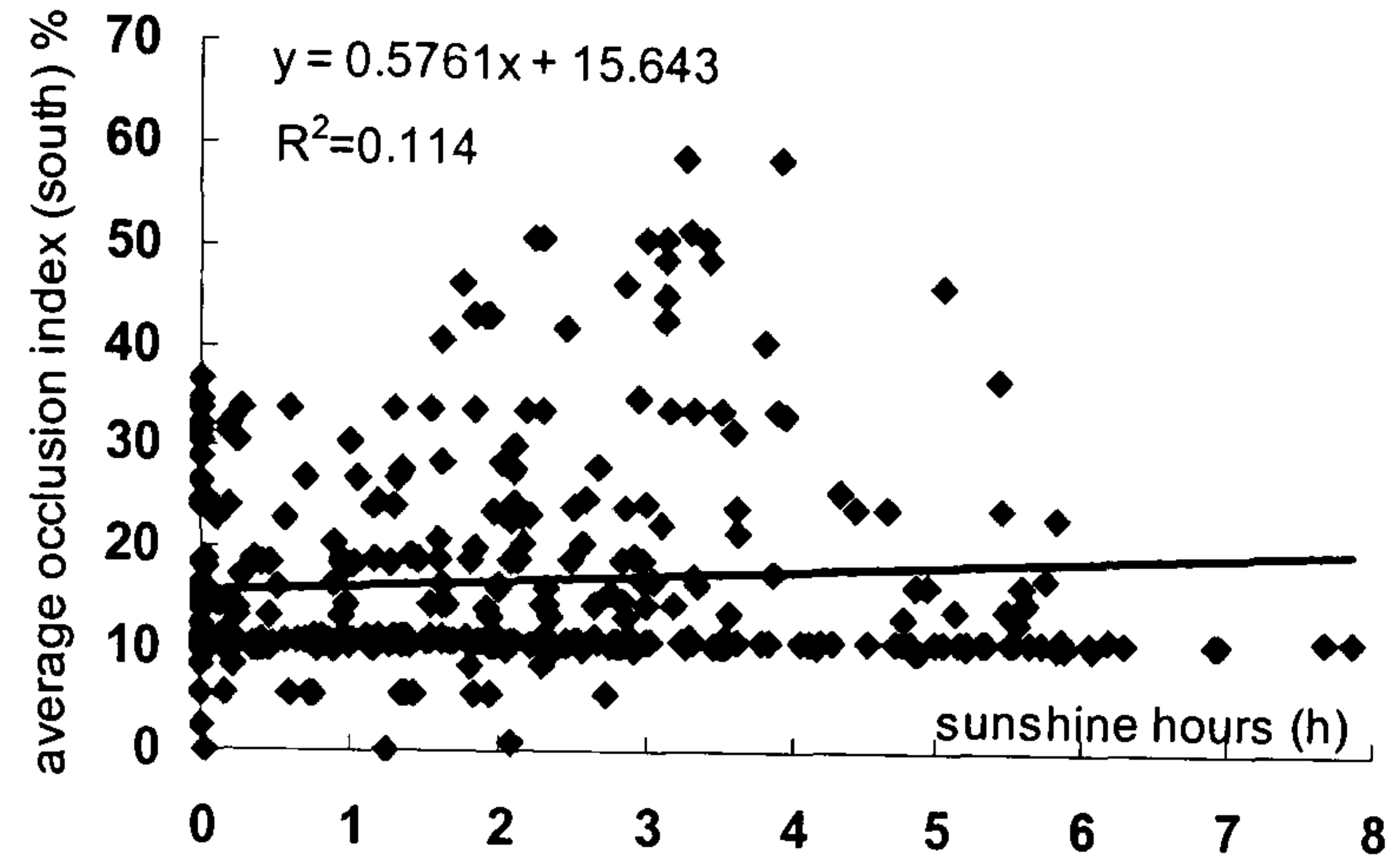


Figure 6.106 Correlation of the average occlusion index to sunshine hours

Generally, the sunshine hours have a positive effect on the operation of the south window blinds. More sunshine hours can be loosely corresponded to higher blind occlusion with a R^2 value of 0.114 (Figure 6.106). From the results, it appears that not only sunshine hours but also the solar altitude may have an impact on occupant control of the south blind roll (Figure 6.107). This is especially true when the solar altitude is low during the winter time. However, compared with the situation in the case of Arts Tower, this impact is alleviated due to its well-designed working stations. In addition, this particular case can also establish a connection that the overriding motivating factor which causes the shading roll to be pulled down is the sunlight rather than air temperature. Higher temperature doesn't lead to more glazing area occluded. On the contrary, the frequency of pulling blinds up and/or down is much higher between 0 and 12°C (Figure 6.108). Roughly, the outdoor air temperature may account for -0.327 of the observed variance.

