# Daylight and Planning in Europe

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A thesis submitted in partial fulfilment of the requirements of
London Metropolitan University
for the degree of
Doctor of Philosophy

August 2004

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*Dedicated to*

Manuel

Wherever you are whatever you do let the light guide you through

# Abstract

This work addresses issues related to daylight in urban canyons in predominantly sunny climates. Reflected sunlight from obstructions and ground is a major contribution to the illumination of buildings in orientations and at times when the sun is behind the building.

Physical measurements collected in an urban canyon in Lisbon showed a linear relationship between the global horizontal illuminance and the total vertical illuminance when the facade is not receiving direct sunlight. Further studies carried out with computer simulations with RADIANCE as well as analytical calculations confirmed this relationship, which is shown to be relatively stable throughout the year, with latitude and orientations and time of day when sunlight is reflected off obstructions and ground. Moreover, the slope of this linear relationship is relatively similar for different floor heights and canyon ratios. Thus, the equation is representative of the whole year condition and fairly robust for individual parameters. It may therefore be used for quick calculations in the initial design stages of the project.

Daylight calculations are commonly based on the daylight factor method regardless of prevailing weather conditions. While this method may be used for overcast sky conditions, it can be argued that it is not appropriate for clear skies.

A relationship emerged which forms the basis for the average total daylight factor calculation in an urban canyon, taking into consideration reflected sunlight. In a similar way to the average daylight factor it may be used as an indicator of how well lit the indoor environment is and allows for the sizing of windows under predominantly sunny climates.

All the above gave the basis to the definition of guidelines for daylight and urban planning in Europe. Two different set of criteria are presented. They apply to predominantly overcast and clear sky conditions. Both, individually or combined, allow for daylight design in European climates.

# Acknowledgements

This thesis would not have been possible without the support of numerous individuals and institutions. Whilst this page is meant to give credit where credit is due, there have been so many contributions in various forms and from so many different sources that it could go on forever and on and still miss out on somebody who was instrumental in the delivery of this thesis. Sincerest apologies to anyone who deserves recognition and is not mentioned.

First and foremost, I would like to thank my Director of Studies Prof. Mike Wilson and my supervisors Prof. Peter Tregenza and Prof. Bob Gilchrist. Their considerable knowledge and expertise in their respective fields of research provided me with exceptionally good tutorials, feedback and incentive to push my research further than I initially envisaged.

During my time in London, all my colleagues in the Low Energy Architecture Research Unit, LEARN, deserve my thanks for providing an inspirational and productive working environment. John Solomon in particular was kind enough to help me with the design and assembly of the instrumentation. To my colleague and partner Axel Jacobs who, above all others gave me invaluable advice and constant support.

I am grateful to the Instituto Nacional de Engenharia, Tecnologia e Inovação in Portugal, INETI, for providing financial support and allowing me to focus exclusively on this thesis. I would like to express my particular gratitude to INETI's former president Prof. Henrique Machado Jorge and my Directors Doctor Helder Gonçalves and Doctor António Joyce who supported my application and gave me the opportunity to go abroad to carry out my research.

My special thanks to the Fundação da Ciência e Tecnologia for the financial support I received through their scholarship.

Since English is not my first language, Phil Wilkins was patient enough to proofread this document and improve upon its readability which, I am sure, will be much appreciated by the reader.

The part of my research that was about taking physical measurements in an urban street very much relied on the tenants and owners of flats that kindly allowed me to put up the instrumentation in the windows of their apartments.

This thesis was written with the LyX/LaTeX text processor under the a GNU/ LINUX operating system. Other open source software, including RADIANCE and Open Office was used preferably. I hereby express my sincere recognition to the open source community for providing me with the tools to carry on my work.

Many of my friends in the United Kingdom and in Portugal have help my surviving in and enjoying a foreign country. A special thanks goes also to Ines Fonseca for aiding me with the statistical analyses.

My biggest 'Obrigada' has to go to my parents, my brother Pedro and my sister Isabel who have been very supportive over the last four years and helped me keep a strong link with Portugal. My father in particular has provided me with helpful criticism and many suggestions, while my mother allowed me to keep in touch with my family. I hope this thesis satisfies, if not exceeds their expectations in me.

The last but not by no means the least person to mention is my brother Manuel who, unknowingly, was a source of inspiration to carry on with my education.

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| | |
|---|---|
| $A$ | is the total area of interior surfaces, ceiling, floor and walls including windows [$m^2$] |
| $A_a$ | is the area of the atrium [$m^2$] |
| $AR$ | is the aspect ratio in an urban canyon |
| $A_{si}$ | is the area of surface with index $i$ [m] |
| $A_w$ | is the net glazed area of window [$m^2$] |
| $CF$ | configuration factor |
| $C_o$ | is a coefficient dependent on the obstruction outside the window. For a continuous obstruction, is given by $\frac{\theta}{2} - 5$ where $\theta$ is the vertical angle (in degrees) of visible sky measured at a section perpendicular to the facade at the centre of the interior plane of window opening |
| $D$ | daylight factor [%] |
| $\overline{D}$ | average daylight factor [%] |
| $D_c$ | sky component for the daylight factor calculation [%] |
| $D_{CIE}$ | is the CIE standard overcast sky daylight factor at a given point [%] |
| $D_e$ | externally reflected component for the daylight factor calculation [%] |
| $D_i$ | internally reflected component for the daylight factor calculation [%] |
| $D_R$ | required daylight factor [%] |
| $D_v$ | daylight factor on the outside face of the window [%] |
| $E$ | illuminance [lux] |
| $E_{dh}$ | outdoor unobstructed diffuse horizontal illuminance [lux] |
| $E_{dP}$ | diffuse (from sky) illuminance at point $P$ [lux] |

| | |
|---|---|
| $E_{eD}$ | is the design external illuminance [lux] |
| $E_{dv}$ | is the diffuse vertical illuminance [lux] |
| $E_{gh}$ | is the global horizontal illuminance [lux] |
| $E_{id}$ | diffuse (from sky) illuminance interrefected (in the canyon) [lux] |
| $E_{in}$ | indoor illuminance [lux] |
| $\overline{E_{in}}$ | average illuminance indoors [lux] |
| $E_{is}$ | solar illuminance interrefected (in the canyon) [lux] |
| $\overline{E_n}$ | average illuminance index $n$ [lux] |
| $E_P$ | illuminance at point $P$ [lux] |
| $\overline{E_R}$ | is the require average illuminance on the work plane [lux] |
| $E_{sn}$ | solar normal illuminance [lux] |
| $E_{sP}$ | solar illuminance at point $P$ [lux] |
| $E_{sp}$ | illuminance at the sun patch [lux] |
| $E_{sv}$ | solar vertical illuminance [lux] |
| $E_{tv}$ | total vertical illuminance [lux] |
| $f_\circ$ | is a window orientation factor, to take account of different amounts of diffuse light received at different windows orientations for no-overcast sky conditions |
| $H$ | height of the atrium [m] |
| $h$ | height of the canyon [m] |
| $h_P$ | height of the point P [m] |
| $HSA$ | horizontal shadow angle [deg] |
| $K_R$ | is the conversion factor of the RADIANCE system's own value of luminous efficacy, with a fixed value of 179 [lm/W] |
| $L$ | luminance [cd/m$^2$] |
| $L_a$ | length of the atrium [m] |
| $L_{clz}$ | is the luminance at the zenith in a clear sky [cd/m$^2$] |

| | |
|---|---|
| $L_{ocz}$ | is the luminance at the zenith in an overcast sky [cd/m$^2$] |
| $L_s$ | is the luminance at surface [apostilibs] |
| $L_\zeta$ | is the luminance of a sky element [cd/m$^2$] |
| $L_{\zeta\alpha}$ | is the luminance in any arbitrary sky element [cd/m$^2$] |
| $L_z$ | is the luminance at the zenith [cd/m$^2$] |
| $l$ | length of the canyon [m] |
| $M$ | is a correction factor for dirt and glazing bars |
| $P$ | point on the facade |
| $P_e$ | perimeter of the floor plam of an atrium [m] |
| $R^2$ | coefficient of determination |
| $rd$ | is the room depth [m] |
| $rw$ | is the room width [m] |
| $S$ | astronomical daylength |
| $S_i$ | surface of the canyon index $i$ |
| $S_p$ | size of sun patch [m] |
| $S\%$ | percent relative sunshine duration |
| $T_A$ | is the atmospheric turbidity factor, taken by default as 2.75 |
| $TD$ | total daylight factor [%] |
| $\overline{TD}$ | average total daylight factor [%] |
| $VSA$ | vertical shadow angle [deg] |
| $W$ | width of the atrium [m] |
| $w$ | width of the canyon [m] |
| $wh$ | the window head height above floor level [m] |
| $x$ | height of the sun patch on the obstruction [m] |
| $y$ | size of the sun patch on the ground [m] |

| | |
|---|---|
| $Z$ | is the angular distance between a sky element and the zenith $Z = \pi/2 - \zeta$ [rad] |
| $Z_s$ | is the angular distance between the sun and zenith [rad] |
| $z$ | is the size of the projection on the obstruction from the sun patch on the ground [m] |
| $\alpha_{av}$ | is the area weighed mean absortion factor of indoors surfaces |
| $\alpha_i$ | is the vertical angle of the obstruction measured at a section perpendicular to the facade at the height of the point [deg] |
| $\chi$ | is the angular distance between a sky element and the sun [deg, rad] |
| $\gamma_s$ | solar altitude [deg] |
| $\phi$ | luminous flux [lm] |
| $\phi_0$ | flux entering the room [lm] |
| $\phi_{abs}$ | flux absorved by indoor surfaces [lm] |
| $\phi_{dt}$ | total diffuse flux entering the canyon [lm] |
| $\phi_{in}$ | flux incident on indoor surfaces [lm] |
| $\phi l_{sp}$ | flux leaving the sun patch [lm] |
| $\phi r_{sp}$ | flux reaching the sun patch [lm] |
| $\phi_{st}$ | total solar flux entering the canyon [lm] |
| $\phi_t$ | total flux entering the canyon [lm] |
| $\rho$ | reflectance of a surface |
| $\rho_{av}$ | is the area-weighed average reflectance of interior surfaces |
| $\rho_{avera}$ | is the average reflectance of the obstruction and ground in the canyon |
| $\rho_b$ | the average reflectance of surfaces in the rear half of the room (away from the window) |
| $\rho_{cw}$ | is the average reflectance of the ceiling and parts of the wall (excluding the window wall) above the mid-height level of the window |
| $\rho_{fw}$ | is the average reflectance of the floor and parts of the wall (excluding the window wall) below the mid-height level of the window |

| | |
|---|---|
| $\rho_{pond}$ | is the average reflectance of the surfaces in the canyon including a virtual ceilling enclosing the canyon with $\rho = 0$ |
| $\sigma$ | is the angle of incidence of the sun beam on the vertical facade [deg] |
| $\tau$ | is the diffuse light transmittance of the glazing |
| $\theta$ | is the vertical angle of visible sky measured at a section perpendicular to the facade at the centre of the interior plane of window opening [deg] |
| $\theta_v$ | angle of incidence of sunlight on the vertical facade [deg] |
| $\zeta$ | is the elevation angle of a sky element above the horizon [rad] |

# Chapter 1

# Introduction and research aims

## 1.1 Daylight and planning

The ultimate source of all daylight is the sun. However, weather conditions and climate, building orientation and time of the day can suppress sunlight access to buildings. In these cases, interiors are dependent on light from the sky and that reflected by surrounding surfaces.

This work addresses issues related to daylight in buildings in predominantly sunny climates. Daylight calculations tend to underestimate daylight levels, with particular reference to the reflected light from obstructions in urban canyons and might lead to inappropriate urban planning and window design.

There are several factors affecting the light reaching a building. The geographical set related to the sky condition and latitude affect the quality and quantity of the light in a place. The local variables, also external to the building, are related to its orientation, the distance to height ratio of the building opposite and the reflectance of the external surfaces. The last set, the internal variables, are related to the size of the window, the transmittance of the glazing material and the reflectance of the interior surfaces.

Daylight calculations are usually based on uniform or overcast skies, where the sunlight contribution is excluded, but under locations where clear skies are predominant, it might lead to an underestimation of daylight availability. Although there are several methods for daylight analysis under sunny conditions, all require well advanced states of the project or tend to be difficult to use by architects. A simple daylight calculation taking into consideration the sun component is therefore of major importance in the initial phases of the project.

In urban canyons, facing buildings provide considerable obstruction to daylight access by reducing the skylight contribution and sometimes blocking the access to sunlight. However, reflected sunlight from the obstructions or the ground can play an important role in the illumination of buildings, particularly in orientations and at times of the day where sunlight is not incident on windows. Furthermore, obstructions and ground can redirect the light to other interior surfaces rather than the horizontal plane, and lead to a greater uniformity of the light inside the space.

## 1.2 Aims

The main aims of this investigation are:

- to predict the contribution of the reflected component in sunlit obstructions;
- to suggest a simplified daylight calculation using a clear sky distribution in an urban canyon;
- to generalise appropriate planning guidelines for Europe.

## 1.3 Structure of the work

This thesis can be divided into three main parts. Chapters 1 to 3 contain the introduction and the research aims, the literature review and the development of an analytical calculation for daylight analysis that takes into consideration the sun component reflected from obstructions and ground.

An introduction presents the background for this research and defines the aims and methods used in the work. An initial reference to sky types and solar geometry gives the basis for the understanding of daylight variability and availability. Some of the more commonly available methods for daylight design and estimation of illuminance levels as well as daylight regulations or recommendations in Portugal and in the United Kingdom are addressed.

Background research of the methods used for daylight analysis revealed the wide acceptance of the daylight factor approach. The simplicity of the calculation and disregarding of the sky brightness make it the most frequently used approach, regardless of the prevailing climatic conditions at the site. However, the exclusion of sunlight from the calculation makes it inappropriate where sunny skies are predominant. Also the judgement that designing using overcast skies conditions is likely to be sufficient under clear sky distributions can be erroneous, particular for orientations and times of day when sunlight is excluded.

The analytical calculation, presented in chapter 3, was developed in order to understand the contribution of reflected light in a canyon. It separates the skylight and sunlight contribution and considers with reasonable accuracy the first reflection of sunlight from obstruction and ground and the interreflection contribution for the successive reflections in the canyon. Results obtained and validation of the theoretical model are presented in chapter 6. Although not a substitute for more accurate methods, this calculation results in a useful tool enabling the user to quickly analyse and change parameters of interest.

The second part of the thesis, chapters 4, 5 and 6, involves the analysis of results from real measurements, from computer simulations performed with RADIANCE and from those achieved with the analytical calculation.

The importance of reflected light from the obstruction and ground, both from the sun and the sky, was analysed and variables such as the orientation of the building, the angle sustained by the obstruction and the reflectance of the surfaces are addressed.

Real data collected in Lisbon as well as simulations undertaken with RADIANCE showed a linear relationship between the global horizontal illuminance, $E_{gh}$, and the total vertical illuminance, $E_{tv}$, at the building facade when the facade is not receiving direct sunlight. The 'total vertical illuminance' is defined as the sum of sunlight, skylight and the interreflected component that falls on a vertical plane per unit of area. This relationship can be described by a linear equation of the form $E_{tv} = k \cdot E_{gh} + C$, where the slope $k$ depends on the reflectance of the obstruction, the geometry of the canyon and the position on the facade. The constant $C$ is mainly the contribution of the diffuse sky illuminance to the building's daylight and is more significant at higher floors.

Further studies undertaken with RADIANCE and the analytical calculation developed confirmed that an approximately linear relationship existed except under specific conditions occurring mainly in the summer when the ground was fully sunlit. However, they do not weight significantly on the average. Depending on the accuracy of the calculation, this relationship can be representative for the whole year. Tables of the coefficients for different reflectance and canyon ratios provide parameters to be used in the simplified calculation presented in the third part of this research. Conclusions emerged from the analyses of the variables of interest give the basis for the suggested guidelines presented in chapter 8.

The last part of the thesis deals with the definition and application of a simplified method of daylight analysis in a space in an urban canyon for clear skies. Daylight criteria and strategy are discussed and guidelines for window and urban planning design are presented. Chapter 9 summarises the conclusions of this research and presents suggestions for future research.

So far, all the daylight calculations have been made at the external surface of the buildings in an urban canyon. Chapter 7 focus on the light entering the room through a side lit window.

The definition of a good visual environment is somewhat subjective and should not be based exclusively on absolute values. The perception of how well a room is daylit is influenced by the light level, the uniformity ratio of the illumination of surfaces in the space but also by the relation to the outside ambient light.

Previous research has presented a simplified relationship between the global horizontal and the total vertical illuminance when the building does not receive direct sunlight and is looking into an urban canyon. Given this relationship, if the constant is excluded, there is a direct proportionality between these two illuminance values. This gives the basis for the definition of a simplified calculation similar to the daylight factor but including reflected sunlight.

A calculation similar to the average daylight factor, but taking into consideration the sun component, can address a characterisation of how well the space is lit as well as a corresponding recommendation of minimum percentage for window areas. This method can be applied for similar geometries and locations where sunny skies are predominant. An average total daylight factor, defined as the ratio between the mean total illuminance in a space , i.e. direct and indirect for both sky and sun, to the external unobstructed global illuminance is presented for a north facing building in a canyon for three different canyon ratios and building reflectance.

Considering all the previous results, chapter 8 presents criteria to be used for planning and window design depending on the frequency of a certain sky distribution for that location and the scene geometry.

The last chapter presents the final conclusions of the research and suggests future areas of interest to be developed.

## 1.4 Methodology

In daylight calculations it is customary to ignore the sunlight component. From the literature review of the typical methods for daylight analysis two points emerged. The first forms the major hypothesis of this thesis that reflected light can give an important contribution to the illumination of buildings. The second revealed the need for a simple calculation that considers the sunlight contribution. This way, this research is focused on studies of an urban canyon under clear sky conditions where the reflected sunlight is an important contribution mainly at times of the day when direct sunlight is not available.

An urban canyon geometry was used to investigate the role of variables of interest to the illuminance on buildings, such as the angle sustained by an obstruction, its orientation and the reflectance of the surfaces. The primarily location was set in Lisbon, with the urban canyon dimensions being based on the Portuguese regulations. An analysis of the influence of reflected light as a contribution to the overall illuminance was made under overcast skies and then under clear skies. A similar study was undertaken for the London location to provide results for a different latitude

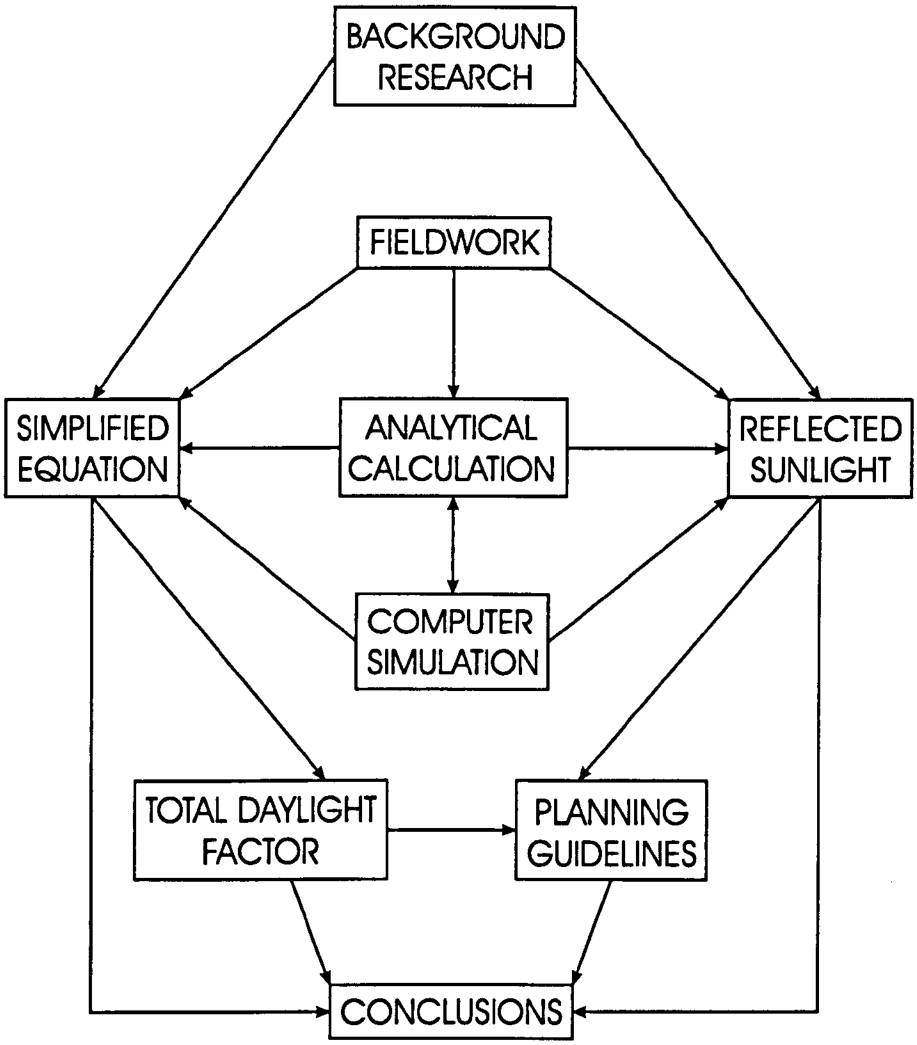


Figure 1.1: Structure of thesis.

and canyon geometry.

Three main methods were used: field experiments, computer modelling and an analytical calculation. Although the three methods may be used similarly they can also be complimentary.

Field experiments were used for collecting empirical data. Global horizontal and total vertical illuminance readings were collected in an urban canyon and plotted against one another.

The importance of reflected sunlight as well as the relationship between the global horizontal and the vertical illuminance were further analysed analytically. This relationship is dependent on numerous interactions that occur simultaneously and the computer simulations and the analytical calculation helped distinguish their effects and thereby increased the understanding of the process.

Computer simulations and analytical calculation were used to model similar scenarios and simulate different assumptions: latitude, orientation, time of the day or year or different canyon ratios and surface reflectance to derive emergent characteristics from assumed or derived relationships.

Because the relationship which emerged was confirmed by the three methods, the level of confidence was increased. Statistical methods showed high coefficients of determination, considered a good index of a reduced error between the values calculated and the estimated values. The correlations obtained were statistically significant at the 1% level.

Analysis of results may help in formulating new hypotheses to be tested further: if this relationship does not change significantly for other days in the year it can be said to be representative of the year condition.

The average illuminance within a room was based on the principles of the integrating sphere, which forms the basis of the average total daylight factor calculation.

Just as the average daylight factor method is used to analyse how well daylit a space is under an overcast sky, a similar analogy is used under sunny climates. Tabular data of average total daylight factors are presented for different canyon dimensions.

A final aspect of the research concerns the generalisation of previous results and the provision of guidelines for good practise on daylighting in Europe.

# Chapter 2

# Daylight context

## 2.1 Introduction

People spend nearly 80% of their lives inside buildings. Therefore it is essential to promote a good indoor environment for improved work performance and increased human well being. A well daylit space is perceived as more healthy and attractive and windows provide a better contact with the exterior. However, there has been a tendency to reduce daylight in domestic buildings. (Wilson and Brotas, 2001) Emphasis on heat losses through windows have resulted in Building Regulations that encourage a reduction in window size, thereby reducing daylight access. Moreover, the substitution of single by double or even triple glazing has contributed significantly to the reduction of daylight access. Although several recommendations towards daylight design exist, they are rarely considered as a main criterion in planning and building design.

There are several factors that affect the daylight availability in a space. Some are related to the outside environment such as the sky conditions and the latitude of the place, the orientation of the building, the layout of surrounding buildings and the properties of the external surfaces. Others are mainly related to the indoor environment such as the size and location of the windows, the glass transmittance, room dimensions and the properties of the interior surfaces.

Over the years, several methods for daylight analysis have been developed. Traditionally they have been based on uniform or standard overcast skies, where sunlight is excluded from the calculations. (Collins, 1984; Hopkinson, 1963; Lynes, 1979) If, in locations where cloudy conditions predominate the sun component may be disregarded, in predominantly sunny climates direct or reflected sunlight can make a significant contribution to the illumination of buildings. Although some prediction daylight methods consider the sun's contribution, sunlight reflected from the obstructions and ground is still an underestimated area of research. Whereas reflected light has long been suggested as an important contribution to the illumination of buildings, it has only recently become an object of detailed analysis. (Hopkinson and Petherbridge, 1953; Tregenza, 1995; Tsangrassoulis et al., ; Ricardo Carvalho Cabús, 2002)

An urban canyon[1] can be considered a good example of a geometry where reflected sunlight can play an important role in illuminating buildings. Unfortunately there are still comparatively few studies in this type of geometry. However, the geometric similarity between an urban canyon and a linear open atrium design means that research available on the latter may provide evidence for studies in the former. Daylight prediction methods for atria buildings reviewed by Wright et al (Wright and Letherman, 1998) emphasise the reduced availability of methods that can be easily employed in the early phases of the design and under clear sky conditions.

This chapter introduces the daylight context to this thesis. It starts with the description of the sky types, the solar geometry and factors affecting the daylight availability in a space in an urban canyon. Next, some methods and criteria for daylight design are addressed and a review of the state of the art of daylight in urban canyons and atria buildings is discussed.

The final section gives an overview of the regulations and recommendations for daylight in Portugal and in the U.K. All the above give the basis for the research to be developed in the following chapters.

## 2.2 Types of sky

For any place, daylight illumination changes as a result of the permanent diurnal and annual change of the sun position, of the sky conditions and the weather. As the distribution of real skies may be difficult to quantify, several sky models to be used in daylight calculations have been developed.

### 2.2.1 Sky models

The simplest sky model distribution is the uniform or isotropic sky. It is characterised by a constant brightness in all directions. Initially proposed as a representation of a cloudy sky, it was later recognised as an unrealistic condition due to the luminance gradient that occurs in real skies. However, the uniform sky is still used for simple calculations and for discussion of 'Rights of Light', see section 2.8.3.

The overcast sky was proposed by Moon and Spencer (in 1942) as a basis for design in climates where overcast conditions prevail. The overcast sky model can be

[1]Urban canyon is a long street, a contiguous corridor of buildings and facing obstructions limiting its longest horizontal axis.

represented mathematically as[2]

$$L_\zeta = \frac{L_{ocz} \cdot (1 + 2\sin\zeta)}{3} = \frac{L_{ocz} \cdot (1 + 2\cos Z)}{3} \tag{2.1}$$

where

$L_\zeta$ is the luminance of a sky element [cd/m$^2$];

$L_{ocz}$ is the luminance at the zenith in an overcast sky [cd/m$^2$];

$\zeta$ is the elevation angle of a sky element above the horizon [rad];

$Z$ is the angular distance between a sky element and the zenith. $Z = \pi/2 - \zeta$ [rad].

This distribution was adopted as a standard by the CIE[3] in 1955.

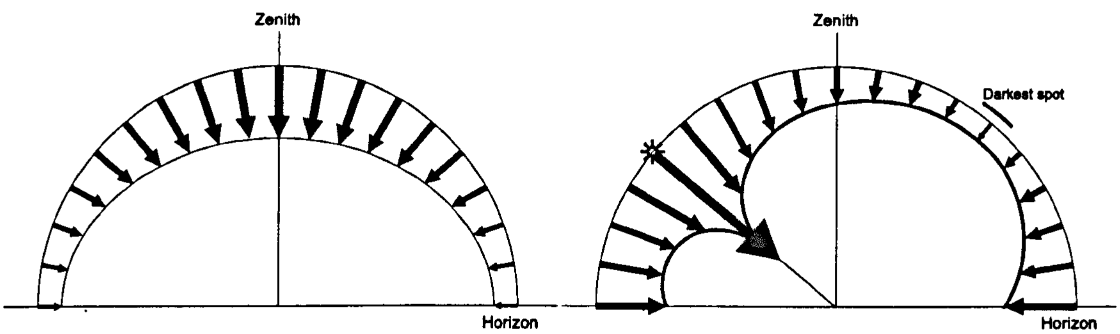


Figure 2.1: Schematic distribution of an overcast (left) and a clear sky (right).

This function expresses the fact that the zenith is three times brighter than the horizon. The distribution is independent of the solar azimuth (see fig. 2.1).

The diffuse horizontal illuminance, $E_{dh}$, can be found from the zenith luminance as

$$E_{dh} = \frac{7}{9}\pi \cdot L_{ocz} \tag{2.2}$$

This equation is the result of the integration of the illuminance of an element of the sky over the whole sky.

The computer simulations made with RADIANCE presented in this research use this CIE overcast sky distribution where the zenith luminance, in cd/m$^2$, is a function of the solar altitude expressed as ($L_{ocz} = (8.6\sin\gamma_s + 0.123) \cdot 1000/203 \cdot 179$). (Larson and Shakespeare, 1998)

This overcast sky distribution is still relatively simple and has therefore been adopted in the majority of daylight calculations.

[2]Symbols altered.

[3]Commission International de L'eclairage, Paris, France.

On the other hand, the clear sky distribution is a much more complex mathematical representation. Derived by Kittler in 1967, it is expressed as[4]

$$L_{\zeta\alpha} = L_{clz} \frac{(1 - \exp^{\frac{-0.32}{\sin\zeta}})(0.91 + 10\exp^{-3\chi} + 0.45\cos^2\chi)}{(1 - \exp^{-0.32})(0.91 + 10\exp^{-3Z_s} + 0.45\cos^2 Z_s} \tag{2.3}$$

where

$L_{\zeta\alpha}$ is the luminance of sky element [cd/m$^2$];

$L_{clz}$ is the luminance at the zenith in a clear sky [cd/m$^2$];

$\chi$ is the angular distance between a sky element and the sun [rad];

$\zeta$ is the elevation angle of a sky element above the horizon [rad];

$Z_s$ is the angular distance between the sun and zenith [rad].

This distribution was adopted as a standard by the CIE in 1973.

The luminance distribution of this sky changes during the day with the altitude and azimuth of the sun. The luminance of a sky element depends on the angle between that element and the sun, as well as the angle between that element and the zenith.

For the computer simulations made with RADIANCE presented in this research, the zenith luminance, in cd/m$^2$, is calculated as[5]

$$L_{clz} = [(1.376 \cdot T_A - 1.81) \cdot \tan\gamma_s + 0.38] \cdot K_R \tag{2.4}$$

where

$T_A$ is the atmospheric turbidity factor, taken by default as 2.75;

$\gamma_s$ is the is the solar altitude;

$K_R$ is the conversion factor of the RADIANCE system's own value of luminous efficacy, with a constant value of 179 lumens/Watt (Larson and Shakespeare, 1998).

The brightest part of a clear sky is the circumsolar area. It is followed by the band next to the horizon. The darkest spot is situated at around 90° opposite to the sun (see fig. 2.1)

The CIE overcast and clear sky models are representations of two extreme skies: densely cloudy or perfectly clear. The intermediate sky model is a combination of both.

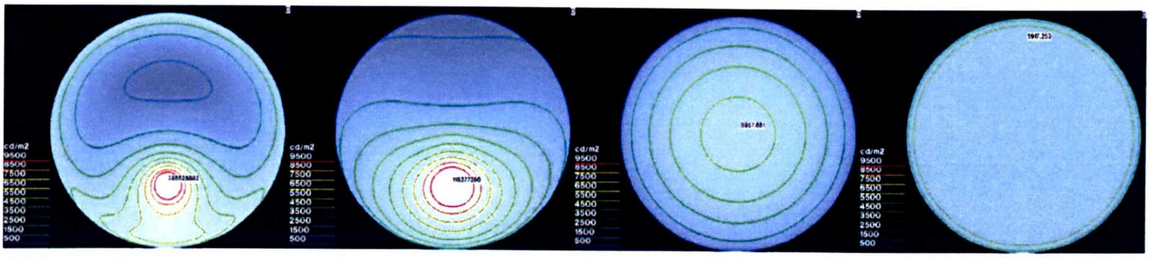


Figure 2.2: Sky luminance for clear, intermediate, overcast and uniform sky in Lisbon ($\gamma_s = 60°$) on 21$^{st}$ March at 12:00h solar time. Rendering of RADIANCE.

See fig. 2.2 for the rendering of the previously defined sky types.

However, these sky conditions rarely correspond to the real sky. The CIE has recently published a new standard general sky (S 011/E:2003), that lists 16 luminance distributions in recognition of a wide range of conditions from a heavily overcast to a cloudless sky. (CIE, 2002)

### 2.2.2 Real skies

The sun is the source of all natural light. Different weather conditions and the sun's changing position throughout the day and year will affect the sky luminance and its distribution.

The atmosphere of the earth is more or less translucent and scatters the sunlight. This scattered light is referred to as skylight. It excludes the direct beam, while sunlight is the visible part of the direct solar radiation. When light passes though the atmosphere, it is affected by gases, water vapour and particles, changing its path, spectral composition and intensity.

The selective scattering of sunlight by molecules in the atmosphere (oxygen and nitrogen) and very small particles is called Rayleigh scattering. It is wavelength dependent and is around 10 times higher for short visible wavelengths than it is for long wavelengths. This effect is what creates the blue colour of the sky. The scattering by larger particles such as pollutants is called Mies scattering. Unlike Rayleigh scattering it is not very wavelength dependent, so all wavelengths are more or less equally affected. Mies scattering is responsible for the white circumsolar area, the whiteness of clouds, mist and fog.

Real skies can be characterised either by their luminance distribution (see fig. 2.3), or by the illuminance they create at a given point (usually an unobstructed horizontal plane). Data collected over a certain period can be analysed in order to define daylight availability for a site. Statistics for daylight design may involve data on sunshine duration, frequency of occurrence of a particular sky condition or percentage of hours for which a certain illuminance value will be exceeded.

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[4]Symbols altered.

[5]RADIANCE source code.

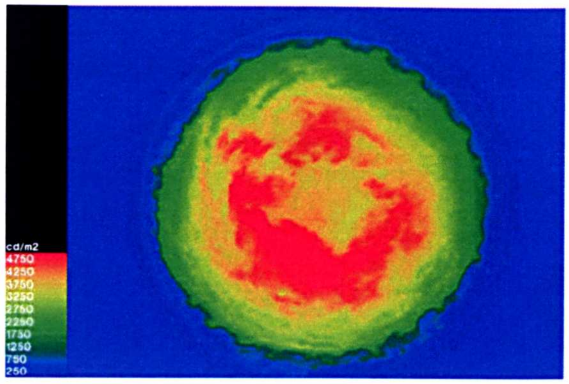


Figure 2.3: Sky luminance distribution of a real sky $29^{\text{th}}$ March in London. False colour image with RADIANCE from a HDR (high dynamic range) image based on 5 exposure-bracketed photographs. (webpage, 2004a)

Some recent research has been concerned with the definition of a daylight atlas. The CIE has launched an 'International Daylight Measurement Programme', IDMP, providing guidelines for the setting up of daylight measurement stations worldwide.

The Satel-Light project consists of the development of the 'European Database of Daylight and Solar Radiation' in which values are stored for every half hour based on Meteosat images. It provides on-line access to solar and daylight data for any location in Europe. (webpage, 2003a) Examples from this database are presented in chapter 8.

## 2.3 Solar geometry

The earth is of near-perfectly spherical shape and revolves anti-clockwise around the sun in an elliptic orbit that takes 365.26 days[6] The distance to the sun is about 150 million km. The earth is closest to the sun at the *aphelion,* on $1^{\text{st}}$ January ($147 \cdot 10^6$ km) and furthest away at the *perihelion,* on $1^{\text{st}}$ July ($152 \cdot 10^6$ km). Changes in the seasons occur due to this annual rotation around the sun. See fig. 2.4.

The earth also rotates anti-clockwise around it's own vertical axis every 24 hours, creating the periods of day and night. Solar noon occurs when a point on the surface of the earth is directly opposite to the sun, i.e. the time when the sun appears to cross the local meridian. The sun's apparent position at that time is due south for the northern hemisphere. The earth axis of rotation is tilted 23.5° from the normal to the plane of its orbit around the sun. The declination is the angle between the plane of the equator and the line from the centre of the earth to the centre of the sun (earth-sun line). It varies between +23.5° on June $22^{\text{nd}}$ and -23.5° on December $23^{\text{rd}}$.

[6] As the calendar year is 365 days, one extra day every four years compensates for the 0.25 days difference per year, as the remaining 0.01 days is adjusted by one day per century.

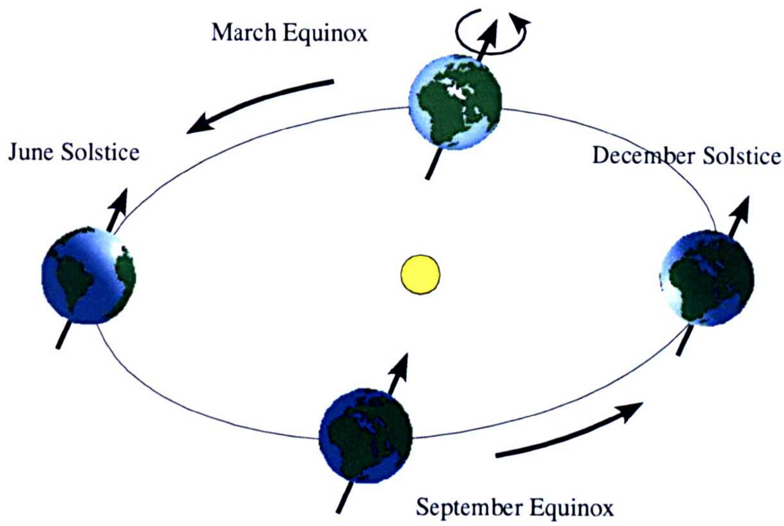


Figure 2.4: The earth's path around the sun.

The geographical latitude of a location, as the angle subtended at the centre of the earth between the plane of the equator and radius to the point on the earth surface, has a major importance on the apparent sun position in the sky at the location, as well as the daylight availability throughout the year. The position of the sun in the sky varies with the time of day and the time of year due to the combined effect of the previously described rotations and tilt.

The angle between the plane of the sun's apparent movement in the sky, see fig. 2.5, and the vertical for any location will be the same as its geographical latitude, see fig. 2.6. Therefore, the solar altitude, as the angle in the vertical plane between the sun direction and its projection on the horizontal plane, varies for different latitudes. See fig. 2.7.

The azimuth angle, as the angle in the horizontal plane measured clockwise between the north and the projection of the sun's direction, varies with the rotation of the earth around its axis.[7]

Particular sun/earth constellations occur during the rotation around the sun. They define the summer and winter solstice at 22$^{nd}$ June and 23$^{rd}$ December, respectively for the northern hemisphere and inversely for the southern, and the equinox at 21$^{st}$ March and 23$^{rd}$ September.[8]

At the summer solstice, the north pole is inclined at 23.5° towards the sun (north latitudes). At noon, the rays of the sun are normal to latitude 23.5° $N$, defined as

[7]Some authors and programs, such as RADIANCE, measure the azimuth angle clockwise (negative) and anticlockwise (positive) from south.

[8]For the purposes of this work, all the equinox and solstice days will be considered at 21$^{st}$ day of the respective month.

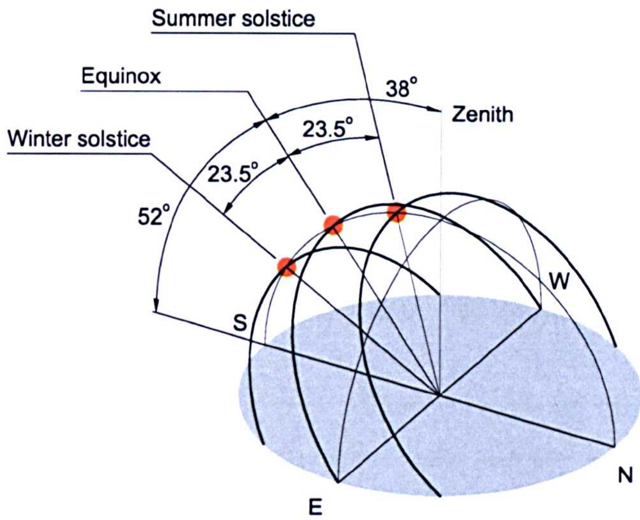


Figure 2.5: Apparent movement of the sun in the sky in the northern hemisphere for Lisbon latitude.

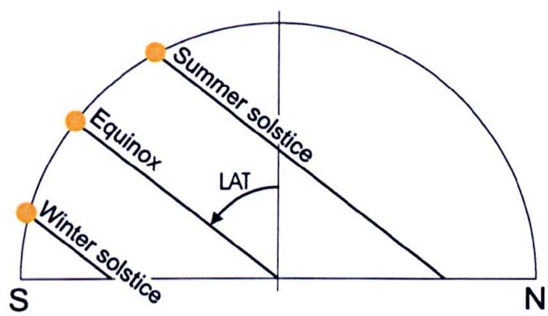


Figure 2.6: Sun Path plane for London latitude. Angle with the vertical equal to the geographical latitude of the place.

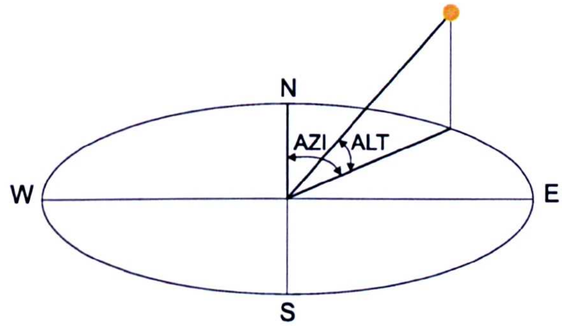


Figure 2.7: Sun's altitude and azimuth angles.

the Tropic of Cancer. Locations with latitudes above 66.5° $N$ (Arctic circle) have natural light for 24 hours while those with latitudes beyond 66.5° $S$ are in complete darkness. Inversely, at the winter solstice the north pole is inclined 23.5° away from the sun. Locations with latitudes above 66.5° $N$ have night for 24 hours while those with latitudes above 66.5° $S$ have continuous daylight. At noon the rays of the sun are normal to a latitude of 23.5° $S$, defined as the Tropic of Capricorn.

At the equinox, both poles are equidistant from the sun and all geographical locations have 12 hours of daylight and darkness. At noon, the rays of the sun are normal to latitude 0° - the equator.

Solar time is different from clock time. Two corrections are necessary to take account of the difference between the true solar time and the local mean time (clock time) and the longitude of the place to the meridian where the local mean time is taken as a reference. The first correction is necessary because of the orbital speed variation, which is faster at the perihelion but slower at the aphelion. Apparent solar time is based on the true orbital speed, whereas mean solar time, upon which local mean time is based, assumes a uniform speed. The equation of time refers to this difference and its variation is between about 13.5 min on 22$^{nd}$ February to around 16.5 min on 1$^{st}$ November.

The local mean time of a zone is taken with reference to the 0° meridian at Greenwich in the United Kingdom. As the rotation of the earth takes 24 hours, one hour corresponds to 15° of longitude. Time is subtracted for locations east of this 0° meridian and added for locations to the west. (Szokolay, 1996)

## 2.4 Contributors to daylight

The latitude of the location has a major influence on the access to sunlight. In regions close to the equator the sun reaches higher altitude angles than at locations near the poles. Furthermore, the higher the latitude, in the northern or southern hemisphere, the higher the difference in daylight hours between the winter and summer period.

The orientation of a building will have a major impact on it's access to sunlight. The sunlight availability for a specific orientation is dependent on the variation of the sun's azimuth and altitude which both vary for different times and days of the year. In the northern hemisphere, south oriented surfaces will receive direct sunlight for longer periods than any other vertical surface orientation. North oriented surfaces only receive direct sunlight in early and late hours of the day between 21$^{st}$ March and 21$^{st}$ September.

Obstructions have an effect on illumination in two ways. On one hand, they reduce the light contribution of the sky and can block out the access to sunlight. On the other hand, they can reflect the light from other parts of the sky or even promote reflected sunlight when the sun is behind the building. See fig. 2.8.

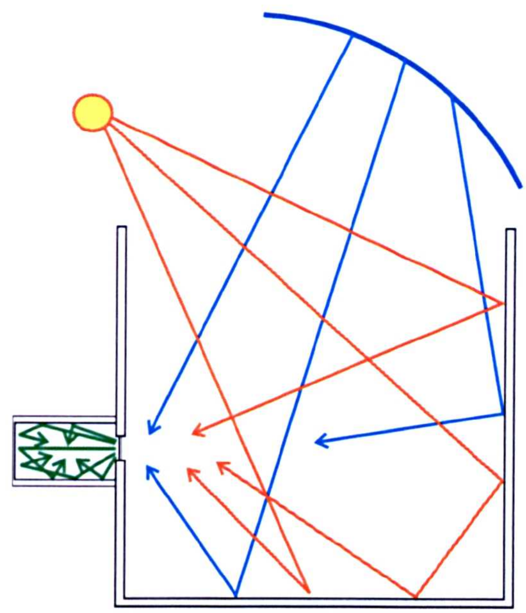

Figure 2.8: Interreflections within an urban canyon.

An obstruction can be characterised geometrically by the solid angle subtended when it is looked at from a specific point of view or by the vertical and horizontal angles of its edges and the average reflectance of the materials of which it is composed.

The reflectance of the material will affect the quantity and distribution of the reflected light. Upon reflection, the light changes of direction and a reduction of it's intensity occurs. Even the most reflective materials absorb part of the luminous flux. The less reflective a material is, the higher is it's absorption (for opaque materials). A perfect diffuser will reflect light evenly into all directions. A perfectly specular surface will reflect light in a unique direction, defined by Snell's law whereby the angle of incidence is equal to the angle of reflection, relative to the surface normal. Most real material exhibit both behaviours to a varying degrees. A combination of both characteristics will define a diffusing material with a dominant reflection direction. See fig. 2.9.