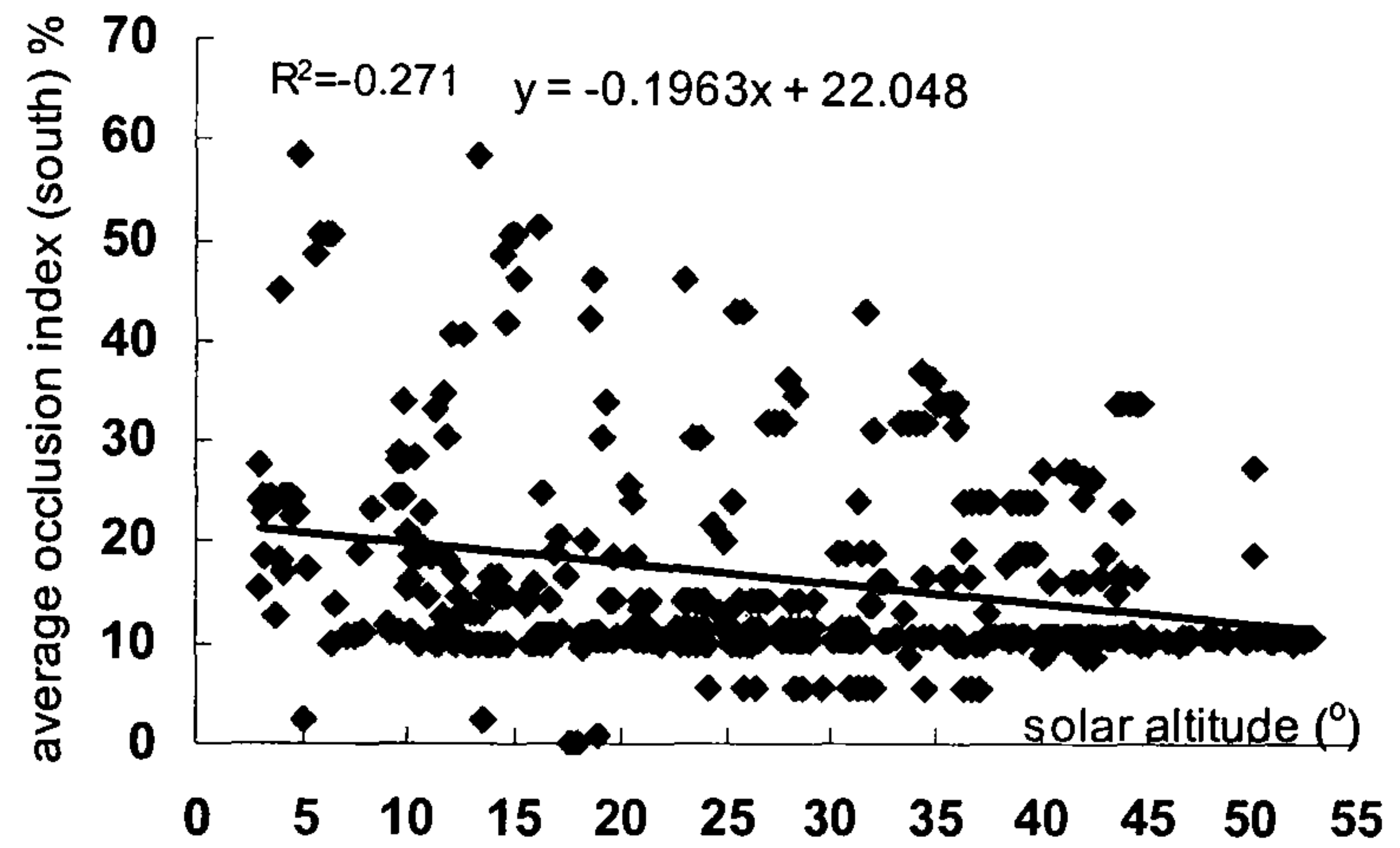


Figure 6.107 Correlation of the average occlusion index to solar altitude

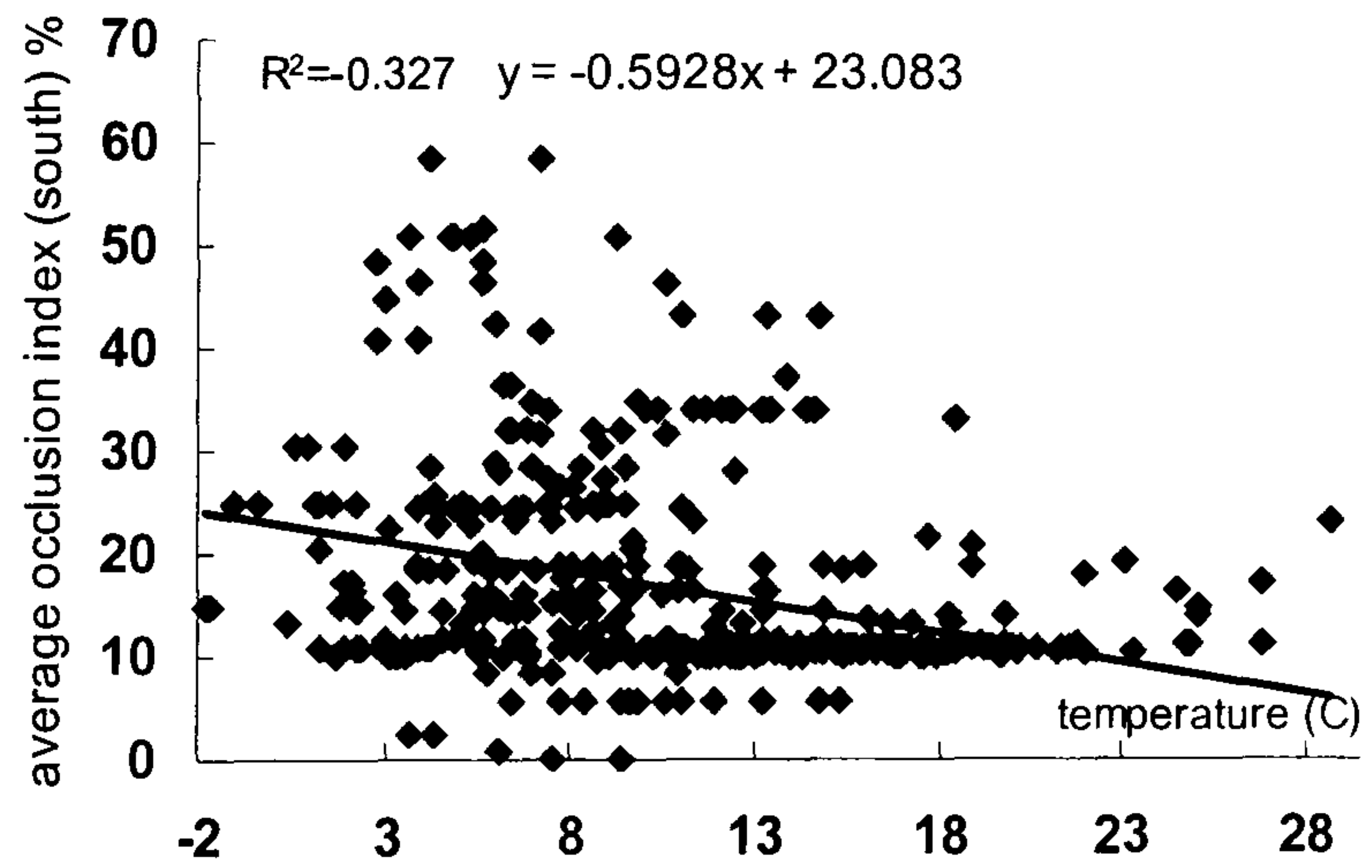


Figure 6.108 Correlation of the average occlusion index to air temperature

The north blind, in contrast, presents a quite different pattern of variation. The occlusion index is kept in a low position, which means most of the windows are exposed to the daylight. Basically, it has a clear ascending inclination with one situation lasting for a period of time. From the record of site observations, some of the blinds once lowered are usually kept in that position all the time without being raised again. This feature can be established as one important contribution to the ascending inclination. Because it enjoys the most constant and uniform daylight where there is little direct solar radiation during the day and across the year, it seldom experiences problems with glare disturbance and overheating discomfort. And with only a small area of occlusion by blinds, the large glazing area can still provide the necessary daylight and manage to link the interior to the exterior surroundings. Compared with the one for the south, the north occlusion index cannot be related to the sunshine hours or other weather parameters. The correlation coefficient is nearly 0 (0.008). Although it also presents a regular variation, other factors instead of weather may affect matters greatly. Further work is needed to reveal the main motivation of manual control.

6.4 Summary

This chapter mainly explores the results and analysis concerning the two investigated buildings. The first part concentrates on the occupants' perception, comfort level and experience of the thermal, visual and acoustic environment in their working space. In the Arts Tower case, it also reveals the occupant's preferences in terms of window, blind, door and artificial lighting positions in the different weather conditions and the impact of these strategies on the environment. And in the ICOSS case, the temperature, humidity, air movement and lighting in terms of different seasons are also evaluated by occupants. The second part focuses on the occupants' control over the built environment. It concentrates on how they actually operate the windows and shading coverings, rather than on their own views and how they were presumed to engage with the environmental control strategies.

In the Arts Tower case, three highly variable factors that impinge on occupant control of windows and blinds: room usage, room orientation and room size are discussed and analyzed in a time series order from Jan/05 to Apr/06. Among these main effects, the combination of the interaction is also carefully selected to find out on what levels these different issues influence the motivating forces for manual control.

Compared with the case study for occupant control in the Arts Tower, the ICOSS one is more like a preliminary pilot study. Although there are only six room spaces involved in this part of study, there are still many other variables that may affect the occupant's operation of windows and blind rolls and which make the results inconsistent with the simple interpretation that occupants manipulate these in order to increase the ventilation rate, avoid solar radiation and/or reduce daylight penetration. Nevertheless, the tentative interpretation can still indicate that occupant use windows and blinds correspond to air temperature and sunshine hours.

So far, the results from the questionnaire survey, site observation, physical measurements and building simulations are presented and analysed. The main theme of the study is to have a deep understanding of how the control strategies affect the indoor environment, the occupant's perceptions and comfort level and their actual manual operation of the environmental control strategies, with special attention given to the window and internal shading coverings. As such, the next chapter will be intended to reflect on the study as a whole, such as the main findings drawn from the current study and the work which may be carried out in future studies etc.

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Chapter Seven

Conclusion

People do research for two reasons: the first because it is interesting, and the second because it may be useful. The relations of researchers with men of action are sometimes complicated by the fact that useful knowledge is not always interesting, or interesting knowledge necessarily useful.

- Max Milikan, Inquiry and policy: the relation of knowledge to action

Chapter Seven
Conclusion

7.1 Introduction

In the previous chapter, Chapter Six, the main theme of the study was presented with an examination of the various environmental issues related to occupant comfort level and control behaviour in two naturally ventilated buildings. It attempts to reflect on what have been investigated so far and try to make the information useful and bring them to the attention of decision makers, designers and professionals in the concerned field. Given the fact that the hypotheses has been tested and generally confirmed in the previous chapters, this concluding chapter is intended to reflect on the study as a whole. It comprises three sections. Section one summarizes the main findings of the research with general and specific discussions. Section two explores the limitation and weakness of the research, both in the research scope and in the research methodology. The final section, section three, suggests the possible direction for further studies and finally brings the whole research to a conclusion.

7.2 Key Findings of the Study

The overall study has aimed at the establishment of a comprehensive understanding of the various environmental issues. These have included such matters as the motivating forces and influential effects related to occupant comfort control behaviour. As noted in the Introduction (Chapter One) and the Literature Review (Chapters Two and Three), this study is motivated by a desire to test one hypothesis. It looks at how occupants attempt to control and balance their thermal, visual and acoustic comfort levels in a naturally ventilated environment with special attention given to the manual operation of the window and internal shading coverings. Not only are the predominant climate, time of the year looked at as potentially influential forces affecting their actual responses in environmental control strategies, but also occupancy patterns, room orientations and sizes. Nevertheless, although the answers to the questions that this research attempts to answer are by now fairly clear, the major conclusions deserve to be restated here.

7.2.1 General Findings

The results from questionnaire survey, physical measurement and computer simulation illustrate the respondents' personal comfort conditions and their responses to the environmental control strategy that is in place. Although these respondents are all occupants of naturally ventilated buildings with the same location, their responses are varied, especially with respect to those opinions expressed vis-a-vis satisfaction and/or dissatisfaction regarding their thermal, visual and acoustic environment that further affect their behaviour in terms of environmental control. As expected, the time of year and the predominant climate both play a significant role in affecting the occupants comfort perception and control behaviour. Also it is found that the impact of the room orientation cannot be ignored. Although in terms of window seat preference, view appreciation, noise disturbance, this doesn't seem to make much difference (on the basis of what is known from the occupant responses at any rate) regarding the seasonal satisfaction level and frequency of glare disturbance, its influence becomes very evident. This is especially true when it comes to the manual operation of those simple, easy-to-use control means.

This finding has serious implications in that it reinforces the findings of similar surveys done in recent years which have proved that the occupant is far more sensitive to the variation of hour-by-hour changes in the built environment and that people are not inert recipients of the environment, but interact with it to optimise their own conditions and use the various means at their disposal to improve their comfort situation [1]. More importantly the study has shown that even given the same location (Sheffield) and the same building type (naturally ventilated building), the comfort sensation is different if the interior environment of the building is significantly different. It is showed from the occupant not only in variously oriented rooms within the same building but also between buildings of an old post-modern office block and an advanced passive ventilated laboratory. Because the occupants respond to changing conditions in light of their preferences and the needs of the moment, this implies the existence of a major variable factor in the balance of occupant manual control that is quite separate from climate issues and far removed from the ways in which the environment is conventionally described. In order to thoroughly understand the triggers of occupant control, the building fabric, room features and occupancy patterns etc have to be examined as a totality.

With particular respect to the operation of window and internal shading covering, this finding draws further attention to another perspective from which the daily routines and practices of building occupants and how they modify and adjust their environment may be observed in this study.

Data analysis shows that the main motivating forces for manual control of windows and internal shading coverings in a natural ventilated environment are quite different, although these two are generally regarded to work in unison. For example, window opening is found to be strongly related to the outdoor air temperature: the individual occupant is found to be quite sensitive to the short-term fluctuations of air temperature that make differences to the internal environment of the building and cause window adjustment. In other words, the higher the outdoor temperature, the more likely windows are to be opened by occupants. The impact of the room usage, orientation and volume doesn't make much difference in this case in terms of the high correlation between the number of opened windows and the air temperature. Instead, it is weakened only when the occupancy is low in density, intermittent, of short duration and composed of floating users.

However, blind control is another matter. Blind occlusion is found to have a weak relation with sunshine hours: a day with longer sunshine hours can result in a greater glazing area being blocked by shading blinds/rolls. This influencing factor becomes evident if only one particular season is involved which means the correlation between blind operation and sunshine hours is strengthened in terms of a single seasonal effect. Apart from the climate, room usage, orientation and volume also affect this correlation a great deal. The strongest correlation is presented when the user is in a south medium room that is occupied continuously at a low density and by fixed users. However, the impact of the time of the day is not significant because the occupant does not change the blind position more than once within a day even though the solar radiation changes dramatically on a clear day. Occupants' preferences for blind position seem based on a long-term perception of sun light, sun heat and the built environment they are accustomed to.

The findings from site observation are consistent with other similar field studies. People tend, at least on average to use window opening to increase the ventilation rate and to use blind (shading roll) to adjust the penetration of direct sunlight, thermal radiation or both into the building room. Naturally this interpretation of window opening and blind occlusion may be premature for other buildings. It is still too early to make general predictions of window opening and/or blind occlusion values for all combinations of influential effects. However, it gives a better view of how the user model is going to be developed in terms of manual window and blind control, and, more importantly, this strongly implies that the occupant's management of operable windows and shading coverings needs to be considered as an important issue when the thermal and visual environments are evaluated at the design stage, especially with the aid of computer modelling and stimulating. Furthermore, it can also be used to empower the occupants to control the environment of a building and result in increased levels of comfort as they can have greater opportunities to improve their comfort level as it has already been demonstrated that there is a strong relationship between perceived control of the built environment and occupant satisfaction [2].

7.2.2 Specific Findings

Although this study only concentrates on two buildings and almost everything that has been discussed passes through the mesh of gross occupant environmental control, the combined weight of all these small things can point to the interaction between the occupants comfort and control strategy as an essential part of the design of a better built environment. The main specific findings, implications and suggestions in this study are presented below:

- It is not temperature or humidity that causes a thermally high dissatisfaction level for the occupants of the Arts Tower. The main problem is the stuffy air resulting from poor ventilation. The other factor is the cooling or heating of parts of the body by radiation. Large areas of glazing in this case intensify the asymmetry of thermal radiation from both solar and cooling radiation. The study strongly suggests improving the indoor environment by using double façade designs that can make the ventilation rate easily controllable and filming part of the glazing area so as to resolve the radiation effect.