## 2.5 Designing for daylight

Daylight design can be done using graphical methods, mathematical calculations (manual or computerised) or physical scale modelling. There are several methods available for the different approaches and they vary substantially in their reliability and accuracy, as well as in the time involved to learn and use them. Some examples

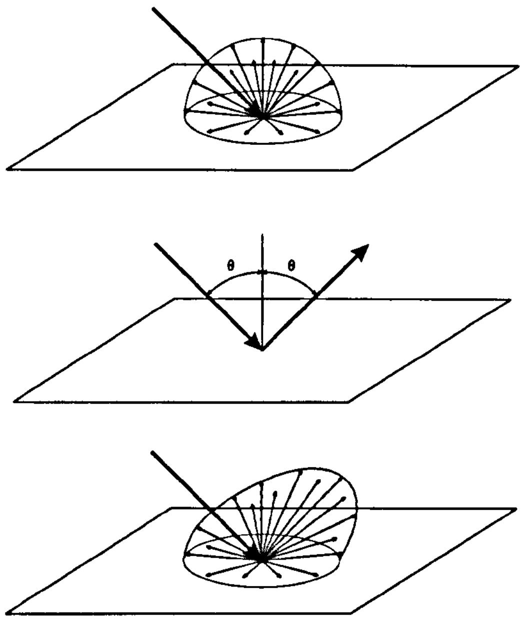

Figure 2.9: Reflection of light in a diffusing, specular and a combination of both behaviours surfaces. The latter defines a diffusing material with a dominant reflection direction.

are presented below. The selection was based on the reference to regulations and future work to be developed. A more extensive review of design tools can be found in *Daylighting in Architecture* (CEC, 1993) and on IEA *Survey Simple Design Tools* (IEA, 1998).

### 2.5.1 Daylight factors

'The daylight factor method of analysis is the most commonly used calculation procedure for predicting levels of daylight in buildings.' (Robbins, 1986) It is the recommended procedure of the CIE.

The *daylight factor, D*, at a point is the ratio of the indoor illuminance, $E_{in}$, to the outdoor unobstructed horizontal illuminance, $E_{dh}$, expressed as a percentage. Both illuminance values are calculated under the same sky conditions, usually the CIE overcast sky. By definition, the direct sunlight is excluded from the calculation.

$$D = \frac{E_{in}}{E_{dh}} \cdot 100\% \tag{2.5}$$

For the calculation of the daylight factor, it is usual to consider three components: the sky component, $D_c$, the externally reflected component, $D_e$, and the internally reflected component, $D_i$. The daylight factor is then the sum of these three components. Corrections for glazing other than clear glass, for dirt on the glass or reductions originated by the window frame and glazing bars can be applied to the total. (Tregenza and Loe, 1998)

The sky component is the light reaching a point in the interior directly from the sky. It is the ratio of the illuminance received directly from a sky of assumed or known luminance distribution to the horizontal illuminance due to an unobstructed hemisphere of this sky. It can be determined by several graphical or mathematical methods, some presented in *Daylighting* (Hopkinson et al., 1966). Of those, the BRS[9] simplified sky component table and the BRS Daylight Protectors are the ones most commonly used. (CIBSE, 1987)

The externally reflected component is the light reflected by the external obstructions illuminated directly or indirectly by a sky of assumed or known luminance distribution. It is defined by the ratio of the illumination on a reference point, received directly from the external obstructions, to the horizontal illumination due to an unobstructed hemisphere of this sky. The externally reflected component can also be described as a function of the configuration factor of the reference point with relation the obstruction, and the luminance of the obstruction to that of the sky.

> "In practice it is customary to assume an average luminance for all external obstructions expressed as a fraction either of the luminance of the sky which these obstruct, or alternatively as a fraction of the average luminance of the whole sky. In the case of a uniform sky these two concepts are identical, and it is usual to take the luminance of external obstructions as one-tenth that of the sky. In the case of the C.I.E.[10] Standard Overcast Sky, the luminance of obstructions near the horizon is taken as one-fifth that of the horizon sky which is thus obstructed or one-tenth the average luminance of the whole sky." (Hopkinson et al., 1966)

The externally reflected component, expressed as a percentage, is equal to the product of the obstructed sky component and the average reflectivity of the exterior obstructions. This 'equivalent sky component' can be calculated using the same methods as for the sky component. Typical values of the reflectivity of building materials are available in appendix 13.1 of *Daylighting design & analysis* (Robbins, 1986).

The internally reflected component refers to the light reflected by the internal surfaces. For a sky of assumed or known luminance distribution, this component is the ratio of the illumination on a reference point, received from internal reflecting surfaces, to the horizontal illumination due to an unobstructed hemisphere of the same sky. The most widely used method to calculate an average internally reflected component is based on BRS split-flux principle. (Hopkinson and Petherbridge, 1954) It is given as[11]

[9] Building Research Station, actually denominated BRE - Building Research Establishment, Garston, Watford, United Kingdom.

[10] Commission International de L'eclairage.

[11] Symbols changed.

$$D_i = \frac{\tau A_w}{A(1-\rho_{av})}(C_o \rho_{fw} + 5\rho_{cw}) \tag{2.6}$$

where

| | |
|---|---|
| $\tau$ | is the diffuse glass transmittance, assuming a value of 0.85 for single glass; |
| $A_w$ | is the net glazed area of window [m$^2$]; |
| $A$ | is the total area of internal surfaces, ceiling, floor and walls including the window [m$^2$]; |
| $\rho_{av}$ | is the area weighted average reflectance of internal surfaces, expressed as a fraction; |
| $\rho_{fw}$ | is the average reflectance of the floor and parts of the wall (excluding the window wall) below the mid-height level of the window; |
| $\rho_{cw}$ | is the average reflectance of the ceiling and parts of the wall (excluding the window wall) above the mid-height level of the window; |
| $C_o$ | is equal to the daylight factor on the outside of a vertical surface without the light incident from below the horizontal. It is a coefficient dependent on the obstruction outside the window. For a continuous obstruction, it is given approximately by $\frac{\theta}{2} - 5$ where $\theta$ is the vertical angle (in degrees) of visible sky measured at a section perpendicular to the facade at the centre of the interior plane of the window opening (Lynes, 1979). |

Corrections may be applied for glass transmission other than for single clear glass, dirt on the glass, obstructions caused by the window frame and bars and deterioration of room reflectance. It is more convenient to apply these corrections, with the exception of that due to deterioration of room reflectance, to the total daylight factor instead of to the components separately. See *Daylighting and window design* (CIBSE, 1999) for correction factors.

The coefficient $C_o$ and constant 5 assume a CIE overcast sky distribution and that the luminance of the ground and obstructions are one-tenth of that of the average luminance of the sky. Also, the obstruction is assumed infinite with a skyline horizontal and parallel to the window wall.

In theory the split flux method defines the average value of the internal reflected illumination over all the surfaces. However, it has been reported to be for architectural purposes sufficiently close to the mean internally reflected illuminance on the horizontal working plane, therefore may be adopted as such. (Lynes et al., 1966)

The total daylight factor at a point in the working plane is given by the equation (Lynes, 1968)

$$D = [a \cdot (D_c + D_e)] + (v \cdot e \cdot \frac{g}{f}) \qquad (2.7)$$

where

$(D_c + D_e)$ is the sum of the sky component and external reflected component;

$a$, $v$ and $e$ can be obtained from table A.1, A.2 and A.3, respectively, in Appendix A;

$\frac{g}{f}$ is equal to the ratio of glazing area to floor area.

The internally reflected component in eq. 2.7 is calculated for the point of analysis and this illuminance is not assumed as being equal to the average illuminance obtained for all surfaces in the space.

The sky condition is sometimes described in terms of the *design external illuminance* ($E_{eD}$), which is determined by the percentage of days in a year a required illuminance level is achieved by daylight. The illuminance and sky conditions for daylight design vary for different countries and $E_{eD}$ is usually defined by local standards. Daylight design for a required illuminance can be expressed by the *required daylight factor,* $D_R$, as a percentage as[12] (Majoros, 1988)

$$D_R = \frac{\overline{E_R}}{E_{eD}} \cdot 100\% \qquad (2.8)$$

where

$\overline{E_R}$ is the require average illuminance on the work plane [lux];

$E_{eD}$ is the design external illuminance [lux].

### 2.5.2 Average daylight factor

The *average daylight factor,* $\overline{D}$, is the ratio between the mean illuminance in a space and that from an unobstructed external sky, generally assumed to be the CIE overcast sky.

The average daylight factor obtained as an equation and not as an average of daylight measurements on several points in a plane was developed by Lynes. The expression is based on the average illuminance in an enclosure defined by Sumpner. (Lynes, 1979)

[12]Symbols altered.

The average daylight factor is averaged over all the surfaces and is not related to a specific reference plane. It is given by the expression, expressed as a percentage as[13]

$$\overline{D} = \frac{\tau A_w \theta}{2A\,(1 - \rho_{av})} \tag{2.9}$$

where

| | |
|---|---|
| $\tau$ | is the diffuse light transmittance of the glazing, including the effects of dirt, expressed as a decimal. Maintenance factors are presented in *Daylighting and window design* (CIBSE, 1999); |
| $A_w$ | is the net glazed area (not including frames, glazing bars or other obstructions) [m$^2$]; |
| $\theta$ | is the vertical angle of visible sky measured at a section perpendicular to the facade at the centre of the interior plane of the window opening, see fig. 2.10 [deg]; |
| $A$ | is the total area of the interior surfaces, ceiling, floor and walls including windows [m$^2$]; |
| $\rho_{av}$ | is the area-weighted average reflectance of the interior surfaces. |

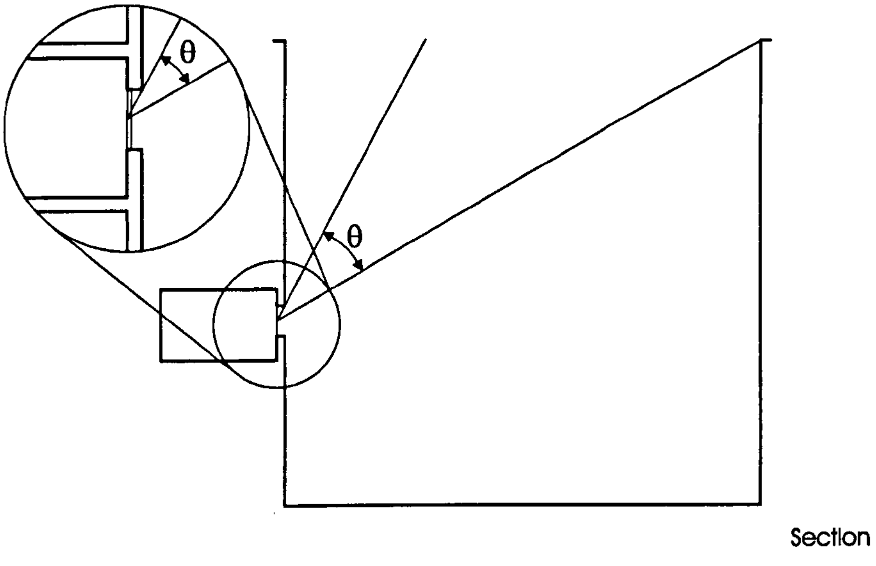


Figure 2.10: Vertical angle of visible sky.

In theory the average daylight factor on the working plane should be higher than the value obtained by the eq. 2.9.

[13]Symbols altered.

Later work developed by Crisp and Littlefair derived the average daylight factor on the working plane, (assumed at 0.85m), expressed as a percentage as[14] (Littlefair, 1988)

$$\overline{D} = \frac{M\tau A_w\theta}{A\left(1-\rho_{av}^2\right)} \tag{2.10}$$

where

$M$ is a correction factor for dirt and glazing bars.

All the other symbols defined for eq. 2.9 apply.

The average daylight factor has an advantage over other prediction methods because it does not require the window shape and position to be defined. As it is proportional to the window size, it can be a useful method for estimating windows sizes in the early phases of design. Rearranging eqs. 2.9 and 2.10, one can determine the window size to be used for a defined average daylight factor as:

using Lynes's formula

$$A_w = \frac{2A\left(1-\rho_{av}\right)\overline{D}}{\tau\theta} \tag{2.11}$$

using BRE's formula

$$A_w = \frac{A\left(1-\rho_{av}^2\right)\overline{D}}{M\tau\theta} \tag{2.12}$$

Additional information on the calculation of average daylight factor for roof-lights can also be found in BRE information paper IP 15/88 (Littlefair, 1988).

For complex obstructions an equivalent vertical angle of visible sky can be calculated from the vertical sky component (see appendix C of *Site Layout planning for daylight and sunlight* (Littlefair, 1998)).

### 2.5.3 Vertical sky component

The amount of skylight falling on a vertical surface can be quantified as the *vertical sky component.* It is the ratio of the illuminance received on the outside of a vertical window or surface directly from an overcast sky, of assumed or known luminance distribution, to the horizontal illuminance due to an unobstructed hemisphere of this sky.

When the height of different opposite obstructions is roughly the same, a value of an average height is a reasonable estimate, otherwise a plot of the surroundings should be used. The vertical sky component, in percentage terms, outside of a

[14]Symbols altered.

window wall should be calculated using a skylight indicator or a Waldram diagram, see fig. 2.11.

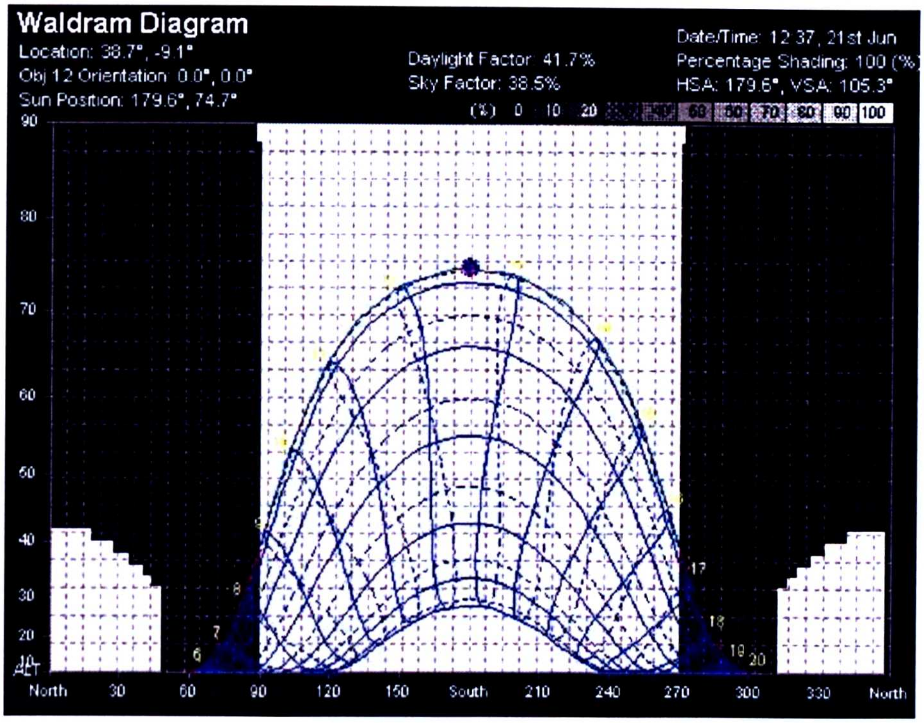


Figure 2.11: Waldram diagram of an urban canyon with an obstruction height equal to the distance to the building.

Appendix A and B of *Site Layout planning for daylight and sunlight* (Littlefair, 1998) explains how to use these methods.

The *sky factor* is defined as the ratio of the illuminance at a point on a given plane which would be received through an unglazed opening from a sky of uniform luminance to the horizontal illuminance due to an unobstructed hemisphere of this sky. It is usually expressed as a percentage. Although this isotropic sky distribution is unrealistic, this sky factor calculation is still used in 'Rights of Light' arguments due to its simplicity. See section 2.8.3.

### 2.5.4 Sunlight hours

Daylight analysis is often related to an annual period, which refers to the illuminance values and the expected length of time, namely the quantity during a given period of the year, for which a given value can be expected. Meteorological data on diffuse and direct light is available for some locations, but reference data years (ex. daylight availability curve) are usually achieved by statistical analysis of several years, with a probability of 50%.

"By calculating the astronomical daylength $S$, using the appropriate mid-month values of the declination and latitude of the site, one can express the *average monthly* *sunshine* as a percentage ratio to the maximum possible mid-month sunshine. This ratio is called the percent relative sunshine duration, $S\%$. The percent relative sunshine duration enables the designer to perceive the relative sunniness of any specific month at any place" (Page and Lebens, 1986)

"*Probable hours of sunlight* is the long-term average of the total number of hours during the year in which direct sunlight reaches the unobstructed ground. A period of probable sunlight hours is the mean total time of sunlight when cloud is taken into account". (BSI, 1992)

A calculation procedure is given in the BS 8206 : Part 2 : 1992. (BSI, 1992) It uses a probability diagram, a distribution of sunlight, based on statistics for London, considering the solar altitude and azimuth. There are 100 dots on the diagram, each representing 1% of probable sunlight hours, and the density of dots is proportional to the probability of the sun shining from a particular area of the sky. A line defines two zones: the summer and the winter months. By superimposing this diagram of dots unto a stereographic sunpath diagram with the shadow periods caused by the building itself and with its surroundings marked on it, it is only necessary to count the dots on the winter and year periods to obtain the percentage of hours of probable sunlight.

A similar calculation procedure is given in *Site Layout planning for daylight and sunlight* (Littlefair, 1998) using a sunlight availability indicator.

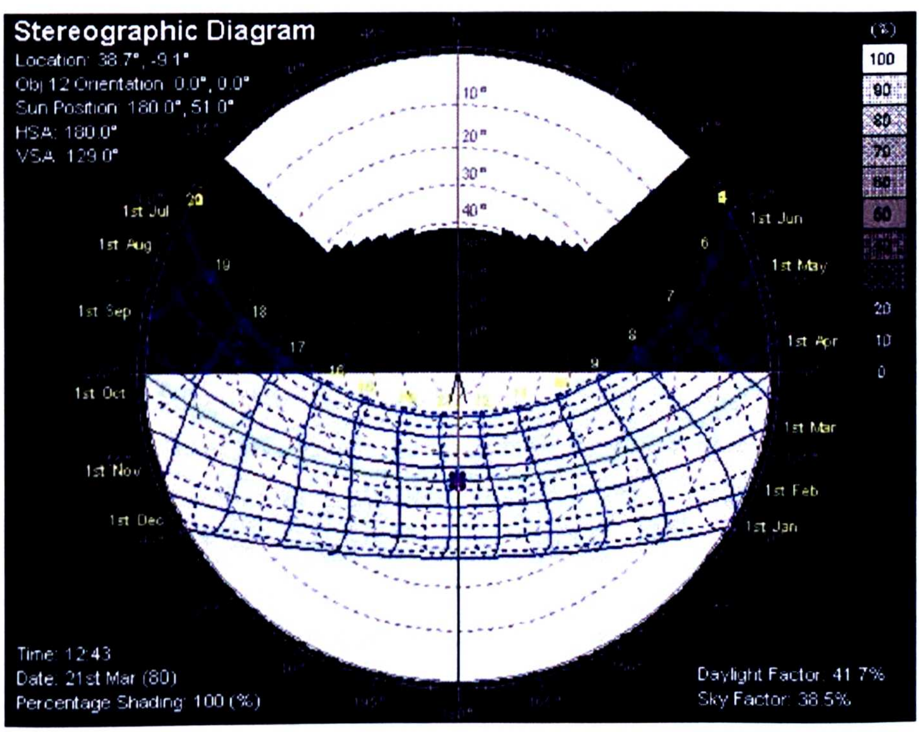


Figure 2.12: Stereographic sunpath diagram with shadow mask caused by an obstruction angle of 45°.

### 2.5.5 RADIANCE software

The RADIANCE lighting simulation software is considered to be the most powerful and accurate simulation software for lighting simulation. It uses a hybrid deterministic and stochastic ray tracing technique to provide an accurate calculation (correct numerical results) and a highly sophisticated lighting visualisation system similar to photographs. Also it provides a high flexibility to enable the simulation of complex situations.

The system uses backward ray-tracing from the point of view to the light source.

## 2.6 Literature review - daylight in atriums and urban canyons

Although cities have predominantly street geometries, there are few studies on daylight in urban canyons. Geometrical similarities with linear open atria buildings provide some background research in this area.

There are several studies of daylight in atria buildings. (Matusiak, 1998; Tregenza, 1997; Mabb, 2001) This type of construction is quite popular in cold climates, as the atrium is likely to have a more pleasant temperature than the outside. However, daylight calculations for atria buildings are usually based on overcast skies, the sky condition predominant in northern Europe latitudes.

Wright et al. (Wright and Letherman, 1998) reviewed the state of the art of daylight calculations in atrium spaces. The poor availability of suitable daylight design methods, predominantly based on rooflight daylight factors or from previous research mainly in atrium scale models, is mentioned. Inconsistencies of results among the various studies, partially attributable to predictions of the components of the daylight factor, limited availability of studies, particularly on building variables, as well as other sky distributions, were suggested as the causes for poor daylighting performance of existing atrium buildings.

Methods and data analysed are mainly based on overcast or uniform skies. The justification for the predominant use of overcast sky models is attributed to daylight designers assuming CIE standard overcast distributions as the worse case scenario. It is argued that in an atrium that might not be the case, particularly when the visible part of a sky may be of lower luminance in a clear sky distribution than on an overcast sky. Under a clear sky, the patch with the lower luminance is located at around 90° opposite to the sun. A building facing this part of the sky may receive less light than it would from a standard overcast distribution where the peak sky luminance is at the zenith.

Mabb (Mabb, 2001) also reviewed daylighting in atrium buildings. Besides a reference to typical methods for daylight analyses, he gave an overview of the factors affecting light levels in rooms adjacent to atria, including the geometry of the room and the atrium space, the reflectivity of materials, glazing properties and sky distribution.

Daylight penetration in the atrium is predicted with the light levels in the wells, floor and adjoining spaces. The most commonly used sky distribution is the overcast sky and results are mainly given in terms of daylight factors, sky component, internally reflected component or dimensional aspect ratios.

Several empirical calculations for atrium illuminance based on real and model measurements, are discussed. (Mabb, 2001) The equations tend to relate to the well index and frequently show an exponential decay law.[15] This index is basically a measure of the well height relative to the width and length of the floor plan. A cubic well has an index equal to 1.0 and two cubic volumes stacked vertically have an index of 2.0.

The atrium geometry is assumed to be an important factor in the penetration of daylight. The opening area and depth of the atrium directly affects the sky component, thereby influencing the amount of light reaching the ground floor. Similarly, in an urban canyon, the aspect ratio, as the ratio of the height of the obstruction to the width of the canyon, will determine the amount of light from the sky that reaches the building.

Another parameter that affects daylight penetration is the reflectance of the surfaces of the atrium. Windows have a reduced diffuse reflectance, so it is suggested that there be a reduction of window area on the top floors of the atrium. The proportion of glazing may vary within the well with small windows at the top and larger at the bottom where light levels are smaller. Splaying the wall may improve daylight at the lower floors of the atrium.

Daylight in the adjoining spaces of atria have been analysed by several authors using two approaches: the first one involves the quantitative method of measuring the light level at various positions in the space by using scale models; the second relates the vertical daylight factor on the vertical window to the average daylight factor inside the space by using analytical equations. (Mabb, 2001)

Matusiak (Matusiak, 1998) investigated daylight in a linear atrium and defined a simplified tool, based on the solid angle method, to be used for daylight calculations in the early stages of design. The calculation applies to unglazed linear atriums, which are similar to urban canyons. Daylight factors are presented for the middle of the atrium floor and the middle of the vertical facade. In a similar way to the majority of the methods reviewed by Wright (Wright and Letherman, 1998) and

[15]Well index is $[(L_a+W)H]/(2L_aW)=HP_e/4A$
where W is atrium width, $L_a$ is length and H is atrium height.
$P_e$ is the perimeter of the floor plan and A its area.

Mabb (Mabb, 2001), the tool was developed for uniform and CIE overcast skies, limiting it's use to cloudy skies.

Further work by Matusiak (Matusiak, 1998) included an extensive analysis of different daylight systems on atria from light reflectors on the atrium facade and in the atrium space, light reflectors with different shapes and materials positioned on the top of the building enclosing the atrium, to building glass roofs with different tilts and shapes, laser cut and prismatic panels. Passive solutions including modifying the area of the glazing and the type of glass were also considered in the study.

Matusiak analysed sunlight availability and penetration using different daylight strategies, namely different glass roof configurations, 3M prismatic panels, laser cut light panels and reflectors panels, with a model placed under a sun simulator. Results were presented for Oslo, latitude $59.93°N$ and longitude $10.75°E$ for summer, Spring/Autumn and Winter days for seven sun positions. They emphasised the importance of tilting the roof glazing to prevent reflection losses during the winter when the sun is low. Horizontal roofs were therefore not recommended. The best performance was obtained from single pitched negatively tilted roofs (35° slope facing south) with recorded sunlight illuminance increase during the winter and a reduction in summer. Both the prismatic and laser cut panels were effective in increasing the daylight level and redirecting sunlight down to the atrium floor or lower part of the north facade. Nevertheless, daylight levels were higher with laser cut panels. When tilted positively by 30°, they performed better than the 18° slope, increasing daylight in the atrium. Both, prismatic panels sloped 10° and 18° and laser cut panels sloped 18°, were effective as sun shading to the vertical surfaces and prevented solar glare.

A reflector on the roof above the facade (tilted accordingly to season to redirect the sunlight to lower floors) showed an increase of sunlight on the opposite facade on lower floors to where it was redirected but also to the floor and lower parts of the south facade. At the equinox it is reported that a 50% increase of sunlight occurred on lower parts of both facades and ground of the atria. However, the illuminance on the remaining top surfaces remained unchanged. Conversely, a reflector positioned on top of south facade (fixed) showed an increase of around 5 times the illuminance on the opposite top floors, but the light level on the other parts of the atrium remained unchanged.

Overall, the reflector placed on the top of the building performed better than the one fixed to the facade. Furthermore, it redirected sunlight that would otherwise fall on the roof of surrounding buildings, increasing the flux coming into the atrium. However, an increase of the building maintenance costs may occur due to the need to adjust the panels seasonally. A particular tilt may allow a better performance of the system and prevent glare. Given its poor performance and it's likelihood to provoke glare, Matusiak suggested that a reflector on the facade should be avoided.

Further simulations with RADIANCE extended the parameter studies (sloping angles and reflectors dimensions) from previous physical models.

Matusiak concluded that both, passive and active strategies, may increase daylight at the bottom of the atrium. The reflectance of the surfaces has a considerable influence on the daylight distribution in the atrium under overcast skies. An increase of the atrium floor reflectance influences the lower floor, whereas an increase of the facade reflectance mainly affects the upper floors.

Active daylight systems allow the redirection of diffuse daylight from excessively lit zones to ones where it is most needed.

Under clear skies, the tilt of the glass roof and reflector systems may affect the illuminance of the space as glass transmittance varies with the angle of incidence and both are dependent on the sun's position. Reflectors positioned on top of surrounding buildings increase the illuminance on the space as they redirect sunlight which would otherwise fall on the roof of the surrounding buildings into the atrium. (Matusiak, 1998)

Although it is the opening area of the atrium that determines the amount of daylight entering the well, it is the reflectance properties of the surfaces that influence the distribution of light to other surfaces. Sharples et al. (Sharples and Mahambrey, 1999) analysed the variation of wall reflectance in an atrium. Although the average reflectance of all surfaces were considered equal, different reflectance bands of various heights, distributed over the walls, were compared on a model in an overcast artificial sky. The usual area weighted average reflectance used in several daylight calculations will not identify how different reflectance distributions will affect the final illuminance. Results suggested that wide bands of different reflectance significant affected the daylight factor on the base of the atrium. However, as the number of stripes increased, the impact of the distribution was reduced. Narrow stripes did not significantly alter the daylight levels. A good agreement in results was obtained by comparison with an analytical estimation of the atrium reflected component. The analysis of specular surfaces presented a consistent increase in the daylight factor but did not alter the conclusions drawn for diffusing surfaces. (Sharples and Mahambrey, 1999)

Tregenza (Tregenza, 1997) derived an analytical calculation for the average illuminance on the floor and walls of an atrium based on the flux that enters the top of the well and the attenuation resulting from the fraction of light that is incident in the wall, which is partly absorbed and partly reflected upwards by the walls. The attenuation follows an exponential decay law and a comparison was made between the fraction incident and the form factor between the two surfaces. Depending on the nature of the light source on top of the well (assumed diffuse) and its dimensions, the fraction of light can be expressed in terms of a constant and the well index.

An initial calculation considered the flux reaching a band in the wall as well as the fraction of this incident light that is reflected downwards. It's integration defines the total flux falling on the walls. For a perfectly diffusing surface, the light reflected downwards was assumed to be half of the reflected component. The other half was assumed to be reflected upwards. If perfectly specular reflections are considered, the part of the flux that is not absorbed is totally reflected downwards. Building facades having both reflective characteristics can be defined as a combination of diffuse and specular reflectance.

The following interreflections in the well were determined assuming two sections with different 'cavity reflectance', defined as the proportion of flux emerging from a cavity to the flux entering it.

Part of the flux passing from the upper to the lower cavity is reflected up by the lower cavity and again downwards by the upper cavity, and so on until all flux is absorbed by surfaces. The interreflection component is then the flux originally reflected upward and then downwards and the flux that has been reflected upwards from the floor and lower cavity following the subsequent reflections in an infinite series. See Appendix B for the formulae.

A good agreement was achieved in the comparison with empirical equations based on real and model measurements obtained by other authors. (Tregenza, 1997)

In a previous paper (Tregenza, 1989), Tregenza presented a modification of the split-flux formula for the average daylight factor to take into account deep window reveals and external obstructions other than those horizontal and parallel to the plane of the window wall. The interreflections between the external surfaces and ground were also taken into account. It was assumed that the mean illuminance from the sky at the obstructions is the same as the illuminance at the window. Then, the luminance of the obstruction is the illuminance at the window times the obstruction reflection divided by $\Pi$. See appendix C for formulae.

The B.R.S. split-flux method assumes the luminance of the obstruction and ground to be one tenth that of the average luminance of the CIE overcast sky. (Hopkinson et al., 1966)

Ng (Ng, 2001) presented a simplified daylight tool, based on the modified split flux method by Tregenza (Tregenza, 1989), for residential buildings in high density areas in Hong Kong. A set of tables defined vertical and horizontal obstruction angles for window glazing areas as a percentage of the floor area. They are defined based on the U.K. recommended 1, 1.5 and 2% average daylight factors for residential areas (BSI, 1992). Results from the modified split flux method correlates better with measurements made in a model under an artificial overcast sky than results from the average daylight factor formulae. With the exception of vertical sky angles, $\theta$, being below 20°, the modified method presented relative errors to the measured results below 10%. (Ng, 2001)

Traditional methods of specifying daylight on the horizontal working plane may give a misleading impression of the light conditions in a room, particularly when they largely depend on light reaching vertical planes. Lynes et al. (Lynes et al., 1966) proposed a method based on scalar illuminance and vector illuminance to overcome the association with the two dimensional approach. They defined scalar illuminance at a point as "the average illumination on the surface of an infinitesimally small sphere at that point, due to light reaching the point from all directions." The nature of light, as well as the perception occupants obtain from it's distribution in a space, are closely associated with a three dimensional overview.

Scalar illumination is a valid index of the quantity, but it does not define the directional nature of incident light. For that purpose, the vector illuminance was the approach selected. The directional quality of the light reaching an infinitesimally small sphere can be examined in terms of the difference between the illuminance on two ends of a diameter. The vector illuminance at a point can be defined as the maximum difference of illuminance on these two extremes. The ratio of the vector to scalar illuminance and the direction of the vector was suggested as the index for modelling light in a space. (Lynes et al., 1966)

In the United States where clear sky conditions can be predominant, research has attempted to consider a similar calculation to the daylight factor under clear skies conditions. The fundamental set-back to its use is that the illuminance indoors depends on the sun position, whereas under an overcast sky it does not. The calculation proposed was far from being simple to use as a reference. Extensive weather data is provided in appendix 3 of *Daylighting* to predict the absolute value of the clear sky daylight factor, based on the illuminance on a horizontal plane. (Robbins, 1986)

IES[16], in its recommended practice for daylight, suggests a calculation that can consider a clear sky distribution with or without the solar source. Based on the Lumen method developed for artificial light, it quantifies the illuminance that may be expected for a particular room geometry at a particular time of day. (IES Daylighting Committee, 1979) Although it can be used for a determined sky condition, namely maximum, minimum or one considered most common during a certain period, it does not provide a method which is representative for the whole year.

Daylight design in an urban canyon under sunny climates is a relatively recent area of research. Although reflected sunlight from obstructions and ground have been recognised as a potential contribution to daylight, it has been systematically ignored in the majority of daylight calculations. Because of the low brightness of the clear skies except for around the sun, sunlight reflected from ground and obstructions

[16]Illuminating Engineering Society (of North America, New York).

is often more important than the light received from the sky. (Lam, 1986)

Reflected sunlight from the ground and opposite facades was considered by Hopkinson et al. as a main source of light in a building, particularly in the tropical areas where sunshine and clear skies are predominant for a great part of the year. (Hopkinson and Petherbridge, 1953)

Apart from the sun, clear skies in dry tropical and subtropical climates are generally of lower brightness than in northern Europe. (Hopkinson and Kay, 1969) Sunlight is therefore the main source of illumination rather than skylight, considered insufficient for provision of required light levels. Clear skies of very low brightness may be a result of a pure (reduced levels of aerosols, cloud droplets and ice crystals) and a dry atmosphere with fewer molecules to scatter light. A combined effect of a reduced Mie scattering and a predominantly Rayleigh scattering at low wavelength results in dark blue, less bright skies.

Model studies of a room in an urban canyon, by Hopkinson et al. (Hopkinson and Petherbridge, 1953), confirmed that levels of illumination as a result of reflected sunlight are considerably higher than the levels received from a low brightness clear sky. The experiment involved a building facing an obstruction subtended by a 20° angle at the observation point. This point was located at the centre line of the room, two thirds away from the window wall, in the plane of the window sill ($\approx$0.76 m). The reflectance of the ground was 0.2 and of the facade 0.5. Measurements made for 5 days at the Tropic of Cancer showed that for a considerable part of the daylight hours the illumination at the reference point was due to reflected sunlight, of the order of 10 to 20 times the illumination due to direct and reflected skylight from a deep blue sky.

The high sun altitude at mid-summer produces a low luminance on the opposite facade and high luminance on the ground. Room illumination is mainly due to the reflections from the ceiling due to reflected sunlight from the ground. At mid-winter the low solar altitude produces high luminance on the opposite facade and lower luminance on the ground. The room illuminance is therefore almost entirely due to direct reflection of the sun from opposite facade.

Relative contributions from reflected sunlight from obstructions and ground depend on the latitude, time of the day and year. In tropical climates the ground was shown to make a higher contribution all the time.

Variations of reflectance factors of the exterior facades and of the interior of the building proved to have a marked effect on the illumination levels. (Hopkinson and Petherbridge, 1953)

Cabús (Ricardo Carvalho Cabús, 2002) analysed the influence of ground reflected light in tropical daylighting. Three types of shading device (overhang, light shelf and horizontal louvre) were studied in regards to the influence of the ground in the illumination of a space. The overhang was considered to increase the ground reflected component in comparison to a plain window. The same trend of results was confirmed for clear, partially cloud and overcast skies. Both, the light shelf and the horizontal louvre, produced a slight reduction in the reflected component. However, they can contribute to minimise glare and reduce insolation, so should be preferred over the plain window.

The extension of the area of ground contributing to the illuminance in an unobstructed room was analysed with 9 horizontal bands parallel to the facade. Cabús concludes that light reflected from the ground is a significant part of the total daylight on the working plane. For the room studied, this ranges from 10 to 40%, depending on the time of year. Reflected sunlight is a significant source of illuminance but reflected skylight should not be neglected. Its contribution is almost the same as the reflected sunlight for a partially cloud sky. Fig. 2.13 shows the peak region where reflected light from ground is highest. This area is defined by the angle $OSA = 45°$at the window sill and $OHB = 70°$ at the window head.

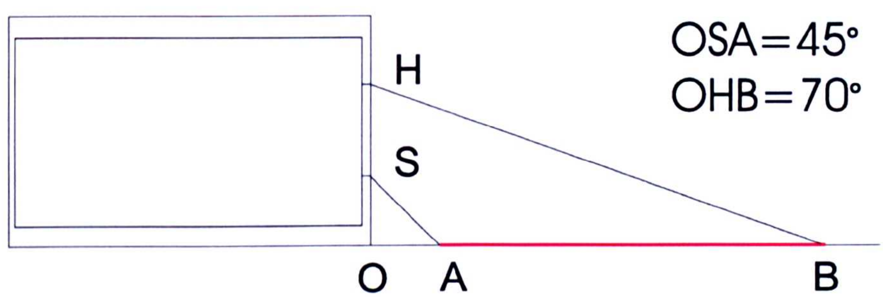


Figure 2.13: Ground plane area that contributed to the illuminance of the space.

Similar results were derived by Robbins (Robbins, 1986). He considered that the ground plane area, at a distance from the building equivalent to the height of the aperture, did not reflect significant light into the opening. However, the area beyond that edge, up to 4 times the height of the window top sill, contributed significantly to the light reaching the ceiling of the space. At greater distances the usefulness of light reflected from the ground plane in enhancing the illuminance of the space was not significant.

Tregenza (Tregenza, 1995) developed a method for estimating mean daylight illuminance in rooms facing sunlit streets that takes into consideration the direct light from the sun and sky, the reflected light from the ground, as well as the interreflections between the facade and the obstruction. Initial illuminance is calculated at the surface of the window. It results from the direct light from the sun if not blocked by the obstruction or positioned behind the building, direct from the visible angle of the sky, reflected light from the ground and the interreflections between the obstruction, ground and the building. A more accurate estimate of the illuminance at ground is achieved by calculating the fraction of the surface that is sunlit. The illuminance from interreflections between the surfaces are the reflected illuminance at the facade due to the illuminance reaching the obstruction directly from sun and sky and reflected from ground, the reciprocal relationship between the illuminance on the facade being reflected to the obstruction and the successive interreflections. It is based on the configuration factor method.

The interior illuminance on the working plane or any other surface is calculated according to the proportion of the light incident on the outside of the window that is distributed to different surfaces, depending on the origin of the light and the redirection given by shading devices. The subsequent internal interreflections are found by assuming the room as an integrating sphere, with the first flux reflected from interior surfaces weighed accordingly to the surfaces and their reflection. The final average illuminance on the working plane, walls or ceiling is the sum of the last two illuminance. See appendix D for formulae.

Tsangrassoulis et al. (Tsangrassoulis et al., 1998) compared the results obtained from the previous method (Tregenza, 1995) with the computer software SUPERLITE for various height/width street ratios and different building surface reflectance. Although hourly results varied, mainly due to the different sky distribution assumed in both methods, the annual average was considered acceptable, with a mean percentage difference of 13%. This year average may be used in simplified daylight methods to be applied in early phases of design. Tregenza's method uses a uniform sky distribution, whereas SUPERLITE uses the CIE clear sky. On an hourly basis, the difference between these two sky luminance is considerable, resulting in significant differences between the illuminance values from both methods.

Tsangrassoulis et al. (Tsangrassoulis et al., 1999b) suggested an Obstruction Illuminance Multiplier, OIM, as a simplified tool to investigate the potential of south oriented vertical surfaces for reflecting daylight onto the opposing buildings. They defined OIM as the "ratio of the illuminance received on a vertical surface due to light received from the sky, ground and the obstruction to the illuminance on the same surface without the presence of the obstruction". The theoretical model used for the illuminance calculations is Tregenza's method, previously mentioned. (Tregenza, 1995) Results were presented for the latitude of Athens, for different obstruction reflectances and heights. For lower surface reflectances the obstruction is considered beneficial in illuminating the facade during the winter months, as values of OIM tend to be greater than 1. Higher obstructions will increase the OIM ratio, therefore increasing the illuminance on the facade. They also reduce the period of inefficiency of the obstruction to two months during the summer. Higher reflectance will emphasise the contribution of the reflected light on the obstruction to the illuminance of the opposite building. For a canyon with reflectance higher than 0.6 and obstruction three times higher than distance to the building the OIM is always greater than 1.

Results presented by Alshaibani (Alshaibani, 2002) using the same method (Tregenza, 1995) for different sun altitudes and azimuths (within an angle of incidence on the obstruction) and sloping obstructions confirmed that reflected sunlight can increase the illuminance of a window facing a south-oriented obstruction.

Tsangrassoulis et al. (Tsangrassoulis et al., 1999a), following the principle of cavity reflectance, presented a method for estimation of mean illuminance on the surfaces of an urban canyon with balconies under sunny skies.

The canyon was divided by structural elements, where the balconies were considered boundary surfaces. Between the structural elements there is an opening, an imaginary plane at which the cavity reflectance is calculated. Given the initial illuminance on each surface calculated accordingly to Tregenza's method (Tregenza, 1995), a set of equations was established. They are based on the flux transfer between the defined surface boundaries of each structural element.

Another simplified approach presented considered the flux leaving one element to the adjacent element as the average internally reflected illuminance of the former multiplied by the area of the opening. The first reflected flux is estimated as the total flux entering, split over a number of surfaces each multiplied by its reflectance. The form factor method is applied in order to determine the flux received by a number of surfaces from the opening surface. The deriving of the internally reflected component is based on the integrating sphere theory. (Tsangrassoulis et al., 1999a)

Alshaibani (Alshaibani, 1997) proposes an average daylight factor for sunny climates based on two main assumptions. The first is that the illuminance on the external point of the window is approximately equal to the diffuse horizontal illuminance. The vertical illuminance is the sum of the direct and reflected light from the sky and the reflected sunlight from surrounding surfaces. Analysis of the ratio of the total vertical illuminance to the diffuse horizontal illuminance, for two different sky turbidities and various sun altitude and azimuth angles, confirmed the initial assumption. The diffuse horizontal illuminance was suggested as a worst case condition, reducing the complexity of the calculation. A new approach, described as an average daylight factor that supposedly includes reflected sunlight, was suggested.

The average internal illuminance on the working plane is a proportion of the external vertical illuminance. The calculation assumes the initial illuminance, based on the light flux that enters the vertical opening being evenly distributed over all surfaces, and the following interreflections based on the integrating sphere method. An important assumption is that the average illuminance over all the surfaces is equal to the mean illuminance on the working plane. The average daylight factor is then assumed as the average internal illuminance over the diffuse horizontal illuminance, which is by the first assumption the same as the external vertical illuminance.

Results for the proposed equation were compared with those obtained with the SUPERLITE lighting simulation program. A good agreement was obtained for 56 case studies, with varying solar altitude, azimuth, room dimensions, window position and surface reflectance.

The relationship between the vertical and horizontal illuminance, which is the basis of the first assumption was also investigated, both, with and without obstructions. The results showed that the vertical illuminance on the window pane was consistently higher than the unobstructed horizontal illuminance. This indicated the possibility of using the horizontal illuminance as the vertical illuminance to represent a minimum possible condition. Although a considerable variation might occur between the illuminance on the vertical window and the horizontal illuminance, this assumption was presented as an easily predictable situation to be set for clear sky conditions.

**Discussion**

The majority of daylight methods presented are based on CIE standard overcast skies. Whereas this sky distribution may be appropriate for daylight analyses in locations where cloudy skies are predominant, it may not be the case where clear skies are more frequent, particularly as the sunlight contribution is excluded. It will be shown that reflected sunlight can contribute significantly to the illuminance on the buildings. In an urban canyon in Lisbon, these contributions add up to 60% of the total illuminance reaching the window. If reflected light is excluded, the light levels in a space may be underestimated, leading to over-sized windows with all their consequent problems, such as heat losses and heat gains.

On the other hand, it will be argued that when there is little reflected light (due to low reflectance or distant obstructions) when the sun is behind the building the luminance of the visible sky on a clear day may be lower than the luminance of an overcast sky. Therefore, the window sized for cloudy conditions may not be sufficient for providing acceptable light levels under clear sky conditions.

The daylight factor approach is the most frequently used method of daylight analysis. One reason for the wide acceptance of the daylight factor approach is that the components of the calculation can be obtained with graphical methods, which is preferred over analytical calculations by architects. Even then, Wright (Wright and Letherman, 1998) pointed out several inconsistencies in the results of daylight analyses in atria, partially attributed to the calculation. This emphasises the importance of simplified calculations, even with a limited accuracy but with a reduced margin for error due to incorrect user input.

Calculations tend to rely on the use of the daylight factor approach, independent of the prevailing weather conditions for the location. The daylight factor is a widely accepted and appropriate calculation for cloudy climates. By definition excluding the sunlight contribution makes this method unappropriated for sunny climates.

Reflected sunlight has long been acknowledged as a significant contribution to the illuminance of buildings, particularly under low luminance clear skies. However, the reflected sunlight contribution has systematically been ignored in daylight calculations. Recent projects have aimed at overcoming this, but they mainly provide results in terms of illuminance levels or areas of the geometry likely to affect the illuminance of buildings.

Some of the methods presented above considered the sunlight contribution, in particular light reflected from obstructions and ground, but are either not representative of a full year or, due to the calculation complexity, may be difficult to use. Tregenza's method (Tregenza, 1995) has given means to the understanding of the reflected component to the illuminance of the building and has been adopted by other authors. (Tsangrassoulis et al., 1999b; Alshaibani, 2002; Tsangrassoulis et al., 1999a) However, in practice this calculation still requires a computer to deal with owing to its extent and complexity.

A simplified tool OIM by Tsangrassoulis (Tsangrassoulis et al., 1999b) allows the evaluation of the potential of reflected sunlight in buildings based on a monthly average, but still does not provide a representativity for an year condition. However, it provides means for maximising the illuminance on the vertical surface during specific months.

Alshaibani's method (Alshaibani, 1997) also provides a simple calculation for the average internal illuminance considering the reflected light from obstructions and ground. It predicts the average illuminance as a proportion of the vertical illuminance on the external surface of the window. However, an average daylight factor based on his first assumption (vertical illuminance outside the window equals horizontal diffuse illuminance) not only underestimates the illuminance on the vertical facade, but derives an average daylight factor for clear skies that is independent of the existence of an obstruction, its reflective properties and exclusively depends on the window area, glass transmittance and the reflectance of internal surfaces.