- Although the noise level in the Arts Tower is relatively high in comparison with the standard criteria requirements, the occupant doesn't show a high degree of dissatisfaction. Practically speaking, only when the occupant is in a quite moderate environment may the noise level become more evident. In fact, on average, the thermal, visual and acoustic environments are perceived positively. Of these, the visual one had the highest satisfaction level while the thermal one had the lowest.

- Monthly evaluation of the built environment in the Arts Tower showed that, more or less, the dissatisfaction continued to exist in each month. In summer from Jun to Aug, the degree of dissatisfaction reached its highest level. Among the four room orientations, occupants of the south-facing rooms were found to occupy the biggest part of the dissatisfaction distribution. Here, the large glazing area allows for strong and direct insolation into buildings and causes overheating. In this case, the blinds which absorb solar radiation may further intensity the overheating effect. In short, the south-facing rooms must become the main target if the working environment is to be improved.

- Generally there is a high consistency of opinion about how the quality of the view from a room positively affects the occupant's appreciation of the room, and, as such, most respondents were found to prefer a seat near the window. This is true of both the investigated buildings. It is suggested that the working office/station should be arranged near the perimeter façade while for other space usages, such as services and meetings, rooms ought to be placed inside the building. In addition, low-height furniture will welcomed so as not to obscure the view from the rooms.

- Glare is a problem mainly in rooms towards the west and the south, while in the Arts Tower noise disturbance sometimes leads to discomfort without regard to many differences in room orientation. In the case of the ICOSS Building, glare sometimes takes place, while noise levels, especially from the inside of the building, are a little high. The treatment of glazing, for example with a partly low-E coating, can help eliminate this problem in the Arts Tower. Acoustically there do seem to be some problems with the transmission of internal noise, and these need to be addressed by designers in the future.

- The ICOSS Building has a high quantity and quality of built environment in terms of temperature, humidity, air movement and illuminance control. The results, when compared to those from Arts Tower, indicate that occupants of this building generally enjoy very high levels of satisfaction levels.

- When the temperature goes from cold to hot, more than half of those who respond choose to adjust their door from the 'closed' to the 'opened' position. Under the same conditions, 73.8% prefer the same strategy with regard to window use. It is observed that the greater number of respondents prefer window operation on hot days with door operation prefer on cold days to control air velocity in the rooms of the Arts Tower.

- In the Arts Tower, on a cold day, when the weather changes from sunny to overcast, 80.8% occupants switch their lighting from 'off' to 'on'. There are another 28.3% responses from those who always keep the lighting 'on' no matter in what the weather situation. On an overcast and cold day, 87.9% of occupants leave their lighting on, but at the same time, the blinds of only 42.5% are in the 'up' position. These results indicate that artificial lighting strongly weakens the occupant's motivation to exercise control over the daylight entering into a room as a means of adjusting their visual environment.

- Usually most of the windows are closed no matter what the climate/weather conditions: only a small portion (around 6.2% in the Arts Tower, 8.8% in the ICOSS Building) is operated by occupants, and even then only intermittently. The variation of total opened windows responds to the changing season and follows a noticeable pattern. It reaches its highest figures in summer and drops to its lowest in winter.

- For the whole building, most blinds are found to be in the 'up' position (42.6%) with the 'down' position taking second place (27.2%). The average occlusion level is approximately 39.8% in the Arts Tower, which suggests that a small area of glazing may preferable to a large one.

- The seasonal variation of blind occlusion only displays a moderate change with no big difference, except in winter when average blind occlusion clearly increases. Glare and disturbance caused by overheating are the main reasons that cause occupants to pull down the blind in order to block the penetration of the solar radiation.

- The total number of opened windows corresponds to every shift of the outside air temperature and the two vary simultaneously, almost without time lag. The results indicate the impact that the short-term fluctuations of air temperature make on the indoor environment is the main cause of window adjustment by occupants. This is true of both the investigated buildings.

- Both the amount of sunshine and the low altitude sunlight can lead to blind occlusion increasing. The impact of sky conditions on blind control is only felt when change proceeds from bright to very bright but not conversely and/or from dull to bright. Electric lighting is the first option to be prioritized when it comes to changing the visual environment. Also the fact that more than half of the respondents feel that it is difficult to operate the blind further weakens the relationship between the outside environment and blind control behaviour. In practical terms, blind use is not encouraged due to the fact that its quality noticeably deteriorates as time passes.

- In winter, when the temperature is low the occupants keep the window closed no matter what kind of room they are in which means the room orientation, size and occupancy pattern do not affect the occupant window operation behaviour and the amplitude of the variation is very small.

- In summer, when the temperature is higher more windows are opened. But the amplitude of the fluctuation deviates widely: the opened-window ratio of rooms for communication is higher than those for rooms with office, public study and service functions. The room towards the south has a higher ratio than those with other orientations; and the super-large room has the lowest ratio of all the sized rooms. Here, the open plan is encouraged because it is quite flexible in terms of adaptability to occupant ventilation requirements, especially when it is hot.

- The impact of room orientation on blind position is very clear. The value of single data for each orientation tends to accumulate in a certain occlusion range and separate in a quite notable way. The south always has the highest occlusion while the north has the lowest. This feature is only present in the Arts Tower case. For the ICOSS Building, because of its distinct design considerations, the south façade normally keeps to a low occlusion level.

- Basically, regardless of how the data is organized, e.g. in terms of room occupancy, orientation or size, the pattern of variation in blind occlusion is relatively placid without obvious peaks, troughs or bends. But most of them follow a very similar pattern: gently ascending. This indicates once the blind is pulled down, it will be left there regardless of the daylight level from the start to the end of the working day.

- The south shading roll in the ICOSS Building is designed to limit solar penetration. However, the occupants are not very active when it comes to using them and this leads to certain areas suffering from glare problems on the computer screens and to overheating in the warm periods. Therefore, in order to remedy this, an education programme should be implemented to ensure that they are informed of the correct way to control the blinds

7.3 Limitation of the Study

Generally speaking, this study has some limitations and these mainly lie in two aspects: the scope of the research and the methods employed.

Firstly, one of the main limitations is the difficulty in obtaining a large enough sample of buildings to study. In this case only two were selected and they were limited within the threshold of institutional buildings in more or less the same place representing just a part of the occupancy type and the climate situation. In other words, not all buildings fulfilling the research criteria could be observed. Nevertheless, the more sample buildings there are, the more confidently the samples are able to represent the targeted building type. The basis of this small study cannot generate a whole new establishment or be applied to any other buildings, as variables like climate, culture, building structure, and space typology may play a potential role as well.

Secondly, this study has limitations that are to do with questionnaire sampling. Despite having exhausted the resources, the groups of respondents were not as satisfactory as expected. Only those who had fixed working areas were involved in this study. Given that the cases selected were institutional buildings, especially with respect to the Arts Tower, there were still large numbers of users representing the different occupancy patterns who were excluded from this study. In reality, they cannot be separated and ignored as their experiences and responses also have great impact on the issue of environmental control.

Thirdly, the building users, for the purposes of this study, were only able to evaluate their working environments on the basis of physical aspects like the thermal, visual and acoustic conditions within the building. However, as a crucial part of the building design physiological and/or intermediate conditions have been proved to have profound effects on working productivity and thus are of concern to most of the respondents. In the real world, they are never entirely isolated from the occupants' evaluations and experiences of their working environment. Therefore when it is subtracted from its immediate context, the data collected and the results analysed in this study may have been over-simplified in some way.

Fourthly, when it came to designing the questionnaire, ambiguity existed between measures concerning different concepts, despite the best attempts to clarify the difference between these concepts and words in the questions posed. For example, when it came to questions concerning weather conditions like 'sunny/cold', this apparently simple issue was occasionally made difficult by the fact that occupants often related 'sunny' to 'hot' instead of 'cold' no matter what the season happened to be.

Fifthly, accurate everyday monitoring of occupation and absence in the investigated rooms during the observation period was not really possible. This is especially important when considering the operation behaviour of the window and the blind – whether the space is full or empty and how long it lasts. Therefore, the variation analysis of operation control cannot be represented accurately and precisely on a daily basis, but rather only in general seasonal and annual terms.

7.4 Future Work

At this point, it is appropriate to note that the scope of this study was limited by many constraints such as finance, resources and time. There were also other problems but these were, generally, overcome as experience was gained in the study process. This thesis has revealed that the comfort perception and levels of satisfaction in the built environment and the resulting patterns of occupant behaviour impact on the performance of the buildings in question. Some areas and issues need to be explored and considered further by decision makers and designers. Many of them cannot be fully examined in this research for a variety of reasons but deserve more attention in future work. First of all, the issue of user response in the environmental control buildings has been highlighted in this research and needs to be further explored. The list below enumerates the areas that can and ought to be investigated in more detail:

To target the study towards the current two cases:

- When the analysis of the occupant's responses to the questions was discussed, room orientation was the only primary physical variable considered in the study. However, the inclusion of personal variables such as the gender differences, clothing, ages etc. of the respondents in the questionnaire could also have potentially significant influences on the results. These are issues that require attention in order to reinforce a similar survey done in recent years, which has shown that comfort sensations and environmental control strategies will vary from one situation to another.

- The motivating forces behind the manual control of the window and shading coverings are manifold. In this study, only the effects of air temperature on window operation and sunshine hours on blind operation, respectively, were discussed. The other parameters, such as wind speed, solar radiation, noise level and/or air quality, may all to a certain extent play an important role in affecting window and blind operation as well. Further study of these aspects could lead to a more comprehensive understanding of occupant control behaviour.

- When it comes to the operation based on the interaction between variables, only the situations with the highest correlation have been discussed in this study. The other combinations also requires attention in future work as they are also parts of the building and how these work must also contributes to variation in the whole building.

- Data analysis in this study focuses generally on how occupants control the windows and blinds. Even though they are grouped in terms of three main effects so as to facilitate the separate discussion of the different situations, it is still necessary to randomly select some specific rooms to do further investigation. In this case, the room features, e.g. orientation, size and the occupant's personal experience and opinion as revealed on the questionnaire survey, can be combined with how he/she actually controls the environment in reality.

- As the study on the ICOSS Building is only in the preliminary stage, one thing that emerges from the results is an inconsistency with the simple interpretation of the occupant manipulation of the window and blind. Many other variables may at work here, and further tests will have to be conducted and more evidence gathered before it will be possible to establish any underlying principles concerning occupant window and blind operation in this building.

To target the study towards this research field:

- This study is limited to the very buildings themselves. Further studies of other buildings with varied locations, climates, building structures and space typologies are to be desired. The significance of this cannot be overemphasized as it will provide the enhanced understanding needed for preparing appropriate spatial approaches to more buildings and contribute to the formulation of behavioural models in order to predict window and blind status for certain times of the year.

- Further studies can be also identified in the areas where energy expenditure is implied. How and to what degree is that an extension of user control that can lead to increased energy efficiency? Can occupant adjustment here present a viable 'low energy' option in terms of the current building? And how can occupant satisfaction level, preference control and energy consumption balance with each other especially in a naturally ventilated building? There is still a lot to be done in the process of validation, refinement, application and so on.