The reflectance of the surrounding surfaces is recognised by several authors as significantly affecting the illuminance of the buildings. (Matusiak, 1998; Sharples and Mahambrey, 1999) However, the research was mainly undertaken under overcast sky conditions. Tsangrassoulis (Tsangrassoulis et al., 1999a) presented two theoretical methods analysing the importance of balconies to the reduction of the illuminance on lower floors of an urban canyon. The effective reduction of the surface reflectance by shadows cast by balconies is assumed in the second method by considering the percentage of the area that is sunlit.

Daylight analyses tend to be a quantitative method based on a certain illuminance level rather than a qualitative method that takes into consideration the subjective appreciation of the individuals as to how well daylit a space is. Furthermore, is tends to focus on light levels mainly on the horizontal plane, while the brightness of the space also depends on the light reaching the vertical surfaces. The average daylight factor, based on Sumpner's work on average illuminance (over all surfaces) in the space, as well as the work developed by Lynes on scalar illuminance aims at overcoming this association with the two dimensional approach.

Given the fact that daylight methods mainly provide ways of calculating daylight in terms of illuminance, independent on indoor luminance, reflected light from obstructions and ground is still an ongoing area of research, there is the scope for a new approach to be developed which looks for ways of characterising the space in a similarly to the average daylight factor but under clear skies, where the reflected component from the obstructions and ground are taken into consideration. Just as the average daylight factor can be used to dimension windows under overcast skies, the new approach can address a similar calculation under clear skies.

## 2.7 Daylight criteria

Daylight calculations provide the tools for assessing the availability of natural light within a space. Daylight criteria allow for the evaluation of daylight for its use in a certain space and for a particular function.

In urban planning, Littlefair (Littlefair, 1998) defines a 25° obstruction angle from the middle of the window as a good spacing angle for making sure sufficient skylight is available. This rule was derived for UK sky conditions. Is corresponds to approximately to a 27% vertical sky component at this point. See section 2.5.3. This approach was based on the assumption that a horizontal diffuse illuminance of 6300 lx is exceeded for 70% of the time in London. The method can be applied to other latitudes, where the vertical sky component is obtained for the same illuminance on the vertical plane (1700 lx) is met for the same percentage of daylight hours. Results obtained were consistent with recommendations for obstructions angles, measured from ground level, made by Evans for different latitudes in Europe. (Evans, 1980) Table 2.1[17] presents recommended angles for the two methods.

Littlefair advises that a skylight reduction will be noticeable if the vertical sky component with the new layout is reduced below the values in table 2.1 or is more than 20% lower than its former value. The skylight distribution can be estimated for an existing building by plotting the no-sky line, see section 2.8.2.4.

[17]Values of the horizontal diffuse illuminance (Edh) were generated from the Satel-light database

Table 2.1: Spacing angles for light from the sky

| Latitude (deg) | Climate type | Obstruction angle (deg) | Edh exceeded 70% of time | Vertical sky component (deg) |
|---|---|---|---|---|
| 35 | Mediterranean | 40 | 10 500 | 18 |
| 40 | Mediterranean | 35 | 11 000 | 21 |
| 45 | Temperate | 30 | 9 500 | 24 |
| 50 | Temperate | 25 | 8 000 | 27 |
| 55 | Cold Temperate | 22 | 7 000 | 29 |
| 60 | Sub Arctic | 20 | 5 500 | 30 |

Sunlight access is welcome at higher latitudes for much of the year. In warmer climates, it is still welcome during the winter months, but care should be taken to avoid overheating during the summer periods. Different criteria for sunlight were proposed, based on survey results in different countries in Europe. (Littlefair, 2001) Of those, two main criteria emerged: The first one defines the minimum number of hours of sunlight for a particular day, preferably during the winter period. The second criteria suggests a percentage of probable sunlight hours over a whole statistical year. Sunlight should also be available during at least six months in the year. This approach was later adopted by the UK Standard Code of Practice (BSI, 1992).

Littlefair concludes that the probable sunlight hours give more weight to the summer period, because sunlight is more likely to occur during the summer. It is therefore more appropriate for northern climates, where sunlight is likely to be welcome during the whole year. At latitudes above 50° $N$, the centre of a window should receive 25% of the annual probable sunlight hours available for 6 months of the year.

For southern and central Europe, a criteria is suggested based on sunlight hours for a particular day in winter. Between 42 and 50° $N$, the centre of the window should receive 2hrs of sunlight on 19$^{th}$ February.

Another approach defines the recommended or minimum values for the amount of light necessary to perform a visual task. Values are taken from recommendations intended for use with for artificial light. Possibly the most comprehensive guidelines is that given by the IES. Appendix 15 of *Daylighting (Robbins, 1986)* lists the IES illuminance guidelines in terms of illuminance categories and levels for various building types and visual activities. See table 2.3 for an excerpt of typical recommended

(webpage, 2003a)

light levels. Those recommendations have changed significantly since they were first formulated in 1899. (Robbins, 1986)

Illuminance levels at a defined point, as a quantitative method of analysis of the light needed in accordance with the functional use of the building, are independent of the source of light, whether from the sky or provided by artificial lighting.

The appearance of a room under daylight not only depends on the illuminance on the working plane, but also on the luminance of the surrounding surfaces and the view trough the window. The judgement of the interior brightness will also depend on the occupant's background and knowledge. People may tend to assume that clear skies provide higher illuminance levels than overcast ones, therefore they are more likely to assume a space is acceptably lit under a blue sky than a cloudy sky. Conversely, a room with a smaller window may appear as dull under an overcast sky as it would under a clear sky, even if the light level may be significantly higher for a sunny sky.

While these criteria can be subjective, as the apparent brightness of the room is strongly dependent on the brightness of the sky and external surfaces seen through the window, the average daylight factor representing the ratio of the indoor to outdoor illuminance is a good indicator of how well daylit a space is. (Tregenza and Loe, 1998)

The average daylight factor criteria defining the room's appearance can be described as:

Below 2% The room is poorly daylit, and electrical light will be needed during daylight hours;

2-5% The room has a daylit appearance, but electrical light is likely to be used. The purpose of electrical light is to increase the illuminance, enhance the uniformity of the light in the room and reduce glare from the bright window against a poorly lit window wall;

5% or more The room has a predominantly daylit appearance. Artificial lighting is rarely used. However, larger windows are likely to cause overheating problems.

In residential buildings, minimum average daylight values of 1% in bedrooms, 1.5% in living rooms and 2% in kitchens are recommended, even if a predominantly daylit appearance is not required. (BSI, 1992)

Research on apparent brightness and discomfort glare is presented by Hopkinson et al. Although discomfort glare or apparent brightness may correlate to the luminance of the source, there may not be a direct association between the two. While the luminance needs to be raised four times to appear twice as bright, it needs to

Table 2.3: Recommended task illuminance (Tregenza and Loe, 1998).

| Task requirements | Lux | Examples |
|---|---|---|
| General awareness of space; perception of detail is unimportant | 50 | access routes to service areas |
| Movement of people; recognition of detail for short periods; background lighting | 100 | Corridors, store rooms for large items, auditoriums, **bedrooms** |
| Recognition of detail for short periods in areas where errors may be serious | 150 | Plant rooms, **domestic bathrooms** |
| Areas without difficult visual tasks but occupied for long periods; short-period tasks with moderate contrast or size of detail | 200 | General lighting in control booths, foyers, factory areas with automated processes |
| Tasks such as reading normal print (moderate contrast and size of detail) over long periods | 300 | Workshops for large items, general library areas, school classrooms, **domestic kitchens** |
| task with some details of low contrast and moderate size | 500 | General offices, laboratories |
| Task with low contrast and small size | 700 | Drawing offices |
| Very small visual and low contrast tasks | 1000 | electronic assembly, tool rooms |
| Task with extremely small detail and low contrast | 1500 | Fine work and inspection |
| Tasks with exceptionally small detail and very low contrast | 2000 | Assembly of minute mechanisms |

be raised only 1.8 times to appear twice as uncomfortable. (Hopkinson and Collins, 1970)

## 2.8 Daylight and urban planning regulations

'Most countries have standards or codes of practice for the values of required average illuminance and for uniformity of artificial lighting in space for different activities and areas. It is advisable to design the natural illuminance of the interior on the basis of these standard values.' (Majoros, 1988)

When designing for natural lighting, it is advisable to define the sky conditions appropriate for the place and the length of time, usually of working hours, throughout the year, during which natural light will be sufficient to achieve the requirements.

### 2.8.1 Portuguese regulations

#### 2.8.1.1 Introduction

In Portugal, there are no specific regulations regarding daylight, but some references addressed in other regulations, which might influence the illuminance in buildings, are described. The introduction of the general regulation of constructions (REGEU, 1951) refers to and promotes the orientation of new buildings in regard to the sun and dominant winds. One of the aims of this regulation is to provide buildings with appropriate natural illumination in the spaces designed for work and living. It also aims to allow the execution of tasks without physical or mental distress. The constructions should provide good conditions for living, referring to an optimum illumination with regards to the climatic conditions of the country.

#### 2.8.1.2 General application

The regulation, REGEU, must be followed for any new construction, refurbishment or extension of buildings, as well as for any work which alters the topography of urban or rural areas that might influence urban planning or any zone of possible extension (art. 1).

#### 2.8.1.3 Site layout

New or refurbished buildings should be provided with daylight and prolonged exposure to solar radiation (art. 58).

The height of buildings is limited by a ratio of 1:1 defining the height of the building opposite to its distance away from the building under consideration. Any element, with the exception of chimneys and decorative accessories, included in all vertical planes perpendicular to the facade, must be not higher than the limit defined by the line at 45° starting at the intersection of the facing facade with the ground, see fig. 2.14 (art. 59).[18]

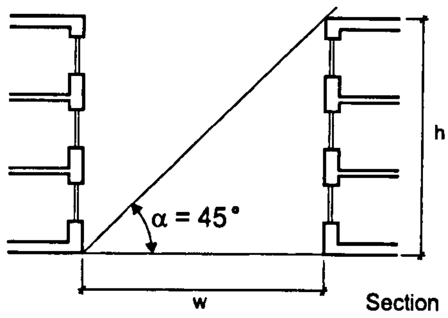


Figure 2.14: Section of an urban canyon with the angle at 45° limiting the height of the obstruction (Portuguese regulations).

Constructions built on the lower part of a sloping street are allowed to exceed the limit by a maximum of 1.50 m. In buildings at the corner of two streets of different width or ground levels, the height limit for the facade facing the narrow street or the lower level may be increased to the limit for the wider street or higher level up by a maximum extension of 15 m. Except for special cases, where buildings occupy the full extension between streets of different width or ground level, the height of the facade must comply with the previous rules. In case of an construction to be erected in a row of buildings with different heights, its height can be equal to the mean height of the adjacent buildings, as long as it complies with the following rule.

Irrespective of the previous articles, the minimum distance between facing facades with openings must not be less than 10 m. In existing streets which are narrower than 10 m, the city council may approve new constructions with distances to the building opposite of less than 10 m, provided that this distance is at least that of the adjacent constructions (art 60).

In corner buildings, the minimum length and width of the backyard can be reduced as long as satisfactory daylight is assured to the building and neighbouring buildings (art 62).

The city councils can not allow any tolerance to the previous conditions, except when justified by exceptional and irreversible circumstances previous to this regulation, or in buildings where its nature, use or architectural restrictions require special conditions. However, satisfactory daylight access and insolation should, if possible at all, be achieved for all floors (art 63).

#### 2.8.1.4 Building interior layout and open spaces

The dimension of the spaces used for accommodation have minimum requirements regarding the area and number of rooms and in any case should respect the following:

[18]This ratio of the height/width in a street will be addressed as the Portuguese 45 rule.

- When the area of the room is less than to 9.5 $m^2$, the smallest dimension must not be below 2.10 m;
- When the area is equal to or larger than 9.5 $m^2$ and less than 12 $m^2$, the inscribed circle must have a diameter of at least 2.40 m;
- When the area is equal to or larger than 12 $m^2$ and smaller than 15 $m^2$, the inscribed circle must have a diameter of at least 2.70 m;
- When the area is equal to or larger than 15 $m^2$, the depth of the room must not exceed twice the width, except if there are additional windows in the back of the room. The inscribed circle must have a diameter of at least 2.70 m (art 69).

The previous article shows that unless a restriction such as a depth not exceeding twice the width for space is clearly defined, as for floor areas bigger than 15 $m^2$, this rule is totally satisfied. The inscribed circle approach allows for the other room areas below 9.5, 12 and 15 $m^2$, to exceed this rule up to 7.1, 4 and 2.8%, respectively.

When a room is composed of 2 spaces which are non-autonomous, the horizontal dimension of the connection must be no less than two thirds of the smaller dimension of the bigger space or at least 2.10 m.

Rooms used for accommodation must always be illuminated by at least one wall opening, in direct contact with the exterior, whose area must not be less than one tenth of the room area. The size of the opening without frame must be at least 1.08 $m^2$ (art 71).

Glazed balconies are considered exterior for the effects of this article and must comply with the following rules:

- The width of the balcony must not exceed 1.80 m;
- The area of the opening to the adjacent room must not be less than one fifth of its area or 3 $m^2$;
- The glazed area of the balcony must not be less than one third of the balcony's floor area or to 3 $m^2$.

Buildings with more than three floors should have, if possible, common stairs with openings in the facade. However, the upper two floors, as well as constructions with less than four floors, can be illuminated by roof lights (art 47).

Ventilation openings in walls adjacent to neighbouring spaces or buildings are not considered openings to provide illumination.

The distance of windows from any external wall or facade must be no less than half the height of the obstruction above the floor level of the room or a minimum of 3.0 m, measured perpendicular to the plan of the window (art 73). In addition, windows must not be obstructed within 2.0 m from either side of the centre and must guarantee for all this extension the minimum 3.0 m previously described, see figure 2.15.

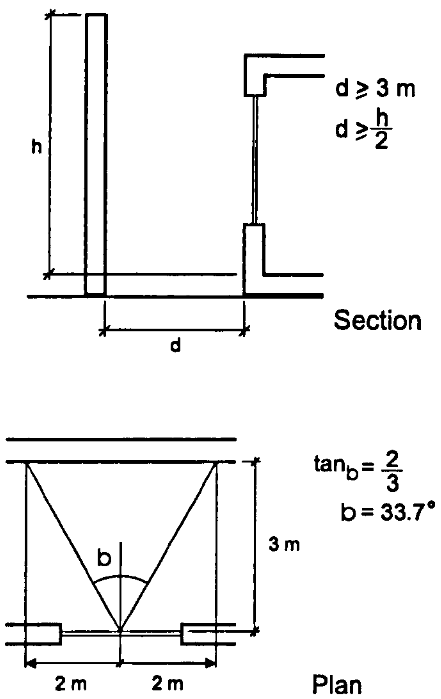


Figure 2.15: Section and plan representing the minimum distances of the obstructions to the window for the Portuguese regulations.

In facades facing courtyards, when the existence of balconies or any elements on the wall are likely to impair the daylight access, the minimum distances defined in article 73 will take effect from the edges of these elements (art 75).

Special conditions apply for basements to be used for habitation (art 77). Besides the compliance for all the rooms with all other regulations the following requirements must be satisfied:

- The cellar must have at least one exterior wall completely unobstructed from 0.15 m below the level of the interior floor;
- All habitable spaces must be adjacent to the unobstructed facade.

In the case of houses that have one facade completely unobstructed and at least two others partially unobstructed, the rooms adjacent to the facade must be located 1.0 m above the interior floor. In the case of a detached house, besides one completely unobstructed facade, it requires only one other partially unobstructed. If it is possible to open windows over the street or terrain around, the windows still must not be less than 0.40 m above the exterior ground.

Lofts and attics can only be used for living purposes provided they comply with the health conditions defined in this regulation for other floors. However, the minimum ceiling height must be guaranteed for half of the room area, and any point more than 0.3 m from its perimeter must have a minimum ceiling height of 2.0 m (art 79).

The bathrooms should have daylight and permanent air ventilation, provided by an exterior rough opening with a minimum area of 0.54 $m^2$ and a minimum opening of 0.36 $m^2$. In special circumstances, openings may be smaller, provided a constant and sufficient ventilation is assured by natural or mechanical means.

The regulations of the thermal behaviour in buildings (RCCTE, 1990) do not include any calculation related to daylight. The calculation provided for the thermal analyses must be carried out unless all of a set of simplified rules are satisfied. One of the rules limits the glazing area to 15% of the floor area (art. 5). One other stipulates that the solar factor of the glazing material for the summer period must be equal or less than 0.15 (art. 6). As the calculation tends to be difficult for architects to achieve, it is common practice to reduce the area of the windows or use coloured glass in order to easily satisfy the regulation. This normally results in a significant reduction in daylight access.

**Summary**

- Although no specific regulations for daylight exist, there are some rules that influence the amount of daylight in buildings;

- The recommendations are based on qualitative suggestions rather than a quantitative method of analysis;

- The obstructions must be below a 45° vertical angle, defined at the ground level of the street section, and the 67° horizontal angle, defined at the centre of the window plan to a depth of 3.0 m;

- The minimum opening area is 10% of the floor area;

- Only in rooms with a floor area larger than 15 $m^2$, the depth must not exceed twice the width. For areas below 9.5, 12 and 15 $m^2$, this rule can be exceeded in 7.1, 4 and 2.8% respectively.

## 2.8.2 English regulations

### 2.8.2.1 Introduction

Although the United Kingdom has a long tradition in research on daylight resulting in several recommendations, there are no specific regulations for daylight and urban planning. This is an indication of the difficulty of fitting daylighting into the other building regulations. An ideal solution for an individual function or performance might not be the best option for others, and a careful decision should be made when designing a building. Although the following criteria are not mandatory, they should be considered as guidance in the daylight design.

#### 2.8.2.2 Daylight criteria

One of the references for daylighting design is the BS 8206: Part 2: 1992 (BSI, 1992) which presents criteria for daylighting design aiming at improving the quality of life and well-being of people inside buildings. It recognises that a good lighting design can go beyond the minimum requirements for task performance and acknowledges the difficulty in finding a balance with other aspects and restrictions involved on a good building design and performance.

Recommendations for window design are addressed in regard to three different uses and characteristics: the provision of a view to the outside, the overall illumination of the interiors and task illumination. When the quantity of daylight is insufficient for ambient and/or task lighting, supplementary artificial lighting should be used to increase the brightness of the space, as well as for task lighting.

For the daylight design and methods of calculation, two sources of daylight are defined: the sunlight, i.e. the light from the sun (direct beam), and the skylight, as the diffuse light from the sky. With different characteristics, these two sources are considered separately and with different methods of calculation. In the calculations laid out, no sunlight reflected by obstructions is considered, but the diffuse light reflected by external and internal surfaces is.

While the sun creates patches of high illuminance and strong contrast enhancing the overall brightness of the spaces, diffuse light is important to reduce the contrast between one space and another, as well as to the outside view. They should be treated differently and, depending on whether sun patches are desirable or not, special care should be taken to prevent thermal and visual discomfort to the users or deterioration of the materials.

The perception of the daylight inside a space is dependent on the amount of light entering the space and the brightness of the surrounding visible surfaces. Reflected light plays an important role in contributing to the overall illuminance. It differs from direct light both in quantity and quality.

Others references for daylight design are available in the BRE information papers and technical reports (BRE, 1986; Littlefair, 1998; Littlefair, 1992b; Littlefair, 1988; Littlefair and Aizlewood, 1998; Littlefair, 1992a; Littlefair, 1987; Littlefair, 2000).

Lynes (Lynes, 1979) proposes a four stage procedure for daylight design. The first stage is to estimate the vertical angle of visible sky subtended at the mid point of the window, see fig. 2.10. The second stage in the daylight design is to check the depth of the room and uniformity of the daylight using eq. 2.13 on page 49 and plotting the 'no-sky line', see section 2.8.2.4. The third stage is to estimate the window size using the eq. 2.11. Attention should also be paid to the thermal performance of the system. Quite frequently the optimal window size according to one requisite is not the ideal to the other and a compromise has to be reached. The last stage involves the shape and position of the window previously sized. Many factors influence the definition of the window, depending on whether the aim is uniformity, distribution over a particular area or a view to the outside. For typical room dimensions the methods previously described will be sufficient to guarantee a pleasant daylight environment. Other cases will involve a point by point analysis of the daylight factor.

#### 2.8.2.3 Site layout

Littlefair (Littlefair, 2001) presents recommendations for providing good access of light from sky and sun to new and existing developments.

The height of the facing obstructions will condition the building planning design. All the elements of an obstruction must be below a 25° line defined in all perpendicular plans to the building facade, at the intersection of a horizontal plane at 2 m above ground and the plan of the facade (figure 2.16).[19] (BSI, 1992) When

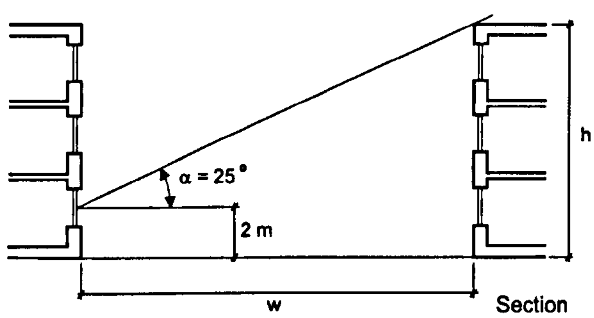


Figure 2.16: Section of a street with the 25° angle delimiting the height of obstructing buildings for new developments in England. The reference line for this daylight calculation is 2 m above ground.

some obstructions are higher than this line, there is still potential for daylighting, provided that the obstructions are not continuous and narrow enough to allow light around their sides. Their impact can be estimated by calculating the vertical sky component (see 2.5.3). Its value at the window, 2 m above the ground, should be bigger than 27%, which corresponds to a continuous obstruction smaller than 25°.

[19]This recommendation will be referred to as the 25 rule.

In new developments or in an extension to an existing building, the safeguard of daylight access to the surrounding buildings should be checked. Both the total amount of skylight and its distribution within the building are important. For the affected windows, a similar procedure is to verify that no element of the new building is above the 25° angle previously defined, now measured at the centre of the lowest window (figure 2.17). If, at any window of the existing building, this angle is more

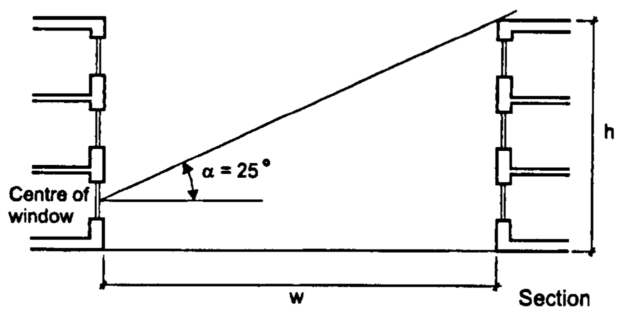


Figure 2.17: Section of a street with the 25° angle delimiting the height of obstructions when checked in existing buildings. The reference line for this daylight calculation is at the centre of the lowest window.

than 25°, the reduction of skylight should be estimated. This reduction can be analysed by calculating the vertical sky component at the centre of the window. If this component is more that 27%, there is still enough skylight reaching the existing building. If the vertical component is both less than 27% and less than 0.8 times the value prior to the new construction, there will be a noticeable reduction in the skylight and electric light will need to be used more often. (Littlefair, 1992a)

Obstructions may affect the amout of light reaching the windows as well as the distribution of light whithin the room.

The availability of skylight inside a space can be found by plotting the no-sky line (see 2.8.2.4 on page 50). If, with the construction of a new building, there is a reduction of the area receiving skylight (behind the no-sky line) to less than 0.8 times its former value, the room will look poorly daylit.

If there are no surrounding constructions, the new development should stand a reasonable distance from the edges of the property to ensure future access of daylight to later constructions and to prevent noticeable reductions of daylight in the building itself. The building should be within an angle to the horizontal of 43°, measured in a section of a plane perpendicular to a boundary, which might affect window access to light, on a point 2 m above this boundary or the centre point of a road it exist. If the building is taller than this level, there is still potential for daylight in the future developments provided the buildings area is narrow enough to allow daylight around its sides. Every point 2 m above the boundary line should be within 4 m (measured along the boundary) of a point with a vertical sky component of 27% or more.

In the early stages of design, considerations as to whether sunlight is desirable should influence the orientation and shape of the building. Special attention should be given to prevent overshadowing of the surrounding areas and buildings.

When sunlight access is to be assessed, this criteria can be used. When it is already below the acceptable recommendation, a similar criteria adopted to that of skylight, of 20% maximum of the former value, can be used.

Different surface orientations receive different amounts of sunlight. A variation occurs also for different periods of the day and year.

A building should have at least one main window facade within 90° of due south. On this wall, all points on the line 2 m above the ground level should be within 4 m (measured sideways) of a point that receives at least 25% of annual probable sunlight hours, including at least 5% of the probable sunlight hours during the winter period, considered to be between 23rd September and 21st March, see section 2.5.4.

The effects of obstructions and orientation on sunlight access at different times of the day and year can be found using a sunpath diagram. (Szokolay, 1996)

With new developments or extensions to existing ones, special care should be taken to prevent a reduction in sunlight access to surrounding buildings. The new construction may affect the sunlight availability of existing buildings if it lies within 90°due south of an existing building and if its height is above the line subtended by the vertical 25° angle defined in the section of a perpendicular plan of the existing facade at the middle point of the window. Access to sunlight should be checked for the main windows of each room that faces 90° due south. If the interior (inner surface) centre point of a window, still receive 25 and 5% of probable sunlight hours, respectively during the year and winter periods, there is still sufficient access to sunlight. Any reduction of this percentage should be kept to a minimum. If the sunlight availability is both less than the recommended and less than 0.8 times their former value, either during the whole year or the winter period, the occupants of the room will notice a loss of sunlight.

#### 2.8.2.4 Building depth and overall size

The diversity of daylight in a side lit room should follow a criteria for the limiting room depth. One uniformity criterion developed by Lynes (Lynes, 1979) is to be satisfied by the equation

$$\frac{rd}{rw} + \frac{rd}{wh} < \frac{2}{(1 - \rho_b)} \tag{2.13}$$

where

$rd$ is the room depth;

$rw$ is the room width;

$wh$ the window head height above floor level;

$\rho_b$ the average reflectance of surfaces in the rear half of the room (away from the window).

'If the room is lit by windows on two opposite facades, the maximum depth that can be satisfactorily daylit is twice the room depth $rd$ , from window wall to window wall'. (CIBSE, 1999)

If the view from the window to the outside is significant blocked by obstructions, the uniformity of the natural light will be impaired.

The *no-sky line* is defined as the line at the working plane beyond which no skylight can be reached. Unless otherwise stated, the working plane is assumed to be horizontal and at 0.85 m for residential buildings and at 0.7, for offices. The position of that line can be obtained from the geometry of the window and opposite obstructions (see fig. 2.18).

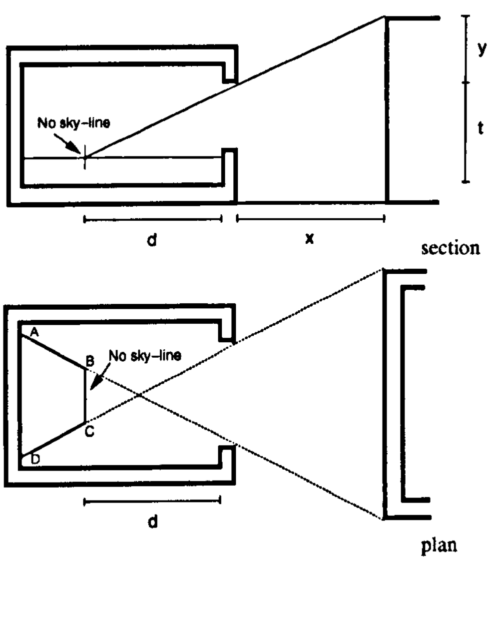


Figure 2.18: Section and plan representing the no-sky area. If the obstruction is narrow the no-sky line is defined by points A, B, C and D. When the obstruction is wider the no-sky line will be parallel to the plan of the obstruction at the distance *d*.

If a significant area of the room lies beyond the no-sky line the room will look gloomy and will need artificial light, even if eq. 2.13 suggests the uniformity criterion is satisfied.

#### 2.8.2.5 Window design

When designing a window with regards to daylight there are some recommendations that should be considered in the early stages of design. The orientation of windows should be designed considering the admission of daylight as well the periods of occupancy and time of the year when the admission of sunlight is desirable.

In the northern hemisphere, to obtain good access to sunlight the sidewall windows should face within 90° of due south. In the southern hemisphere they should be orientated to 90° due north.

Special attention should be given to the size of windows, as oversize ones might cause thermal discomfort and increase the energy consumption of the building. Conversely, undersized windows reduce the daylight appearance of the room increasing the energy consumption for lighting. During winter, solar gains are welcome but during the night heat losses should be prevented. During the summer, shading devices are advisable to prevent overheating causing thermal discomfort or an increase of the cooling loads of air-conditioned buildings.

The Building Regulations Part L: Conservation of Fuel and Power recommends maximum areas for double glazing in walls and roofs to prevent heat gains or heat losses and consequently an increase of heating or cooling loads. In some cases these recommended areas are insufficient for effective daylighting.

Uniformity of a room will be affected if the window head is significantly lower than the ceiling. It will also be affected by the window's shape and position on the wall.

#### 2.8.2.6 View

The position, size and proportion of the window should depend on the type of view, the size of the space and the position of the occupants. Table 2.4 gives guidelines for minimum glazed areas when they are primarily designed for view and windows are restricted to one wall.

Table 2.4: Recommendations from the BS 8206 : Part 2: 1992 for minimum areas for satisfactory view.

| Minimum glazed areas for view when windows are restricted to one wall | |
|---|---|
| Depth of room outside wall (max.) [m] | Percentage of window wall as seen from inside (min.) [%] |
| $< 8$ | 20 |
| 8 - 11 | 25 |
| 11 -14 | 30 |
| $> 14$ | 35 |

### 2.8.2.7 General illumination

Sunlight should be admitted unless the use of the space prevents it.

Sunlight is taken to enter an interior when it reaches one or more window reference point.

Spaces where direct sunlight is desirable should receive at least 25% of probable sunlight hours. At least 5% of probable sunlight hours should occur during the winter months, between 23$^{rd}$ September and 21$^{st}$ March. A calculation procedure is given in the BS 8206 : Part 2 : 1992 (BSI, 1992) (see 2.5.4). It is the duration of the admission of sunlight rather than the intensity or size of patches that correlates best with the occupants satisfaction.

The average daylight factor, $\overline{D}$, see 2.5.2, is used as a measure of general illumination from skylight.

For a room to appear predominantly daylit, without supplementary light, BS 8206 : Part 2 : 1992 (BSI, 1992) recommends an average daylight factor of 5% or more. If the room depth is greater than that recommended in eq. 2.13 or a significant part of the working plane lies behind the no-sky line, the distribution of light (uniformity) is poor and supplementary electrical light will be necessary even when the lighting levels are adequate. If the use of electric light is expected, the average daylight should not be less than 2%. In residential buildings the minimum average daylight values of 1% in bedrooms, 1.5% in living rooms and 2% in kitchens are recommended, even if a predominantly daylit appearance is not required.

The average daylight factor is proportional to window area, and can be used to calculate the window area required to achieve a given average daylight factor.

The perception of a well-lit space (light in a room) is related to the brightness of the surfaces. This depends on the quantity of light entering the room and the reflectance of the interior surfaces. Reflected light is as important as direct illumination. The surface reflectance and the positioning of the window should promote the interreflection and widespread of light in the space. A subtle gradation of luminance from the dark side to the window should be aimed for.

An excessive contrast between the luminance of the visible sky or bright external surfaces and the contour of the window might cause glare. This can be prevented by increasing the illuminance of the window wall with another window or the use of electric light, by reducing the transmittance of the glazing with translucent blinds, curtains or tinted glass or by splaying larger window reveals to increase the area of a intermediate brightness between the interior and exterior. Glare from direct sunlight or sunlight reflected by highly reflective external obstructions should be reduced by the use of shading devices.

#### 2.8.2.8 Task illumination

The principles defined for electrical task illumination (CIBSE, 1994) are applicable to daylight task performance. However, daylight has different characteristics.

Task illuminance for different activities and interiors are defined in table 1 and 2 of BS 8206 : Part 1: 1985. (BSI, 1985)

To calculate the interior illuminance, BS 8206 (BSI, 1992) recommends the daylight factor calculation (see 2.5.1) or the following simple equation as

$$E_{in} = \frac{E_{dh} f_{o} D_{CIE}}{100} \tag{2.14}$$

where

$E_{in}$ is the internal illuminance in lux;

$E_{dh}$ is the external unobstructed illuminance in lux, direct light is excluded;

$f_{o}$ is a window orientation factor, to take account of different amounts of diffuse light received at different window orientations for no-overcast sky conditions;

$D_{CIE}$ is the CIE standard overcast sky daylight factor at a given point, expressed as a percentage.

As daylight illuminance is constantly changing it is more appropriate to quote a percentage of a period of time (usually a year) for which a given illuminance value is exceeded instead of a single value.

The uniformity of daylight in a side lit room mainly depends on the room dimensions and the reflectance of the surfaces. Some criteria are based on minimum to maximum or minimum to average illuminance ratio. BS 8206 : Part 2 advises on the uniformity of daylight illuminance over the task area on the recommended for electric light in BS 8206 : Part 1 (BSI, 1985). A uniformity criterion, in terms of the ratio of minimum to maximum illuminance on the working area, of 0.7 or an equivalent of a minimum to the average illuminance of 0.8, is indicated. Also, the illuminance on the surrounding no-working areas should not be less than one-third of that of the working area. Lynes (Lynes, 1979) suggests that the ratio of the average daylight factor in the front half of the room (closer to the window) to the average daylight factor in the back half of the room should be below 3 for a pleasant uniformity. This calculation forms the basis of the limiting depth previously presented in eq. 2.13.

The luminance of other surfaces as well as their reflectance should be considered as they influence the overall brightness and the performance of visual tasks.

Special attention should be paid to glare and specular reflection. When the visual task is directly facing a bright sky, distraction, poor uniformity between the task and background and discomfort glare may occur. It is advisable to orientate the visual task plane in such a way that the window is at the side instead of within the line of sight. Bright reflections of the sky in glossy surfaces can impair the visibility of a task. At the visual task-site, glare provoked by a view, within the direction of 45°, of the sun or its specular reflection on an exterior surface, should be prevented by the use of shading devices. When the task performance requires good colour recognition, care should be taken in the use of tinted glass as they can affect colour perception.

### Summary

- two sources of daylight are considered: sunlight (direct beam) and skylight (diffuse light from sky);

- sunlight reflected from surfaces is not considered in the daylight calculations, but skylight reflected from internal and external surfaces is. However, special attention is addressed to glare provoked by reflections;

- obstructions should be within the 25° vertical angle defined at a perpendicular plane to the facade, at the middle of the window (for existing buildings) or 2 m above the ground level (for new developments). Otherwise, the vertical sky component at the reference points should be higher than 27%;

- if sunlight is expected in a space, windows should be orientated within 90° of due south, the obstructions should be within the 25° angle previously described and the space should receive at least 25% of annual probable sunlight hours including at least 5% of the probable sunlight hours during the winter period;

- new constructions can affect the daylight access to existing buildings. If the vertical sky component is both less than 27% and 0.8 times its previous value, there will be a noticeable reduction in skylight and electric light will be used more often. If new constructions lie within the angle of 90° due south, and the available sunlight hours are both less than 25% for the annual and less than 5% for the winter period, and 0.8 times its previous value, there will be a noticeable reduction in sunlight and the room will look colder and less pleasant;

- the penetration of skylight within a room is described by the no-sky line. If a significant area lies behind this line, the uniformity is poor and electric light will be needed;

- there is a limit to the room depth in relation to the width defined by the formula 2.13;

- window design is based on provision of view, overall and task illumination;

- for general illuminance, with an average daylight factor of 5% or more, the room is considered strongly daylit and electric light is rarely used, for an average daylight factor between 2% and 5% the room is still daylit but supplementary electrical lighting will need to be used during daytime, and for an average daylight factor less than 2% the room will look gloomy under daylight and full electric light is often needed. For domestic buildings a recommendation of 2% for kitchens, 1.5% for living areas and 1% for bedrooms is acceptable.

- daylight task illumination follows the principles and criteria defined for electrical task lighting. However, as daylight illuminance is constantly changing, it is more appropriate to quote a percentage of a period of time for which a given illuminance value is exceeded instead of a single value.

### 2.8.3 'Rights of Light'

A right of light is an easement, i.e. a right acquired by one party over another one's land. In the U.K. 'Rights of Light' legally protects individuals in their access to daylighting against threats from new constructions or extensions to existing neighbouring constructions. The prescriptive right takes effect if it has been enjoyed for 20 years without interruption of a year or more, unless the right has been waived by express agreement.

If the new development reduces the light to a window that has acquired a prescriptive right to light, the window's owner is entitled to legal remedy. However, if the 50% of the working plane still receives 0.2% sky factor, the light is considered adequate and therefore not to be actionable. This is called the 50/50 rule. Although not a rule of law, particularly for domestic cases, it can be regarded as a convenient rule of thumb.

Where there is a loss of light below the minimum considered to be adequate, then the loss can be quantified by comparing the old and the new 0.2% sky factor contour lines. Depending on the extent of the right of light injury, it can result in compensation awarded, the cutting back of the development, or to court injunctions constraining the original layout. (Anstey, 1992)

## 2.9 Conclusions

CIE sky models are typically used in daylight calculations. Among those the CIE overcast sky has been wide adopted due to its simple distribution and independence of orientation. The overcast sky function expresses the fact that the zenith luminance is three times brighter than the horizon. On the other hand, the clear sky is a much more complex mathematical representation. The luminance distribution changes with altitude and azimuth of the sun and the luminance of a sky element depends on the angle between that element and the sun as well as the angle between that element and the zenith.

While a real sky distribution for the location may prove to be more adequate than a sky model for daylight analyses, there is still a limited availability of data in the visible spectrum for worldwide locations.

There are several factors affecting the daylight availability in a space. Some are related to the outside environment such as the sky conditions, latitude, orientation of the building, layout of surrounding buildings and their surface characteristics. Others, more related to the interior of the space includes size and position of the window, its glass transmittance, room dimensions and the properties of interior surfaces.

Natural light of a location is constantly changing through out the day and time of year due to a permanent rotation of the earth around its axis and around the sun.

Latitude has a major influence on the access to sunlight. So it does the orientation of the building under clear skies.

In urban canyons obstructions may have an effect on daylight availability in two ways. They may reduce the contribution from the diffuse sky and block out sunlight access. Conversely, they can reflect light from other parts of the sky or even promote reflected sunlight to the opposite buildings.

The reflectance of surrounding surfaces in a canyon as well as the surfaces of the room will strongly affect the quantity and distribution of the reflected light.

Although there are several methods for daylight analyses, the daylight factor is the most widely adopted calculation for predicting daylight in buildings. By definition direct sunlight is excluded from the calculation.

Previous research suggested the wide acceptance of the daylight factor and overcast sky as method and sky distribution for daylight analyses. It also revealed as reflected sunlight from obstructions and ground have been systematically ignored in the majority of daylight calculations. However, reflected sunlight may be the main source of light particularly when the clear sky is of low luminance.

Daylight analysis tends to be a quantitative method based on a certain illuminance level rather than a qualitative method that takes into consideration the subjective appreciation by occupants as to how well daylit a space is. Furthermore, daylight calculations are usually associated with the horizontal working plane. However, the nature of light as well as the perception occupants obtain from its distribution in the space is closely related with a three dimensional overview. Moreover, the appreciation of a lit space is strongly dependent on the brightness of the outside view from the window. The average daylight factor, representing a ratio of the indoor to the outdoor illuminance is a good indicator of how well daylit the indoor environment is and allow for the sizing of windows for a recommended criteria.

Even countries with long tradition in daylight research such as the United Kingdom do not have specific regulations for daylight in buildings and urban planning. This expresses the difficulty of combining daylight with the other building regulations. Nevertheless, daylight recommendations provide guidelines for good practice of daylight. In countries such as Portugal they are rather qualitative, defining rules for building spacing and window area in terms of floor area, instead of quantitative methods of analyses.

# Chapter 3

# Analytical calculations

## 3.1 Introduction

Under sunny sky conditions in an urban area, a room may be mainly lit by direct sunlight or by reflected sunlight from other buildings. The following analysis examines the contribution of reflected sunlight and skylight to the illumination of facades not lit by direct sunlight.

The geometry presented consists of an urban canyon with a building surface, $S_2$, orientated north, facing an obstruction plane, $S_3$, of equal height, $h$, and a ground plane, $S_1$, of width $w$. All the surfaces are considered diffuse reflectors with reflectance $\rho_2$, $\rho_3$ and $\rho_1$, respectively. For the calculation of the simplified configuration factors between a point $P$ on the facade of the building and the obstruction and ground surfaces the urban canyon is considered to be extended to infinity. A more complex calculation for finite surfaces can be calculated attributing a length, $l$ to the canyon.

This chapter presents a calculation of the illuminance reaching a point on the exterior of the facade when the sun is not incident on the surface ($E_{sP}(0) = 0$). It calculates for diffuse surfaces the first reflection of sunlight from the obstruction and ground $E_{sP}(1)$, the skylight contribution, $E_{dP}(0)$ and the interreflection contribution for the following reflections within the canyon, $E_{is}(i)$ and $E_{id}(i)$, for both sunlight and skylight.

The total vertical illuminance, $E_{tv}$ on a point of the facade, $P$, is the sum of the previous contributions, and is defined as,

$$E_{tv} = E_{sP}(1) + E_{dP}(0) + E_{is}(i) + E_{isk}(i) \tag{3.1}$$

## 3.2 Reflected sunlight contributions

This section presents a calculation of the contribution of reflected sunlight from the obstruction and ground to the illuminance on the outside of a vertical window when the sun is behind the building.

### 3.2.1 From obstruction

The sun is incident on the obstruction when $\cos\theta_v > 0$ where $\theta_v$ is the angle of incidence of the sun beam on the vertical surface and is calculated by (Tregenza, 1995)

$$\cos\theta_v = \cos\gamma_s \cdot \cos HSA \tag{3.2}$$

or

$$\cos\theta_v = \sin\gamma_s \cdot \frac{1}{\tan VSA} \tag{3.3}$$

where

$\gamma_s$ is the solar altitude angle [deg];

$HSA$ is the horizontal shadow angle, defined as the angle in the horizontal plane between the solar azimuth (due north positive clockwise) and the azimuth of the normal of the vertical surface. see fig. 3.1;

$VSA$ is the vertical shadow angle, defined as the angle measured on a plane perpendicular to the vertical surface between the horizontal plane and a plane tilted from the horizontal axis that includes the sun;

$\tan VSA = \frac{\tan\gamma_s}{\cos HSA}$ .

See appendix E for a detailed explanation.

Considering the solar normal illuminance, $E_{sn}$, the illuminance reaching the obstruction, $S_3$, from the sun is

$$E_3 = E_{sn} \cdot \cos\theta_v \tag{3.4}$$

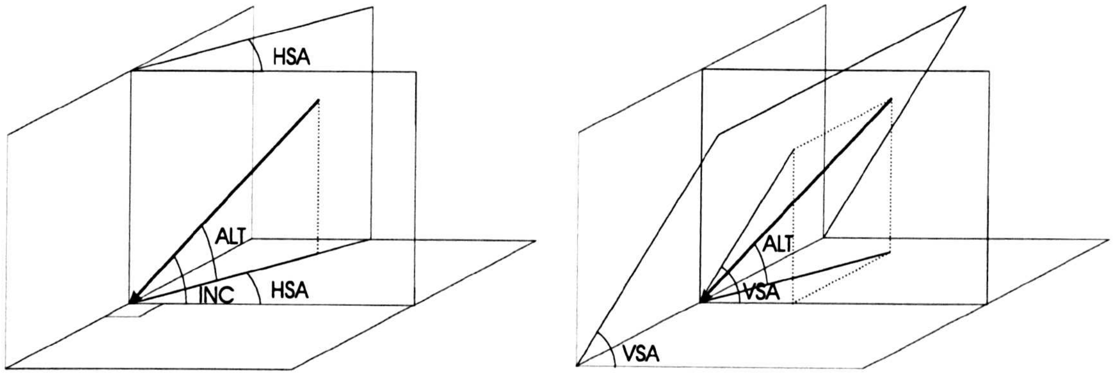


Figure 3.1: Horizontal and vertical shadow angle.

By the definition of the configuration factor, $CF$[1], between a surface, $S_i$, and a point, $P$, with illuminance $E_P$, in lux and a luminance at the surface $L_S$, in apostilibs, the illuminance reaching a point $P$ from a sun patch in $S_3$ is

$$E_P(1) = E_3 \cdot \rho_3 \cdot CF_{3-P} \tag{3.5}$$

as $L_S = E_3 \cdot \rho_3$

The configuration factor of a obstruction with a horizontal skyline parallel to the facade and extended to infinite is $\frac{\sin \alpha_i}{2}$, where $\alpha_i$ is the vertical angle (in degrees) of the obstruction measured at a section perpendicular to the facade at the height of the point. For a finite surface see appendix F.

Considering a sun patch in the obstruction, its size $x$ from top is:

$$x = 0 \tag{3.6}$$

if $\tan VSA < 0$ ;

$$x = w \cdot \tan VSA \tag{3.7}$$

if $\tan VSA > 0$ and $x < h$ ;

otherwise

$$x = h \tag{3.8}$$

[1]The configuration factor describes the flux transfer between an infinitesimal surface element and a finite area of another surface. (Tregenza and Sharples, 1993)

where

| | |
|---|---|
| $w$ | is the width of the canyon; |
| $h$ | is the height of the canyon; |
| $l$ | is the length of the canyon; |
| $x$ | is the height of the sun patch on the obstruction. |

The flux transfer between the point and surface is dependent on the position of the point in relation to the sun patch and is calculated, see figure 3.2, as

$$CF_{3-P} = \frac{\sin\alpha_1 - \sin\alpha_2}{2} \tag{3.9}$$

if $h - h_P > x$ ;
otherwise

$$CF_{3-P} = \frac{\sin\alpha_1 + \sin\beta_1}{2} \tag{3.10}$$

where

$\alpha_1 = \arctan\left(\frac{h-h_P}{w}\right)$ ;

$\alpha_2 = \arctan\left(\frac{h-h_P-x}{w}\right) = \arctan\left(\frac{h-h_P}{w} - \tan VSA\right)$ ;

$\beta_1 = \arctan\left(\frac{x-(h-h_P)}{w}\right) = \arctan\left(\tan VSA - \frac{h-h_P}{w}\right)$ ;

$h_P$ is the height of point $P$ on the building facade.