7.5 Conclusion

The movement towards sustainable development is leading designers towards the consideration of the building's energy and environmental impacts. Fundamentally the purpose of energy use in buildings is to support the activities of the occupants and this means that understanding the occupants' requirements is very important in ensuring that it is possible to use the building with a low input of energy. However, there is another issue to at stake here: this kind of insight will also help ensure that the building *will* be used in this energy efficient way. Therefore, this thesis has set out to investigate the nature of occupant environmental control and the extent of the interaction between the environmental performance of a building and the behaviour of the occupants in the building, including the manner in which the occupants seek to adjust the internal environment based on their comfort perceptions and requirements.

Firstly, the theoretical foundation was reviewed, including two main areas: occupant comfort in a built environment, and building environmental control strategy. They were addressed in order to constitute the conceptual framework of the study and establish the links between what the study was proposing to examine: the interaction between the built environment, occupant comfort and control behaviour. Based on the previous work, two buildings were carefully selected so as to examine the impact of occupants' behaviour on the performance of buildings in use. These case studies were set up to refine the research procedure as well as the way of collecting and processing the data.

Prior to result analysis, basic background information was explored with a preliminary description of the investigated buildings, which mainly focussed on issues like environmental, architectural and occupant features. Then the results from the questionnaire survey, computer simulation and site observation were presented and analysed to characterize the occupant responses to the environmental strategy, highlighting the various influential effects particularly on weather conditions, room features and user identities in order to find out at what levels they influence the pattern of manual control. The limitations and weaknesses of this study are unavoidable, both in terms of the scope of the research and in the research methodology. However, the suggestion of possible directions for further studies can both make up for these deficiencies and further develop this research area.

It is anticipated that the methods and techniques adopted here, together with the results obtained from the investigation, will be useful in answering some essential questions where user response in the built environmental control is involved. It is also expected that this work will assist in the development of a more accurate understanding and help to bridge the gap between the research and the practice of energy modelling, and, moreover, encourage the designer and/or decision maker to put in place the best plans and schemes for the simultaneous achievement of occupant comfort and high built environment quality.

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Appendix I

Questionnaires

Questionnaire for Arts Tower

Record		**Date**		**Observer**	***Yufan Zhang*** School of Architecture University of Sheffield
Room		**Time**		**Email & Telphone**	yufan.zhang@sheffield.ac.uk 0114 222-20370

1. **Please evaluate the overall environment in this room *at this moment* by ticking a score in each row?**

	Very	Fairly	Little	Neutral	Little	Fairly	Very	
Cold	-3	-2	-1	0	1	2	3	**Hot**
Dark	-3	-2	-1	0	1	2	3	**Brigh**
Quiet	-3	-2	-1	0	1	2	3	**Noisy**

2. **Do you feel comfortable toward the overall environment in this room *at this moment*?**

	Very dissatisfied	Fairly	Little	Neutral	Little	Fairly	Very satisfied
Thermal	-3	-2	-1	0	1	2	3
Visual	-3	-2	-1	0	1	2	3
Acoustic	-3	-2	-1	0	1	2	3

3. **Normally, when are you in your office/classroom?**

	Very often	Often	Sometimes	Rarely	Never
Before 9am					
after 5pm					
on Sat. or/and Sun					
on public or/and bank holiday					
on vacation (Xmas; Easter; Summer)					

4. Overall, are you satisfied with the environment in your office? (Note: Please ignore the time that you are not here.)

	Very dissatisfied	Fairly dissatisfied	Neutral	Fairly satisfied	Very satisfied
January					
February					
March					
April					
May					
June					
July					
August					
September					
October					
November					
December					

5a. Do you prefer a window seat in your office/classroom or not?

A. Not at all B. hardly C A little D. Somewhat E. Very much

5b. Does the reflection on the computer screen affect your work due to discomfort glare?

A. Not at all B. hardly C A little D. Somewhat E. Very much

6. Does the view outside affect your appreciation of this room?

A. Not at all B. hardly C A little D. Somewhat E. Very much

7. Generally, do you feel noisy when you are in this room?

A. Very Often B. Often C. Sometimes D. Rarely E. Never

8. When you use the venetain blinds in this room, do you feel it is .... to control (such as open or/and close the slats; adjust the angle of slats)?

A. very easy B. fairly easy C. a little difficult D. quite difficult E. never use it.

9. Thinking back, under such environment below in your office, what did you do normally? Note: it is the ways you *actually* select not you are assumed to do.

	Sunny &Cold	Sunny &Hot	Overcast &Cold	Overcast &Hot
Door	Open	Open	Open	Open
	Close	Close	Close	Close
Artificial Lighting	On	On	On	On
	Off	Off	Off	Off
Window	Open	Open	Open	Open
	Close	Close	Close	Close
Venetian Blinds	Up	Up	Up	Up
	Half Down	Half Down	Half Down	Half Down
	Down	Down	Down	Down
	Down with angle	Down with angle	Down with angle	Down with angle
Move to another place	Yes	Yes	Yes	Yes
	No	No	No	No

Personal Comment

Your personal comment of the environment in this room will help us to understand further your working/studying place, but you could ignore it if you would not like to answer.

This is the end of the survey, thank you very much for participation!

Observation Sheet

Record	
Date	
Time	

Interviewee Information	
Gender	Female Male
Age	under 20 20-29 30-39 40-49 50-59 over 60
Clothing	*T-shirt, (sleeveless/short/long) shirt, (cotton/woollen) jumper, sweatshirt* Shorts, trousers, jeans, skirt (long, short), dress (short/long, no/short/long sleeves) Vest, cardigan jacket (denim/cotton, wool) overcoat

Room Information	
Room Number	
Direction	E S W N E
Occupant	1 2 3 4 5 6 7 over 8
Area	1 2 3 4 5 6 7 over8
Door	Open Half Open Close
ArtificialLighting	On Off

Indoor Climate		
Temperature		°C
Humidity		%
Luminance		Lux
Sound Level		dB

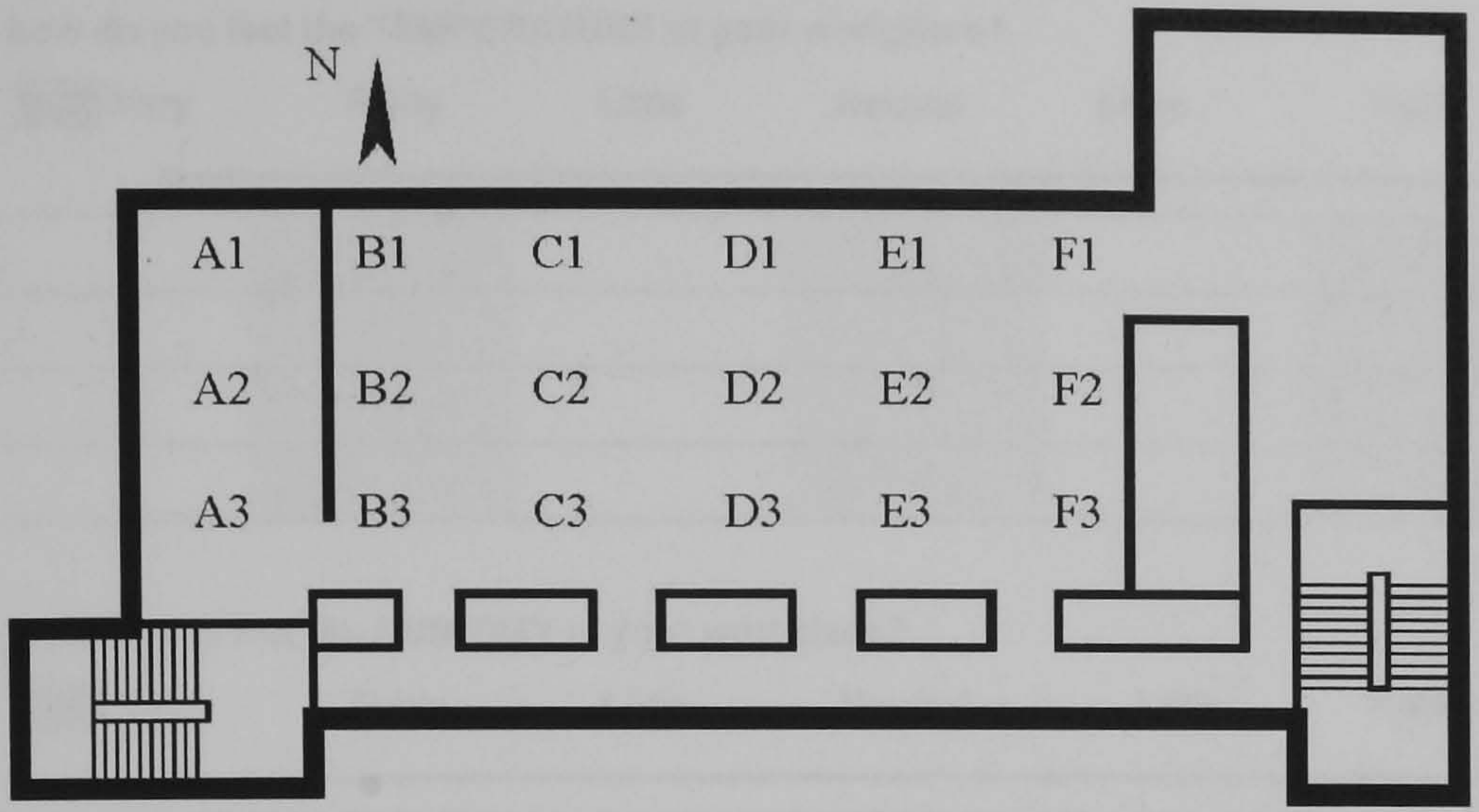
Room Accessory		
Potted Plant	yes	No
Table Lamp	Yes	No
Heater	Yes	No
Electric Fan	Yes	No

Interview Feedback

Questionnaire for ICOSS Building

Record		**Date**		**Observer**	***Yufan Zhang*** School of Architecture University of Sheffield
Room		**Time**		**Email & Telphone**	yufan.zhang@sheffield.ac.uk 0114 222-20370

1. **Which floor you are working on?** 1st 2nd 3rd 4th **Please indicate the place your desk location below:**



2. **Please evaluate the overall environment in your position *at this moment* by ticking a score in each row?**

Very **Fairly** **Little** **Neutral** **Little** **Fairly** **Very**

Cold	-3	-2	-1	0	1	2	3	**Hot**
Dark	-3	-2	-1	0	1	2	3	**Bright**
Quiet	-3	-2	-1	0	1	2	3	**Noisy**

3. **Do you feel comfortable toward the overall environment in your position *at this moment*?**

Very dissatisfied **Fairly** **Little** **Neutral** **Little** **Fairly** **Very satisfied**

Thermal	-3	-2	-1	0	1	2	3
Visual	-3	-2	-1	0	1	2	3
Acoustic	-3	-2	-1	0	1	2	3

4. **Normally, when are you in your office?**

	Very often	**Often**	**Sometimes**	**Rarely**	**Never**
Before 9am					
after 5pm					
on Sat. or/and Sun					
on public or/and bank holiday					
on vacation (Xmas; Easter; Summer)					

5. Does the reflection on the computer screen affect your work due to discomfort glare?

A. Very Often B. Often C. Sometimes D. Rarely E. Never

6. Does the view outside affect your appreciation of this room?

A. Not at all B. hardly C A little D. Somewhat E. Very much

7a. Generally, does the noisy from OUTSIDE affect your work in this room?

A. Very Often B. Often C. Sometimes D. Rarely E. Never

8b. Generally, does the noisy from INSIDE affect your work in this room?

A. Very Often B. Often C. Sometimes D. Rarely E. Never

9. Seasonally, how do you feel the TEMPERATURE at your workplace?

	HOT Very	Fairly	Little	Neutral	Little	Fairly	Very COLD
Spring							
Summer							
Autumn							
Winter							

10. Seasonally, how do you feel the HUMIDITY at your workplace?

	DRY Very	Fairly	Little	Neutral	Little	Fairly	Very STICKY
Spring							
Summer							
Autumn							
Winter							

11. Seasonally, how do you feel the AIR MOVEMENT at your workplace?

	DRAUGHTY Very	Fairly	Little	Neutral	Little	Fairly	Very STUFFY
Spring							
Summer							
Autumn							
Winter							

12. Seasonally, how do you feel the LIGHTING at your workplace?

	DULL Very	Fairly	Little	Neutral	Little	Fairly	Very BRIGHT
Spring							
Summer							
Autumn							
Winter							

13. Overall, are you satisfied with the environment in your workplace, taking into account noise/ temperature/ ventilation and lighting?

Very satisfied Fairly satisfied Neutral Fairly dissatisfied Very dissatisfied

Personal Comment

Your personal comment of the environment in this office will help us to understand further your working place, but you could ignore it if you would not like to answer.

This is the end of the survey, thank you very much for participation!

Appendix II

Publications

Effect of Occupant Environmental Issues on the Passive Design Strategy of a Naturally Ventilated Building

Yufan Zhang[1] **I.C.Ward**[1]

[1]Building Energy Analysis Unit, School of Architecture, University of Sheffield, Sheffield, UK.

ABSTRACT: Architectural passive design strategies play an important role in improving the indoor environment. However, in reality the way occupants interact with passive control systems is poorly understood. This paper based on a naturally ventilated office building examines the occupant's perception and response to indoor the environment, highlighting aspects of practical performance of the south/north facing glazing with internal blinds. Also the effect of the south facing passive stack on air movement is analyzed by onsite observation, physical data collection and a questionnaire survey. The results provide quantitative and qualitative information on built environment impacts that affect and/or are affected by occupant satisfaction, behaviour and interaction with passive control systems.

Keywords: passive design, environment, glazing, blinds, occupant

1. INTRODUCTION

At present, the impact of passive design strategies in architecture has been tested both on the energy use and physical environment during the design stage [1]. These technical design decisions are very often assumed to be used by the occupants to improve the internal environment [2]. However, in reality the way occupants interact with these control system is poorly understood [3]. This study is designed to contribute to and to increase the understanding of the concept of passive design in architecture, especially in terms of occupant control system. The study is based on an existing naturally ventilated building and aims to investigate the effects of occupant issues on the passive design strategy. Based on onsite observation, physical data collection and questionnaire a survey, the results will provide quantitative and qualitative information from the strongest to the weakest link which affect or are affected by occupant satisfaction and interaction with passive control system.

2. METHODOLOGY OF STUDY

2.1 Building identification

The ICOSS Building is a 5-story office building with around 50 occupants who work in it at present. It is 34m long and 17.5m wide with about 2900 m^2 of usable floor space. Figure 1 shows a typical floor plan of the Building. This building has large area windows with manually controlled internal blinds on both the north and south elevations. The building was designed to be naturally ventilated with the 100% glazed south façade providing a natural ventilation shaft, drawing air across the floors from the north elevation. A building management system controls the operation of the windows opening and closing them in accordance with prevailing internal and external conditions. The exposed concrete structure provides a high level of thermal mass which is again cooled by night ventilation. The building is heated by a radiator convective system. In this study, the open plan offices space was investigated.

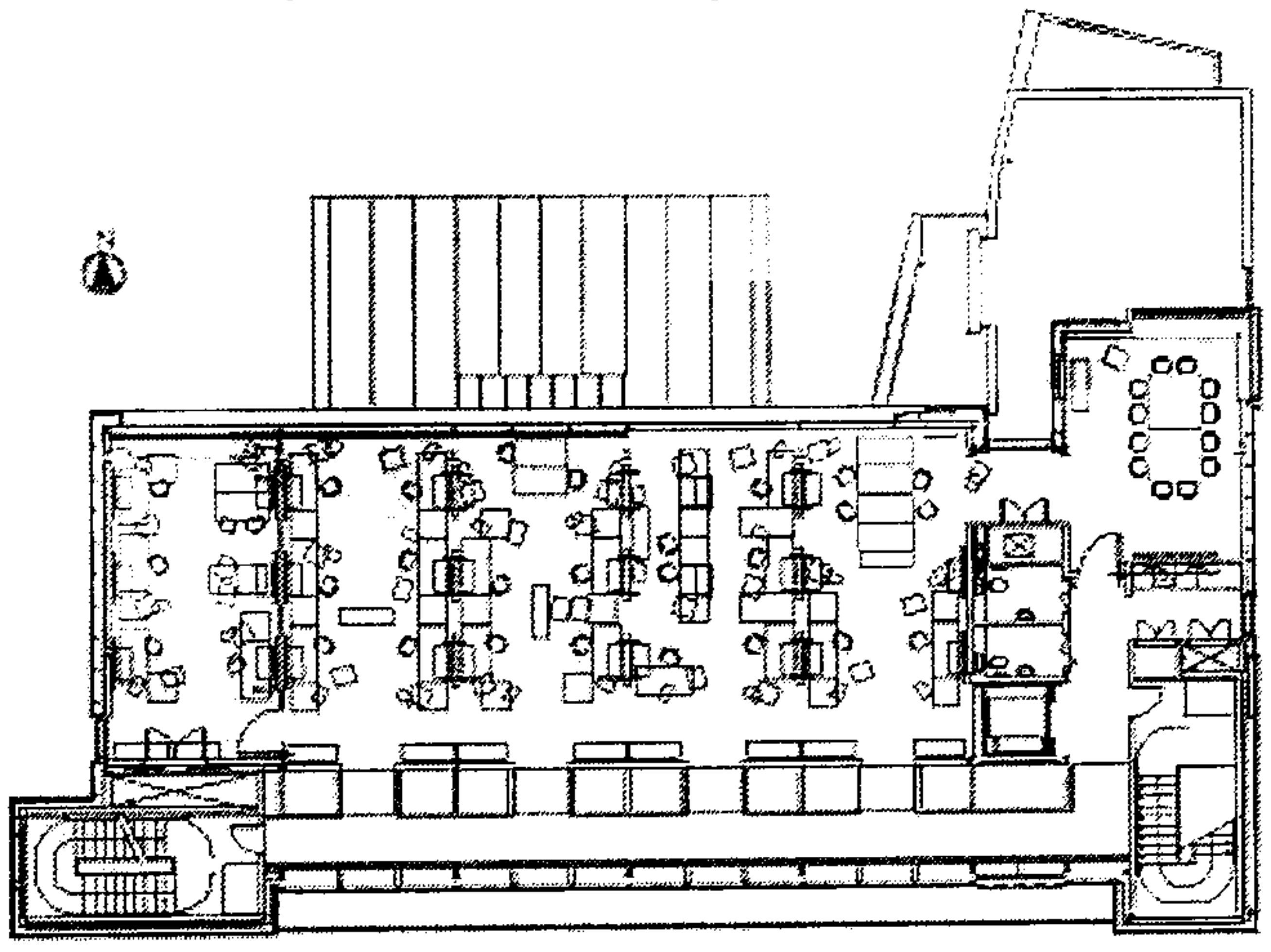


Figure 1: Second floor of ICOSS Building

2.2 Data collection

The data was collected by two methods, firstly a : photo record of the position of the blinds and the weather information. The photo record was aimed at recording the position of each blind on the south and north façades of the building twice per day (10:00 hrs and 15:00hrs). This photo record was carried out from Dec. 2004 and will continue until April 2006.

The main climatic data, hourly: air temperature; relative humidity; solar radiation; wind speed/direction; total cloud cover; daily: mean air temperature; rainfall totals; sunshine hours; and relative humidity were also collected from a local weather station.

2.3 Questionnaire collection

The questionnaire was designed using plain, concise language. It was divided into two parts: observation and survey sheet. The observation sheet was focused on the interviewee information, including gender, age, and clothing level. The survey sheet was focused on the interview's response and opinion on the indoor environment which they are in, including:

- the perception of individual indoor environment at the moment of the survey
- the comfort level of individual indoor environment at the moment of the survey
- the opinion on the physical indoor environment seasonally
- the response to the working environment

A total of 35 sets of valid records (19 female and 16 male) were obtained which accounted for about 70% of total occupants who worked in this building. Data were collected primarily in the morning and afternoon when a high concentration of people could be found in the building.

2.4 Physical measurement

In order to obtain the basic indoor environmental information in association with the occupants' response, some physical parameters were measured when the interviewee answered the survey sheet. These parameters included sound level; luminance; relative humidity and temperature.

2.5 Data processing

The photo survey concentrated on identifying the position of the blinds and each photo was analysed using the positional information as shown in Figure 2. The window position either open or closed was also recorded. The blinds based on their up/down position ranged from 0 to 7 respectively. This value was further divided by its maximum values to obtain the proportion of occlusion [4].