### 3.2.2 From the ground

The sun is incident on the ground when $w \cdot \tan VSA > h$.

The size of the sun patch on the ground, $y$, from the obstruction is given by

$$y = w - \frac{h \cdot \cos HSA}{\tan\gamma_s} = w - \frac{h}{\tan VSA} \tag{3.11}$$

if $x > h \Leftrightarrow w \cdot \tan VSA > h$ ;
otherwise

$$y = 0 \tag{3.12}$$

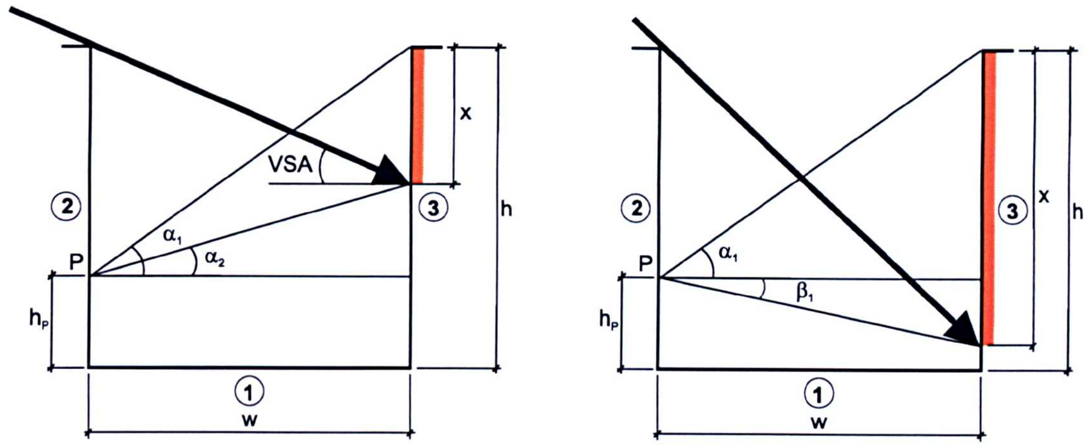


Figure 3.2: Section of an urban canyon showing angles between the point $P$ and the sun patch on the obstruction.

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See fig. 3.3 for details.

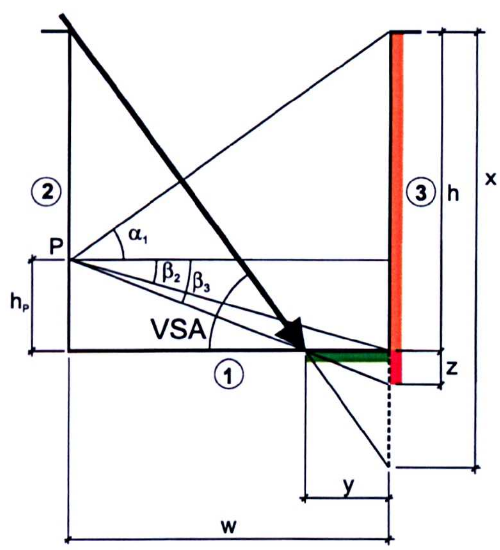



Figure 3.3: Section of an urban canyon showing the angles between a point P and the sun patch on the ground plane extended to the obstruction.

Considering the solar normal illuminance, $E_{sn}$, the illuminance $E_1$ reaching the ground, $S_1$ from the sun is

$$E_1 = E_{sn} \cdot \sin \gamma_s \tag{3.13}$$

To make use of the simplified configuration factor previous presented, $y$ is projected on the obstruction by an equivalent dimension $z$ in relation to the point $P$

as

$$\frac{h_P}{w-y} = \frac{z}{y} \quad \Leftrightarrow \quad z = \frac{h_P \cdot y}{w-y} = \frac{h_P \cdot w}{w-y} - h_P = h_P \left( \frac{w \cdot \tan VSA}{h} - 1 \right) \quad (3.14)$$

Then the flux transfer between the sun patch on the ground and a point $P$ on the facade is defined by the configuration factor $CF_{1-P}$ as

$$CF_{1-P} = \frac{\sin\beta_3 - \sin\beta_2}{2} \quad (3.15)$$

where
$\beta_2 = \arctan\left(\frac{h_P}{w}\right)$
$\beta_3 = \arctan\left(\frac{h_P+z}{w}\right) = \arctan\left(\frac{h_P \cdot \tan VSA}{h}\right)$
The illuminance $E_{sP}(1)$, resulting from the first reflection of the sun beam at the obstruction and ground is

$$E_{sP}(1) = E_3 \cdot \rho_3 \cdot CF_{3-P} + E_1 \cdot \rho_1 \cdot CF_{1-P} \quad (3.16)$$

When the reflectance of the ground is the same as that of the obstruction see appendix G for a simplified formula.

With the following interreflections within the canyon, $E_{sP}(2)+E_{sP}(3)+E_{sP}(4)+ \ldots + E_{sP}(i)$ are much more insignificant and can be calculated based on the theory of the integrating sphere. (Walsh, 1958; Walsh, 1961; Hopkinson et al., 1966) Some assumptions are made such as that all the surfaces are totally diffuse as well as the flux is uniformly distributed over the area of the parallelepiped as it would within a sphere. Furthermore, the illuminance on the point $P$ after the second reflection is equal to the average illuminance of the surfaces.

The total solar light flux, $\phi_{st}$ that enters the canyon is

$$\phi_{st} = E_{sn} \cdot \sin\gamma_s \cdot w \cdot l \quad (3.17)$$

then

$$E_{sP}(2) = \frac{\phi_{s2}}{A_{S1} + A_{S2} + A_{S3} + A_{S4}} = \frac{\phi_{s1} \cdot \rho_{pond}}{\sum_4 A_{Si}} = \frac{\phi_{st} \cdot \rho_{avera} \cdot \rho_{pond}}{\sum_4 A_{Si}} \quad (3.18)$$

where

$\phi_{s1}$, $\phi_{s2}$ are the first and second incident flux on a small element of the canyon;

$\rho_{avera} = \frac{\rho_1 \cdot A_{S1} + \rho_3 \cdot A_{S3}}{A_{S1} + A_{S3}}$ ;

$\rho_{pond} = \frac{\rho_1 \cdot A_{S1} + \rho_2 \cdot A_{S2} + \rho_3 \cdot A_{S3} + 0 \cdot A_{S4}}{A_{S1} + A_{S2} + A_{S3} + A_{S4}}$ .

$A_{si}$ is the area of the surface with the index $i$ and $S_4$ is the virtual ceiling enclosing the canyon with $\rho = 0$ to represent the flux that is lost though the open top surface of the canyon.

The areas and null reflectance of the two open surfaces of area equal to $w \times h$, vertical boundaries of the canyon, were ignored in the calculation because they were considered insignificant in the overall calculation and to reduce the complexity of the calculation.

As the successive interreflections are given by the previous flux multiplied by the $\rho_{pond}$ over the area of the canyon, the total solar illumination in $P$, $E_{sP}(t)$, is

$$\begin{aligned} E_{sP}(t) &= E_{sP(1)} + \frac{\phi_{st} \cdot \rho_{avera} \cdot \rho_{pond}}{\sum_4 S_i} \cdot \left(1 + \rho_{pond} + \rho_{pond}^2 + \ldots\right) \\ &= E_{sP(1)} + \frac{\phi_{st} \cdot \rho_{avera} \cdot \rho_{pond}}{\sum_4 S_i \cdot (1 - \rho_{pond})} \end{aligned} \tag{3.19}$$

If the sun is incident on the facade, then

$$E_{sP}(0) = E_{sn} \cdot (-\cos\theta_v) \tag{3.20}$$

and

$$E_{sP}(t) = E_{sP}(0) + \frac{\phi_{st} \cdot \rho_{avera} \cdot \rho_{pond}}{\sum_4 S_i \cdot (1 - \rho_{pond})} \tag{3.21}$$

## 3.3 Skylight contribution

The clear sky distribution is quite complex and the calculation of the diffuse sky contribution for a point on the facade is simplified by assuming a sky of uniform distribution. For that situation, the illuminance that reaches a point $P$ directly from the sky, $E_{dP}(0)$, and after the first reflection in the canyon, $E_{dP}(1)$, are;

$$E_{dP}(0) = E_{dh} \cdot \left(\frac{1}{2} - \frac{\sin\alpha_1}{2}\right) \quad (3.22)$$

$$E_{dP}(1) = \overline{E}_3 \cdot \rho_3 \cdot \left(\frac{\sin\alpha_1 + \sin\beta_2}{2}\right) + \overline{E}_1 \cdot \rho_1 \cdot \frac{\cos\beta_2}{2} \quad (3.23)$$

where

$E_{dh}$ is the horizontal diffuse illuminance from a clear sky;

$E_{3MAX} = \frac{E_{dh}}{2}$ ;

$E_{3MIN} = E_{dh} \cdot \left(\frac{1}{2} - \frac{\cos\theta_1}{2}\right)$ see figure 3.4 for definition of angles for the sky component;

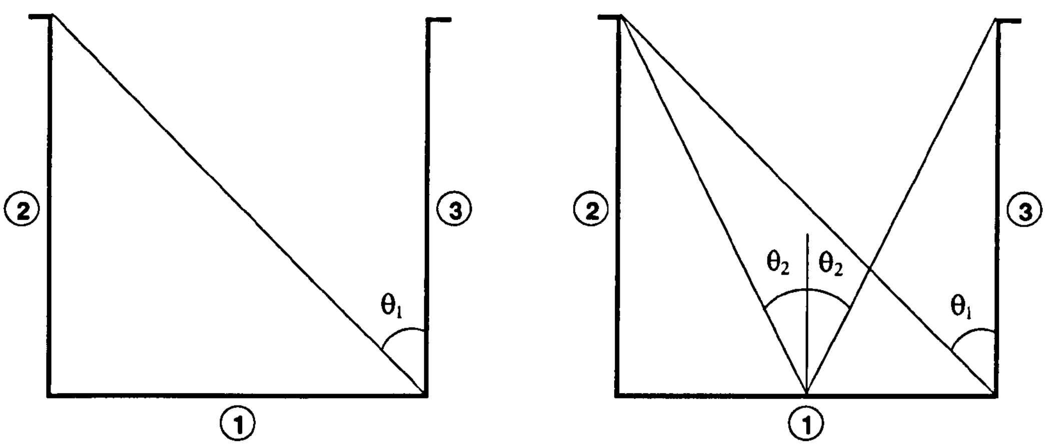



Figure 3.4: Sections of an urban canyon showing the angles for the sky component calculation at bottom of obstruction and middle point of ground.

$E_{1MAX} = E_{dh} \cdot \sin\theta_2$ ;

$E_{1MIN} = E_{3MIN} = E_{dh} \cdot \left(\frac{1}{2} - \frac{\cos\theta_1}{2}\right)$ ;

$\overline{E}_3$ is the average illuminance at the surface $S_3$ calculated as

$\overline{E}_3 = \frac{E_{3MAX}+E_{3MIN}}{2} = \frac{E_{dh}}{2} \cdot \left(1 - \frac{\cos\theta_1}{2}\right)$ ;

$\overline{E}_1$ is the average illuminance at the surface $S_1$ calculated as

$\overline{E}_1 = \frac{E_{1MAX}+E_{1MIN}}{2} = \frac{E_{dh}}{2} \cdot \left(\sin\theta_2 - \frac{\cos\theta_1}{2} + 1\right)$ .

Higher interreflections in the canyon will be considered in a similar was calculated for sunlight with a total diffuse flux entering the canyon, $\phi_{dt}$, as

$$\phi_{dt} = E_{dh} \cdot A_{S4} \tag{3.24}$$

The total diffuse illuminance at $P$, $E_{dp}(t)$, is

$$\begin{aligned} E_{dp}(t) &= E_{dP}(0) + E_{dP}(1) + \frac{\phi_{dt} \cdot \rho_{pond}}{A_t} \cdot \left(1 + \rho_{pond} + \rho_{pond}^2 + \ldots\right) \\ &= E_{dP}(0) + E_{dP}(1) + \frac{\phi_{dt} \cdot \rho_{pond}}{A_t \cdot (1 - \rho_{pond})} \end{aligned} \tag{3.25}$$

The total vertical illuminance at a point $P$ in the facade, $E_{tvP}$, from reflected sunlight by the obstruction and ground, skylight and interreflections is the sum of $E_{sP}(t)$ and $E_{dP}(t)$, equations 3.19 and 3.25.

# Chapter 4

# Fieldwork

## 4.1 Introduction

The sun is the source of all light reaching the earth's surface. For any given latitude, the light reaching a building facade in an urban canyon will be mainly dependent on the building's orientation, the geometry of the canyon and reflectance of the surfaces.

It is possible to define three scenarios regarding sunlight availability on a vertical facade. In the first scenario, the sun is in front of the building and is providing direct sunlight on the facade.

In the second scenario, the sun is still in front of the building but the obstruction is sufficiently high to block direct sunlight. Any point on the facade will receive light from the sun after it is reflected from other parts of the facade and then from the obstruction and ground. As this involves a minimum of two reflections, the sunlight contribution can be significantly reduced. Furthermore, it will be mainly dependent on the reflectance of the surfaces.

In the last scenario, the sun is behind the building and sunlight reaches the facade after it is reflected from the obstruction and ground.

Besides the sunlight contribution, the illuminance on the facade will be a result of direct light from the visible part of the sky and from other parts of the sky vault by reflection at the obstruction and ground. The skylight contribution will be more significant at the higher floors, as they benefit from a wider vertical angle of visible sky.

Lastly, the illuminance on the facade includes the contribution from interreflections within the canyon due to reflected sunlight and skylight.

Under sunny conditions the solar contribution to the global illuminance is much higher than the sky contribution. As an example, at noon during the summer solstice in Lisbon the direct unobstructed illuminance is around 75 000 lx and the diffuse unobstructed illuminance is 12 500 lx.[1]

[1]Values calculated with RADIANCE for a CIE clear sky with turbidity 2.75.

This chapter presents the data collected in urban canyons in Lisbon, during 5 days in August and December 2000 and August 2001.

## 4.2 Real measurements

This section introduces the preparations for the real measurements made in an urban canyon. It includes the details of the measurements taken, the location where they where recorded, the instrumentation used and the difficulties encountered on the survey.

### 4.2.1 Measurements taken

External measurements of the total vertical illuminance were taken for the first and top floor windows of buildings in urban canyons. Simultaneously, readings of the global horizontal illuminance were taken.

The global illuminance, $E_{gh}$, is the sum of the direct light from sun and the diffuse light from the sky that falls onto a horizontal unobstructed plan.

The 'total vertical illuminance', $E_{tv}$ is the sum of sunlight, skylight and the interreflected component (in an urban canyon) that falls on a vertical plane.

The survey covered buildings oriented north, south and east. Results are presented for local mean time (clock time).

It was decided to measure the global horizontal and total vertical illuminance, the former on an unobstructed roof, the latter with the instrumentation being located outside of windows of private apartments overlooking streets with different orientations. If the sunlight was to be measured separately from the skylight, twice the number of instruments would be necessary, one set to measure the global light, the other for the diffuse component only. The instrument used to measure the diffuse light would have to include a shading ring to block direct sunlight. Furthermore, this separation of the two contributions would only be valid on an unobstructed horizontal plane. On a vertical surface, as both direct and diffuse light are also reflected by the obstructions and ground, it is impossible to separate the sun and the sky contribution. As the vertical measurements were to be compared to the horizontal ones, it was decided not to increase the complexity of the instrumentation positioned horizontally.

For the vertical measurement, to be taken in the middle of the window seemed a better location than the window sill. However, for practical reasons (easy fixing), the latter location was adopted.

### 4.2.2 Site layout

The urban canyon chosen was as close as possible to the minimum requirement of the Portuguese regulations in terms of the canyon aspect ratio. Ideally, the building would be oriented north, to have an extended period without direct sunlight, to take into consideration the reflected light from the obstruction. Also, the street and facades of buildings should be free from external obstructions as far as possible.

Unfortunately, the difficulty of finding an ideal situation, worsened by the objections from tenants or owners of the flats to the placement of the instruments on the facade reduced the selection available.

The first and third sets of measurements were taken on the building facing north in an urban canyon with a 1:1.5 aspect ratio[2], see fig. 4.1. The vertical measurements were taken at the $1^{st}$ and $5^{th}$ floors. The second set of measurements was taken in the same urban canyon, on the $1^{st}$ floor of a building oriented south facing a recently painted facade and an old facade.

Figure 4.1: Urban canyon in Lisbon. Street axis in east/west direction.

The fourth set of measurements was taken in a building facing east on the $1^{st}$ and $2^{nd}$ floor in an urban canyon with a 1:1 aspect ratio. See fig. 4.2.

### 4.2.3 Instrumentation

The illuminance measurements were taken with an instrument that was developed specifically for this purpose.

The instrument consists of two main components and is powered by batteries. The first is a photocell connected to a small amplifier and the second a 'TinyTalk'

[2] Aspect ratio, AR, in a urban canyon is the ratio of the height of obstruction to the width of the canyon.

Figure 4.2: Urban canyon with a North/South axis in Lisbon. Fish eye view.

data logger that includes another amplifier, an analog to digital converter and memory non-volatile. Except for the photocell, all parts are housed in an IP rated box (see fig 4.3).

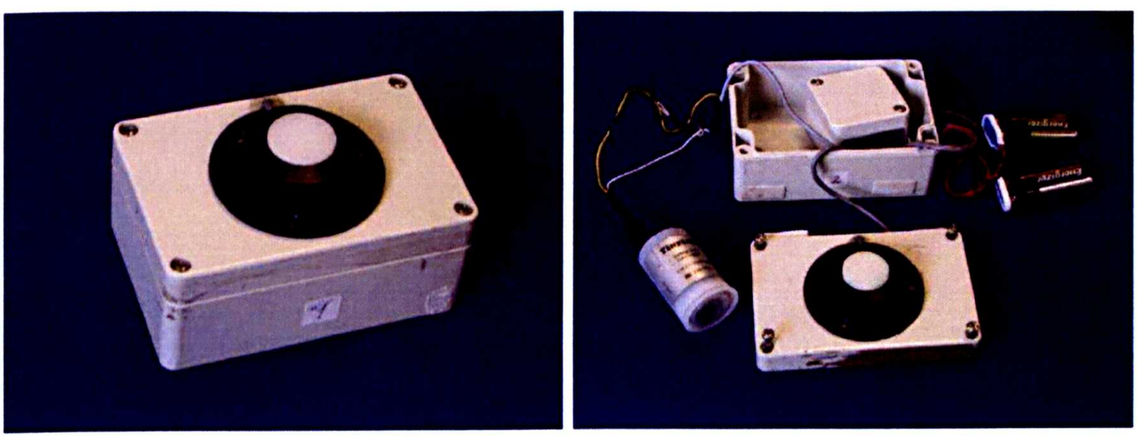


Figure 4.3: View of the instrument to take illuminance measurements.

The dynamic range of the photocell is 0 to 100 000 lx and the small amplifier has an output of 0 to 10 V. The output from the amplifier is linear with respect to the photocell exposure. The sensitivity of the data logger was set to the range of 0 to 10 V. The A/D converter has an 8 bit resolution. When the units of voltage are converted to illuminance, the 100 000 lx are divided into 255 intervals resulting in multiples of 392 lx that can be represented. For this reason, the readings in the graphs will show a step division in this range which is visible particularly on those graphs with a scale of 0 to 10 000 lx or less.

The data logger can record 1 800 readings. Intervals of 4 min were selected which results in a 5 days period of measurements.

### 4.2.4 Difficulties encountered

As said before, it was difficult to find urban canyons with the required orientation, aspect ratio and without significant street obstructions.

Also, it was found that some tenants were afraid of having an instrument located on the outside of their apartments. Furthermore, as they were located on the glass pane of the windows, (for security reasons it was easier to install them on the glass than on a rough surface) it prevented the use of the external shading devices.

Forbidden access to roofs or situations where unobstructed horizontal readings were impossible to obtain resulted in the positioning of the horizontal and vertical instruments in different locations of the city. Rapid weather changes at the different locations of the positioned instruments, especially on partially cloudy days, caused some data discrepancy. However, they were not significantly frequent to affect the overall relation obtained for the period.

Failure of the instruments to record the measurements due to flooding on a heavily rainy day and faulty batteries resulted in the loss of data for two periods.

## 4.3 Data analysis

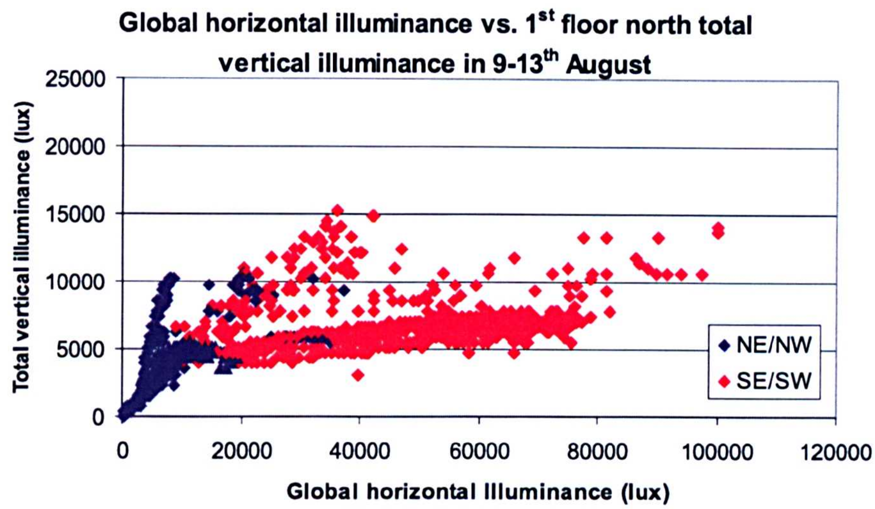
This section presents four sets of measurements obtained in urban canyons in Lisbon. Global horizontal illuminance is plotted against the vertical illuminance and results are discussed.

### 4.3.1 North orientation

In August a building facing north will have direct sunlight in early and late hours of the day, around 7:00 till 9:00 am and 18:30 till 20:30, if the sun is not obstructed by facing buildings. During the rest of the day, it will rely on reflected sunlight from obstructions and ground.

The first set of measurements was made in an urban canyon between 9$^{th}$ and 13$^{th}$ August 2000. The measurements were taken at the 1$^{st}$ and 5$^{th}$ floor of a building facing north. Fig. 4.4 presents the global horizontal illuminance versus north total vertical illuminance at the first and fifth floor window level for that period.