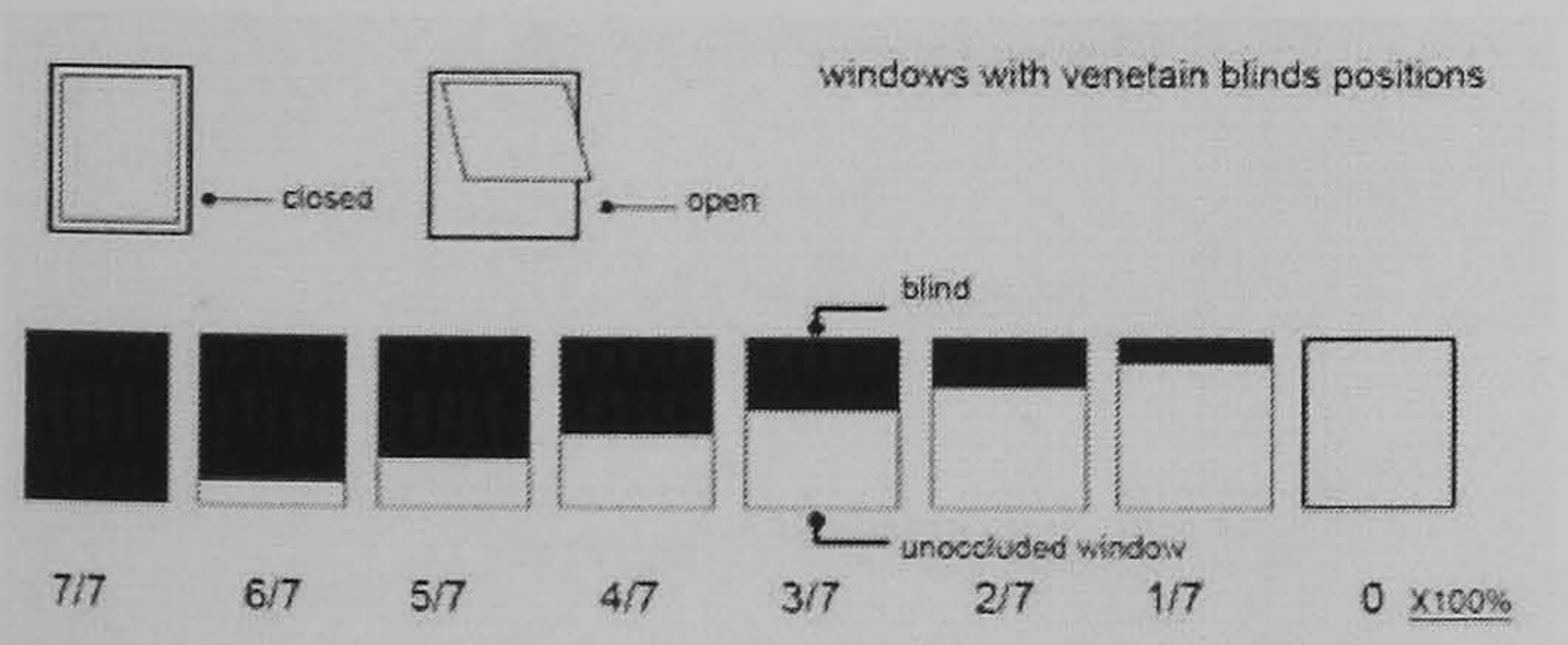


Figure 2: Value of window and blind's position

3. RESULTS

3.1 Visual environment at the user's workplace

In the open plan area of the building, the glazing area is about 100% for the south façade and 70% for the north façade. All glazing has internal blinds. The working area near the north façade was found to have no serious problems from glare or overheating. However, those working near the south façade did experience some problems and it was not until about 4m away from the façade did the problems seem to reduce. [See figure 3]

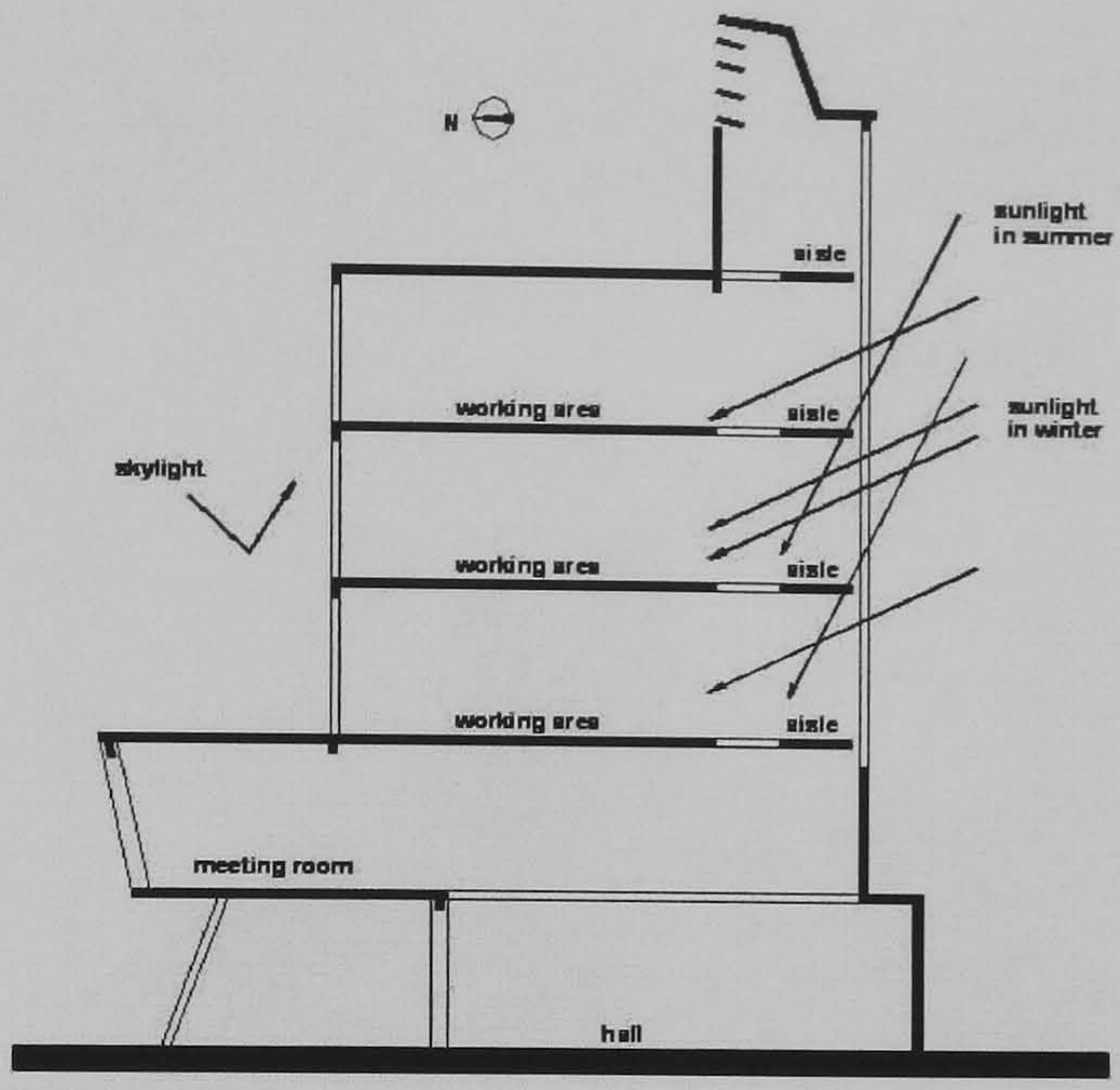


Figure 3: Sunlight penetration in summer and winter

This observation indicates that the blinds were always up during summer time. Figure 4a shows the percentage of occluded window area on the south façade in May and June, 2005. The windows are seen primarily for daylight and glare did not seem to be a major problem. This could be attributed to the fact that the solar angle in summer is high and at about 4m from the façade the penetration of sunlight was minimal.

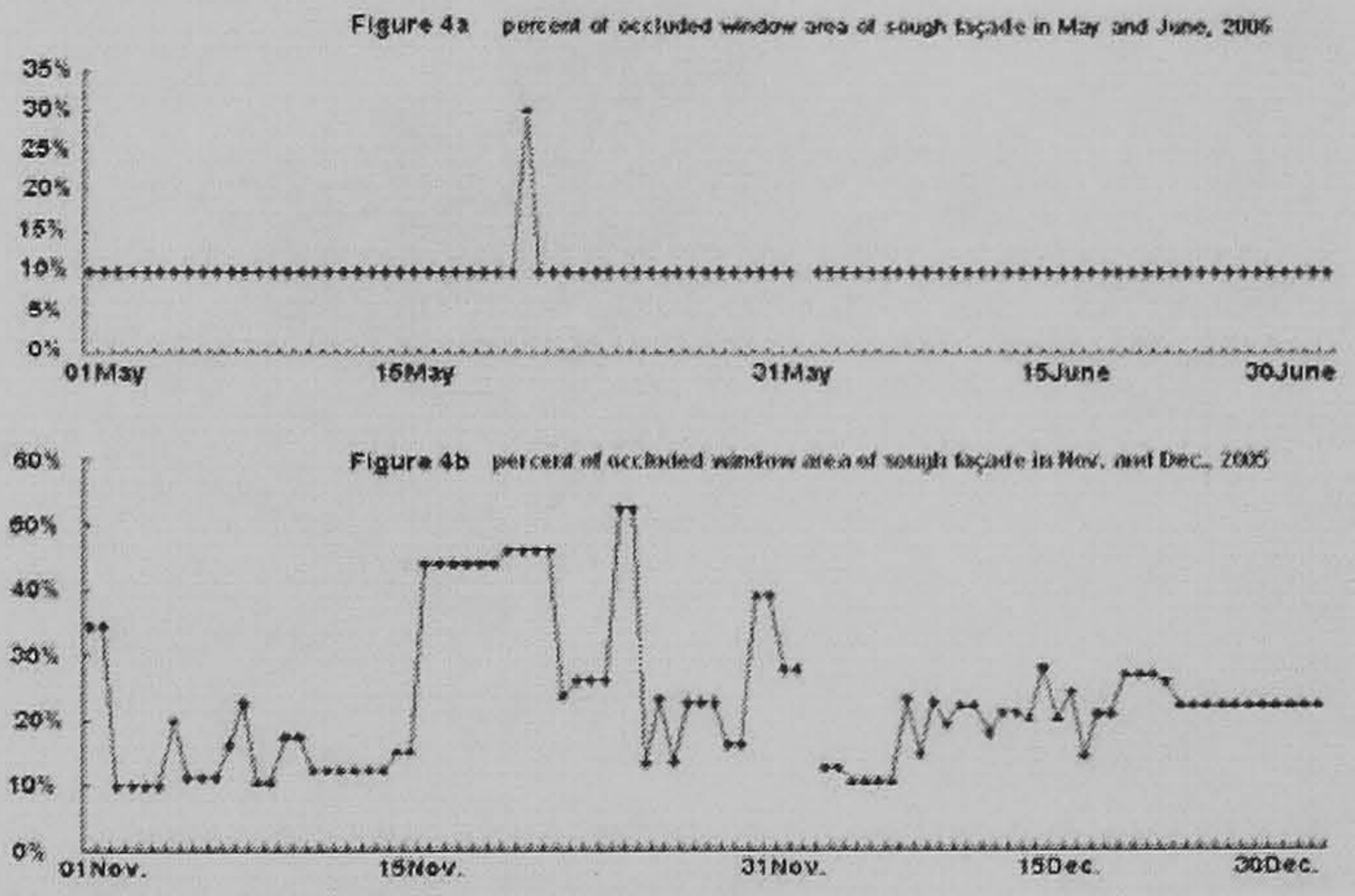


Figure 4: Occluded window area of south façade in May/ June and Nov./Dec.2005

However, in the Nov. and Dec., the solar angle is much lower than in the summer time which means more penetration happened and blinds on south façade has to be used to prevent the glare problem. Figure 4b indicates that the blinds were up and down frequently and diversely to fit the occupants need.

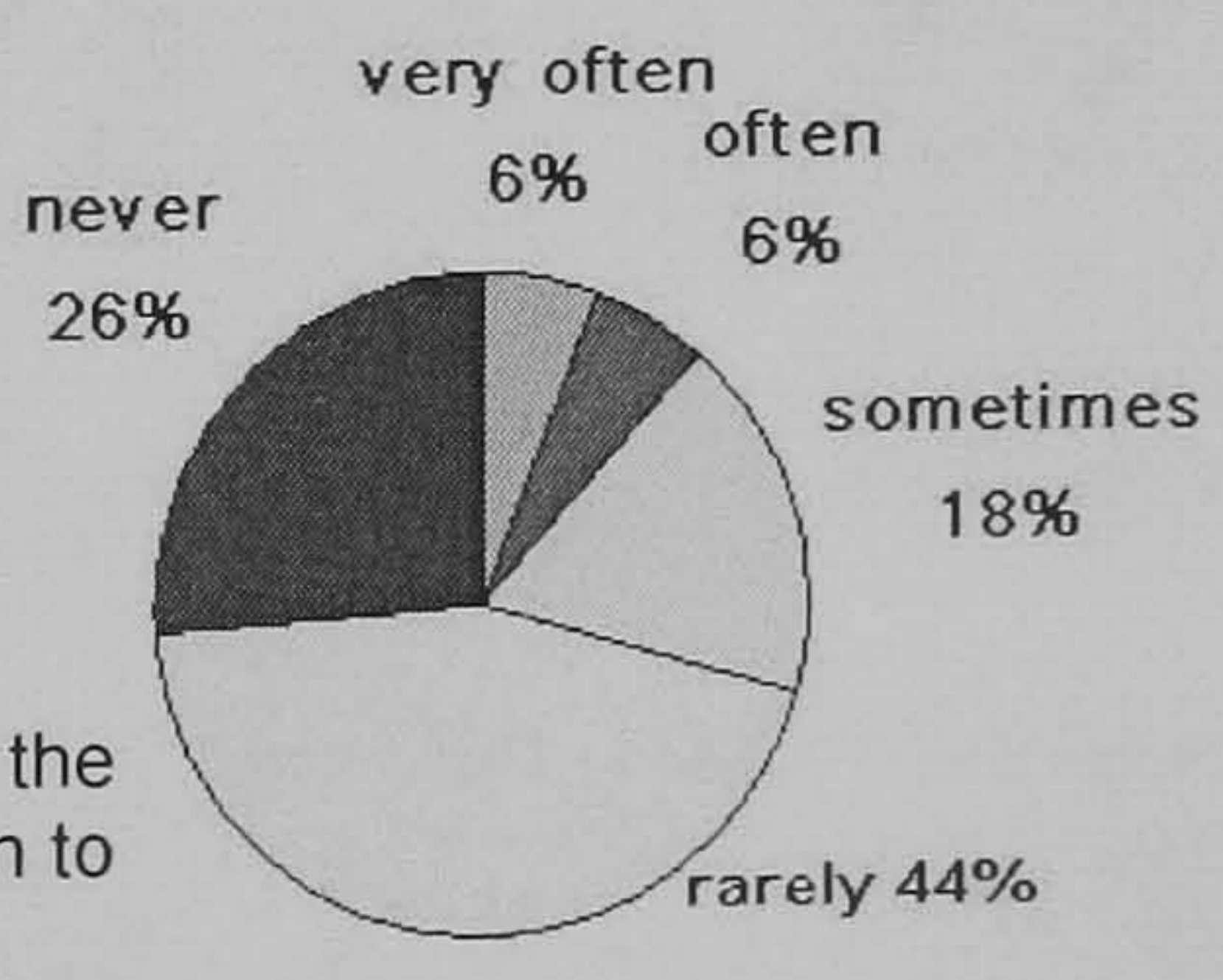


Figure 5: Breakdown of the discomfort glare affection to the occupant

Even with the blinds to control the sunlight, from the survey it appeared that still 6% of occupants reported that discomfort glare occurred "very often" with a further 6% reporting discomfort glare "often". (See figure 5)

Furthermore, from the survey responses for the lighting level, 50% of people felt neutral (neither dull or bright) and 20% of people felt that the light level to be 'very bright' in all seasons. (See figure 6)

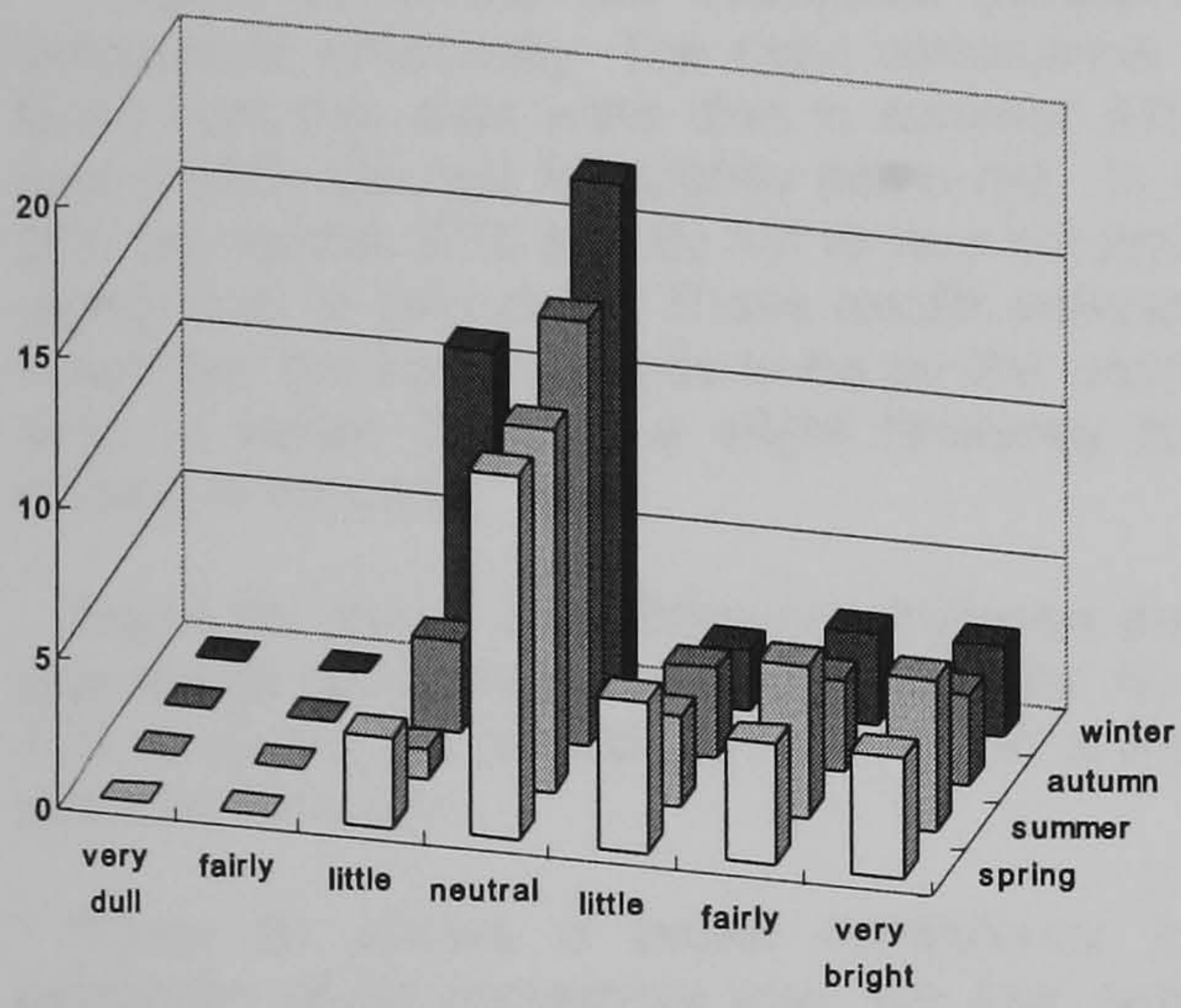


Figure 6: Distribution of responses to the lighting level in the four seasons

In this case, both discomfort glare and lighting level could be helped by encouraging occupants to use internal blinds to maximize their visual comfort and lighting quality.

3.2 Thermal environment at the user's workplace

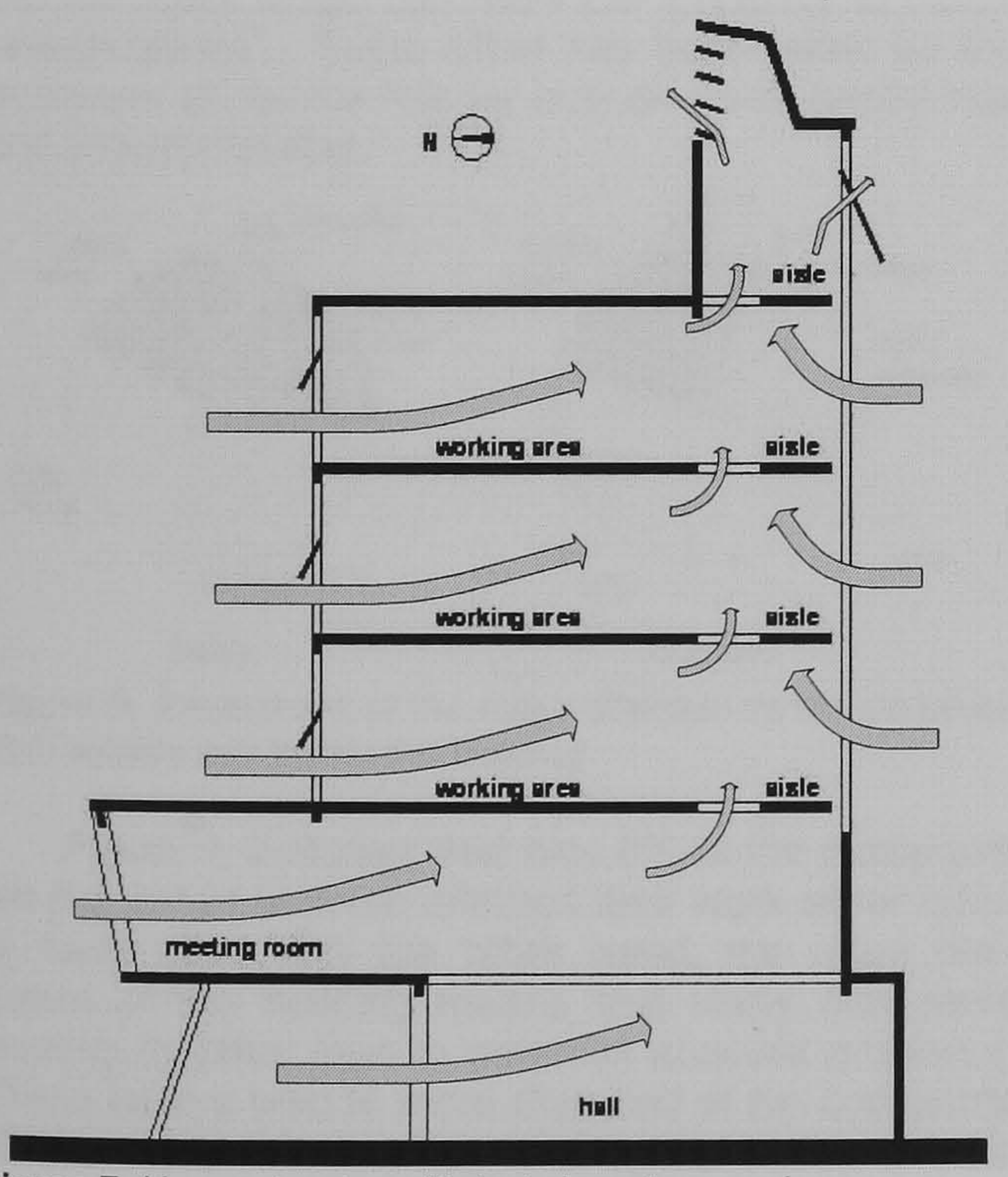


Figure 7: How natural-ventilated clerestory works

As mentioned above, the building has large glazing area both in south and north facades, however in the south side; most of the windows are fixed except in the fifth floor (clerestory floor) where a row of small windows can be opened. On the north façade, 70% of the glazing area is fixed and 30% can be opened. A clerestory on the top floor is designed to provide a means of increasing natural ventilation to all floors.

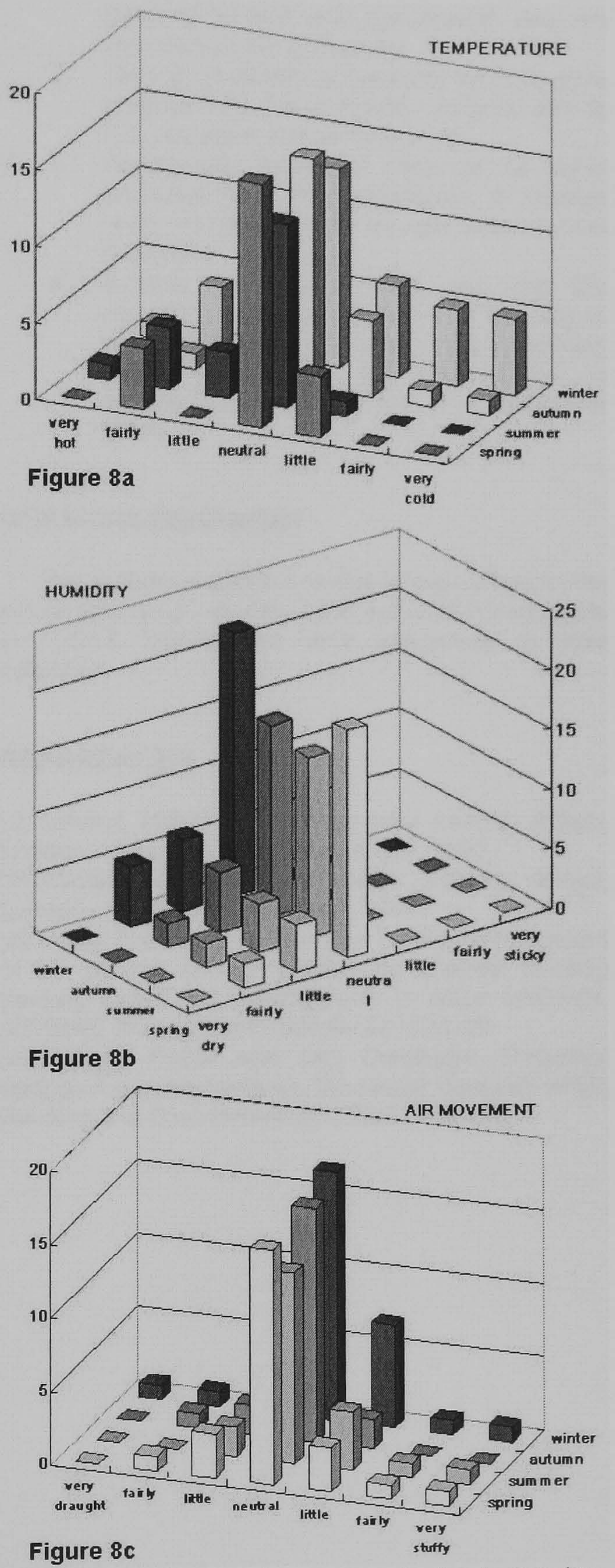


Figure 8a

Figure 8b

Figure 8c

Figure 8: Distribution of responses to the temperature, humidity and air movement in the four seasons

Figure 7 shows how the passive stack ventilation system was designed to promote the flow of air from the north to the south. The clerestory windows provide further openings to vent the warm air out of the building in warm days during summer periods.

Figure 8 shows the distribution of survey responses to the temperature, humidity and air movement for the four seasons. In each diagram, the axis X presents the different levels perception from very hot to cold for temperature; very dry to sticky for humidity and very draught to stuffy for air movement. The axis Y presents four seasons respectively and axis Z indicates the total numbers of responses received.

Figure 8a shows the occupants perception of temperature seasonally. The main conclusions to be found from this data were that in summer 57% felt neutral while the rest felt slightly hot to hot. In winter 36% felt neutral, 21% slightly hot to very hot and 43% slightly cool to very cold. These results indicate that in summer the building tends to be on the warm side while in winter there is a slight tendency for the building to be cool.

Figure 8b shows little difference between the four seasons for occupant perception of humidity. Average 71% occupant felt neutral, while 18% felt a little dry and 11% fairly dry.

Figure 8c shows a broad consistency in the perception of air movement over the four seasons. 62% of occupants felt neutral in summer which dropped to 51% in winter. Also in winter 21% occupant felt a little or fairly draughty while 27% felt very, fairly and a little stuffy.

3.3 Acoustic environment of the user's workplace

This building has a significant amount of exposed thermal mass which can have the tendency to cause reverberations'. Some effort has been taken by the designers to reduce this by including soft furnishings and acoustic baffles.

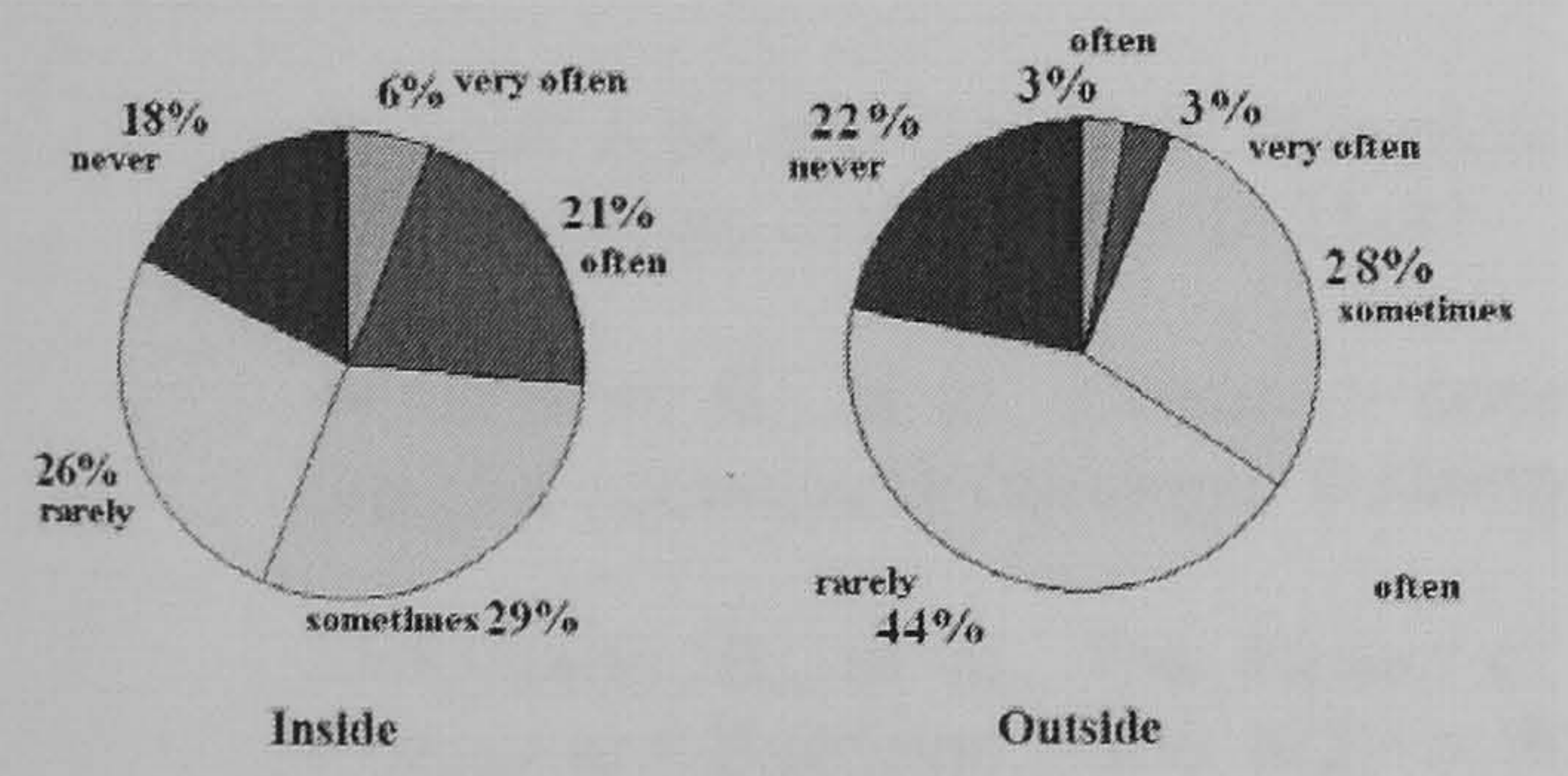


Figure 9: Breakdown of the noise affection to the occupant from outside and inside the building

Figure 9, indicates that only 6% of the occupants felt that external noise affected their work either often or fairly often. On the other hand, the open plan nature of the building means that many occupants working together lead to potential acoustic problems. These factors lead to more than half of the occupants (56%) being affected by the noise inside of the building ranging from sometime (29%) to often (21%) and very often (6%).

4. CONCLUSION

This study has led to the following conclusions:

1. It appeared that the blinds (which were designed to limit solar penetration) were not operated by the occupants.
2. This led to certain areas suffering form glare problems on the computer screens and to overheating in the warm periods.
3. Acoustically there did seem to be some problems with the transmission of internal noise which needs to be addressed by the designers.
4. Another conclusion found was that the occupants were not informed of the way to control the blinds and therefore an education programme should be implemented to ensure that they knew how the control the blinds.

ACKNOWLEDGEMENT

The authors would like to thank Angie Maskrey for kindly arranging interview time and all the occupants in ICOSS building for their assistance in data collection.

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