Two possible scenarios may be distinguished: - the sun is in the northern half of the sky hemisphere, its azimuth is in $NE$ or $NW$ quadrants (see fig. 4.5) and if not obstructed is incident at the facade; - the sun is in the southern half hemisphere, its azimuth is in $SE$ or $SW$ quadrants and the building illuminance will rely on reflected sunlight from the obstruction and ground. Observations of the latter set of results shows an overall trend which is approximately linear. However, some observations in the $SE/SW$ set tend to deviate from this linear trend. Furthermore, some of



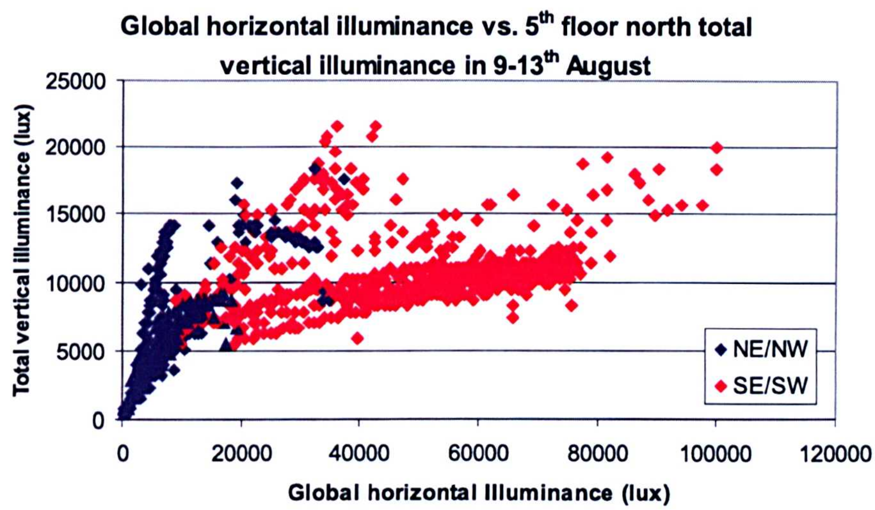




Figure 4.4: Global horizontal illuminance versus north total vertical illuminance between 9th and 13th August 2000. Readings taken at first and fifth floor window level of a building in an urban canyon.

these readings tend to be in the range of the *NE/NW*. Unusual observations can be a consequence of the sun being covered by clouds and of the way they reflected the light.

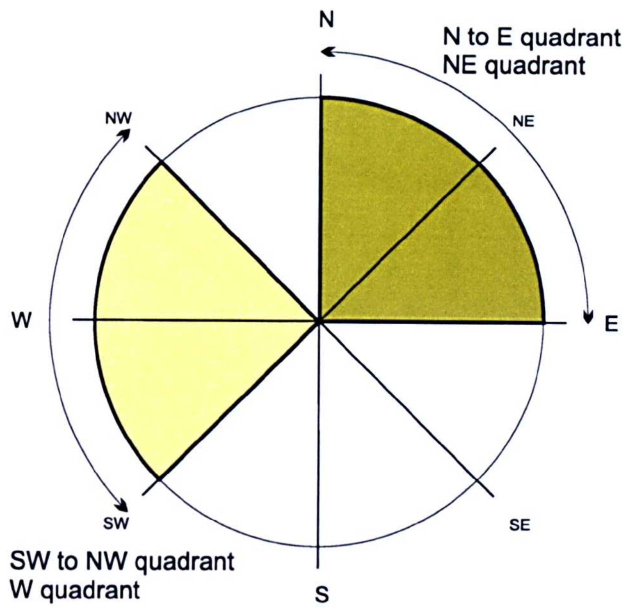



Figure 4.5: Scheme for the quadrant's orientation.

Fig. 4.6 shows the horizontal illuminance over time. The readings for the last two days in the period are for intermediate skies. However, from these readings it is difficult to address patterns of clouds distribution in the sky and consequently the way they affect light reaching the facade and the unobstructed ground.

The linear trend presented in fig. 4.4 when there is no sunlight incident on the facade, defines a relationship between the global horizontal illuminance, $E_{gh}$, and the total vertical illuminance, $E_{tv}$, at the first and top floor on the facade. It can be expressed as

$$E_{tv} = k \cdot E_{gh} + C \tag{4.1}$$

where $k$ and $C$ are constants.

Fig. 4.7 presents the global horizontal illuminance versus the vertical illuminance with the sun's azimuth in the *NE*, *SE*, *SW* and *NW* quadrants for two clear sky days. It shows a linear relationship between the global horizontal illuminance and the north facing vertical when sunlight is not incident on the facade (sun's azimuth in the *SE* and *SW* quadrant). The regression lines represent a coefficient of determination, $R^2$ (R-squared)[3], of 0.64 and 0.74 for the first and fifth floor equations, respectively.

[3]The R-square value, also known as the coefficient of determination is an indicator that ranges between 0 and 1 and reveals how closely the estimated values for the trendline correspond to the actual data. A trendline is most reliable when R-square is at or near 1.

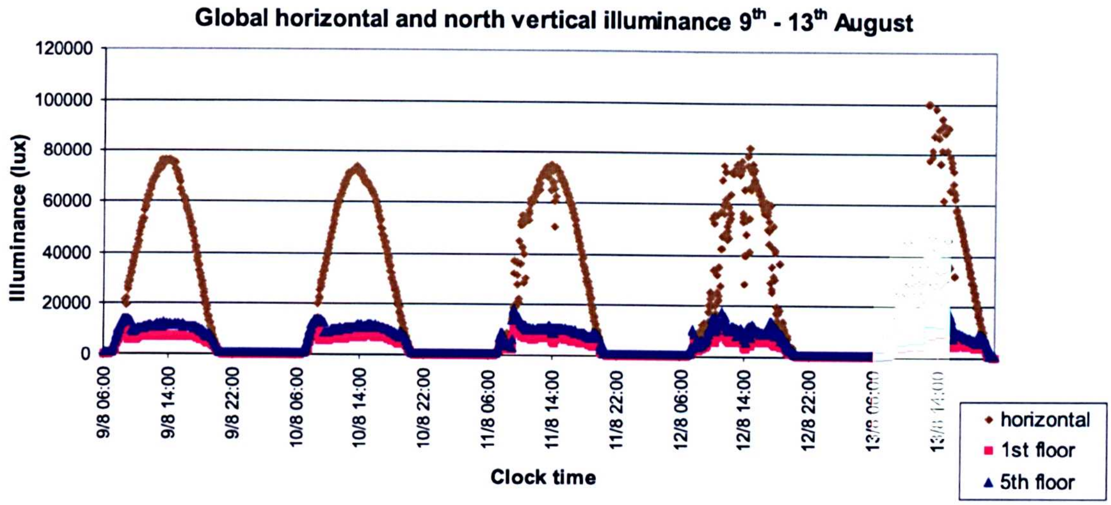



Figure 4.6: Global horizontal illuminance and 1st and 5th floor north total vertical illuminance between 9th and 13th August 2000.

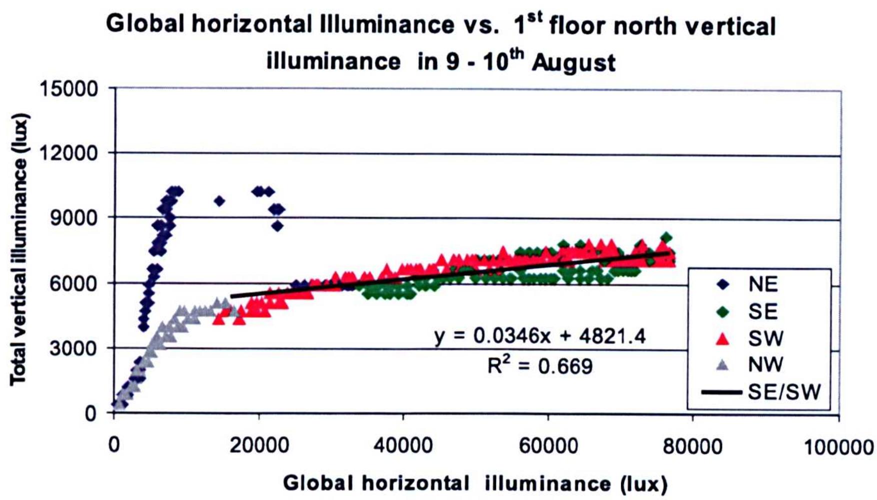
They are statistically significant at the 1% level as P-value[4] is less than 0.01 for each regression analysis.

Because the building is off the *E-W* axis by 5°, the sun can be incident on the north facade when its azimuth is between sunrise and 95° and between 275° and sunset. Therefore, observations occurring when the sun azimuth is between 90° and 95° were considered in the *NE* quadrant. Conversely, when the sun azimuth is between 270° and 275° data was assumed to be in the *SW* quadrant, as the sun is still behind the building. See fig. 4.8.

Besides the longer period of solar access when the sun's azimuth is in *NE* to *E* (early morning) than when it is in *W* to *NW* (late afternoon period) direction, a different facade illuminance is expected. This is a result of different sun angles of incidence. With the building's normal deviated 5° east of north, the sun's angle of incidence on the facade will be smaller for azimuth *NE* compared to a *NW* azimuth. The illuminance on the facade is dependent on the cosine of the angle of incidence. For the same solar intensity, the narrower the angle of incidence the higher will be the illuminance on the facade. Therefore, a solar azimuth angle of *NE-E* will create a higher illuminance in the facade than the *W-NW* azimuths. See fig. 4.9

Given a global horizontal illuminance (in fig. 4.7), higher illuminance values on the facade are obtained when the sun's azimuth is in the *SW* compared to when it is in the *SE*. This confirms the contribution of reflected sunlight. As before, due to the orientation of the building, the angle of incidence on the obstruction is smaller for south-westerly solar azimuths compared to south-easterly ones. This results in higher illuminance on the obstruction and consequently on the facade for solar

[4]P-value show the level at which the association is significant.



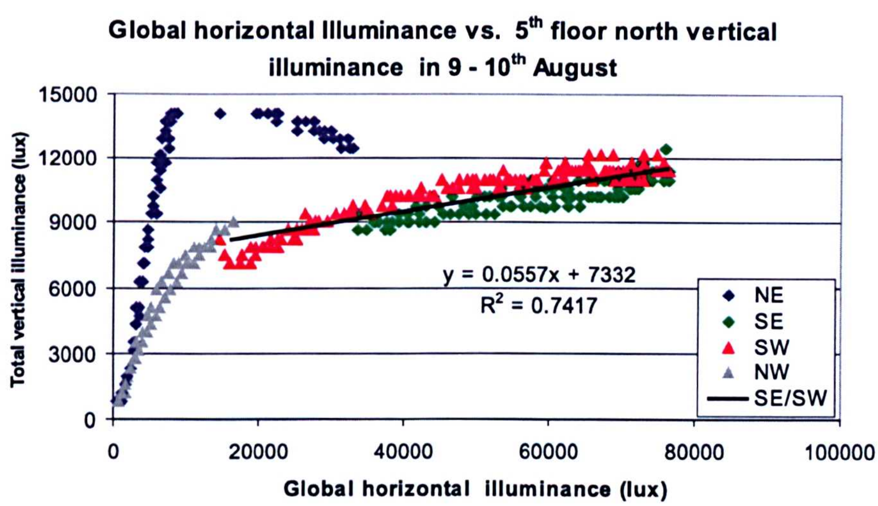




Figure 4.7: Relationship between the total vertical illuminance on the first and fifth floor windows of a building facing north to the global horizontal illuminance for the period of $9^{th}$ and $10^{th}$ August 2000.

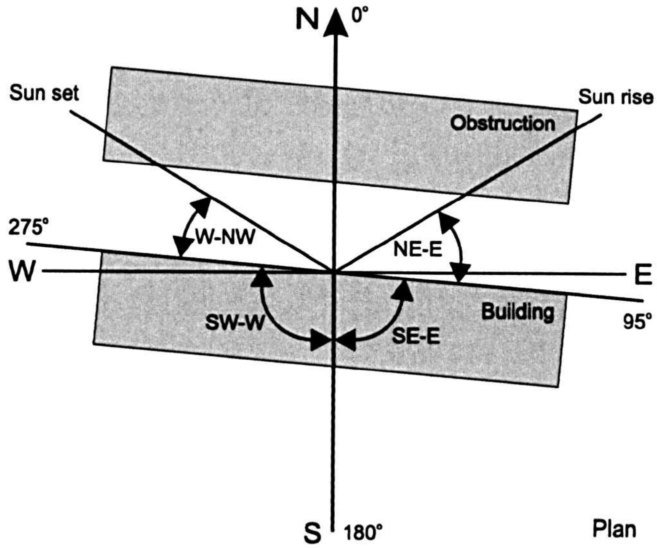



Figure 4.8: Plan of an urban canyon with central axis deviated 5° from E-W, defining different orientation angles when the sun is in front or behind the building. Sunrise and sunset angles for the summer solstice.

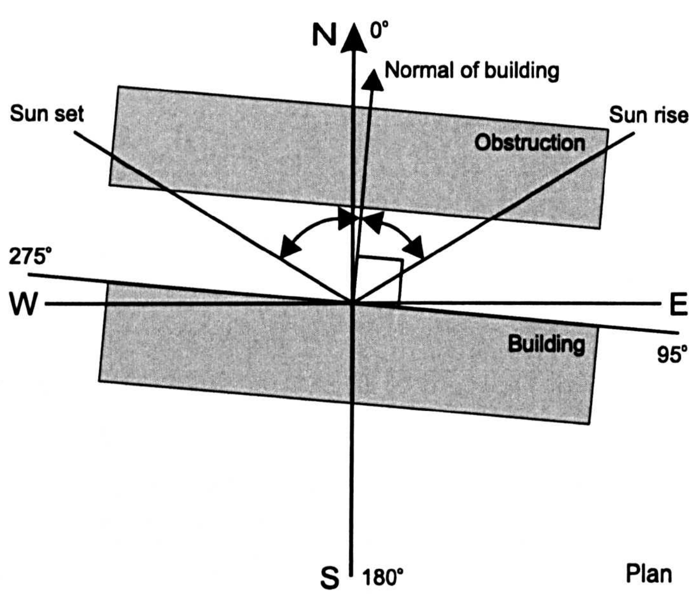



Figure 4.9: Projection of the angle of incidence in the horizontal plane when sun's azimuth is *NE* and *NW* and a building's normal is deviated 5° east from the north direction. Given the same solar altitude for those two azimuths the angle of incidence is directly proportional to the HSA.

azimuths in the $SW$ than in the $SE$. See fig. 4.10. With no obstruction, or one with a reduced reflectance, a facade illuminance would be expected that is lower for $SW$ solar azimuths than it is for $SE$ azimuths. As the illuminance on a facade is cosine dependent, the smaller the angle to its normal the higher is the resulting illuminance. Therefore areas frontal to the building have the highest influence on the illuminance on the facade. As the darkest part of a clear sky is opposite in azimuth to the sun's position, when the sun's azimuth is in the $SW$ this spot is close to the area of higher influence. See fig. 4.11. When the sun's azimuth is in the $SE$ the darkest spot will be further away from this area. Therefore the area frontal to the building will be less bright when the sun's azimuth is $SW$ rather than $SE$ resulting in a lower illuminance in the facade for the former than the latter solar azimuths.

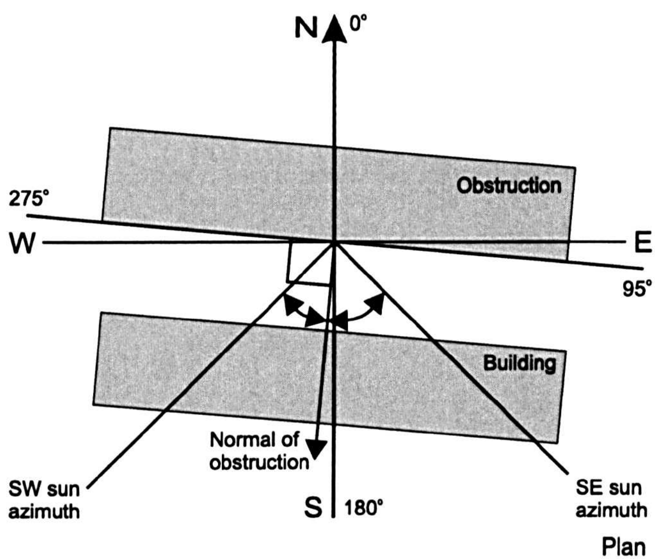



Figure 4.10: Horizontal shadow angles for $SE$ and $SW$ sun's azimuth and a building's normal deviated 5° east from the north direction.

In periods without direct sunlight on the facade, at the top floor of a building a large contribution to daylight is due to the direct contribution of the sky, as the vertical angle of visible sky is wider. On the lower floors this contribution is reduced, due to a much reduced vertical angle of sky. See fig. 4.12. Conversely, the contribution of reflected light from the ground is much reduced at the top floor compared to lower floors as it is further away. However, as the luminance of the ground (except with direct sunlight) is significantly lower than that of the sky, the contribution from below will not be as high as the one from above.

In this urban canyon, in August, when sunlight is not incident, the illuminance at the top floor is on average around 50% higher than at the 1$^{st}$ floor.

An intermediate sky was predominant during the last two days of the recording period (12$^{th}$ and 13$^{th}$ August), see fig. 4.6. However, for the last afternoon of this

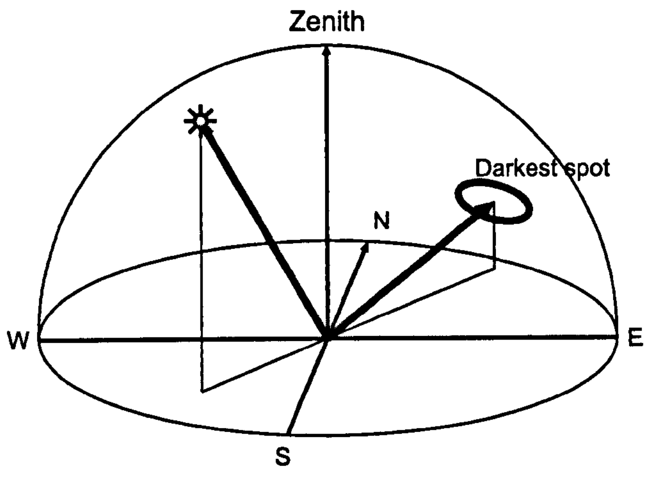



Figure 4.11: Clear sky less bright area opposite in azimuth to sun's position in around a 90° angle.

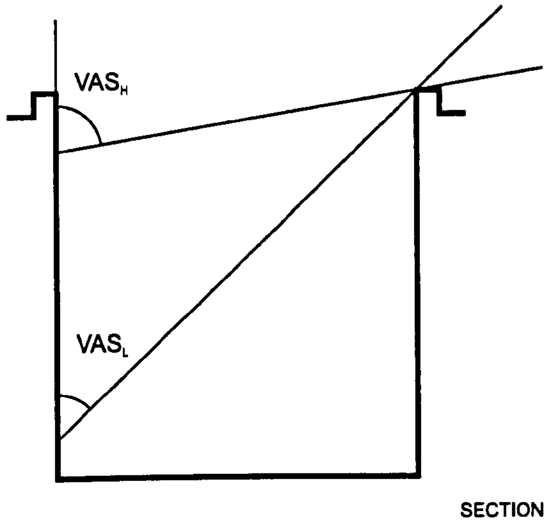



Figure 4.12: Vertical angle of sky in an urban canyon.

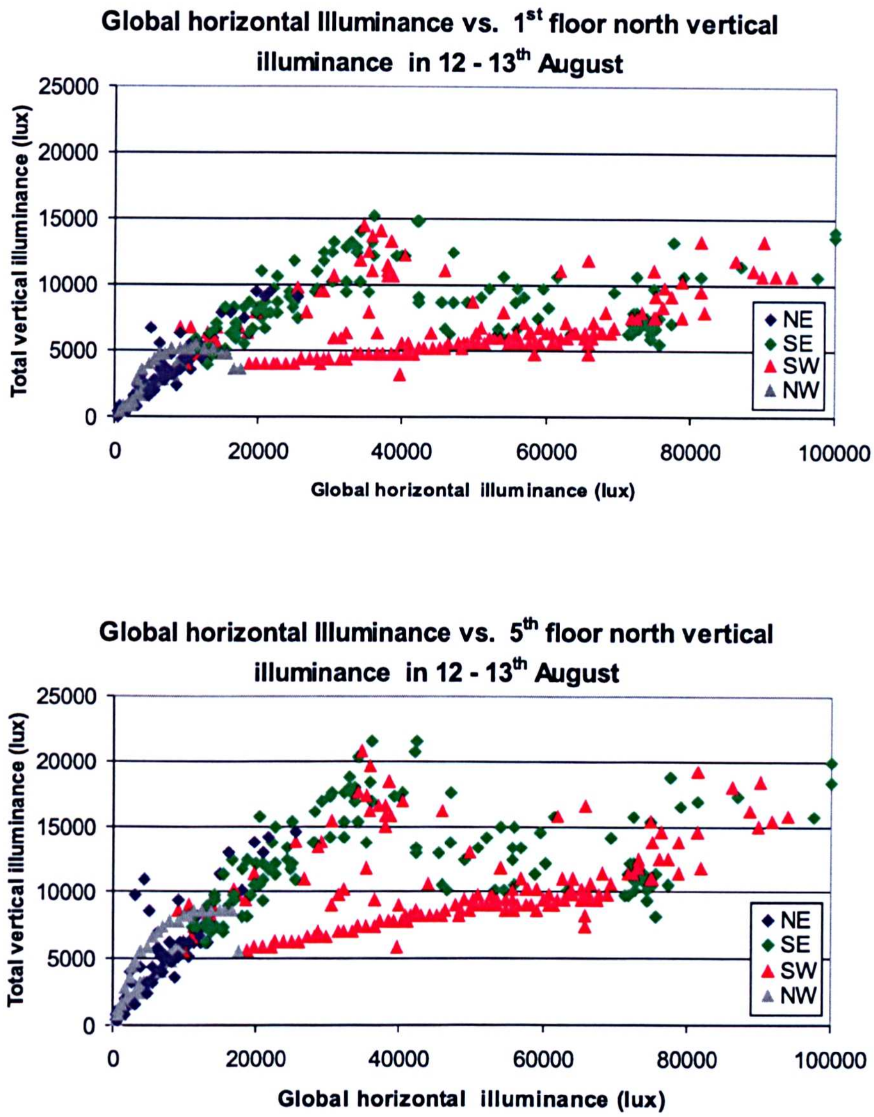



Figure 4.13: Relation between the total vertical illuminance on the first and fifth floor windows of a building facing north, to the global horizontal illuminance for the period of $12^{th}$ and $13^{th}$ August 2000.

period the sky distribution can be considered clear.

Fig. 4.13 presents the global horizontal illuminance plotted against the north total vertical illuminance at the first and fifth floor on those two days. There is clearly a linear relationship between the global horizontal and total vertical illuminance when the sun is behind the building and its azimuth is in the *SW* quadrant.

However, when the sun's azimuth is in the *SE* the observations tend to deviate from this linear trend and define another linear relationship with a different slope. If the measurements taken for that sun azimuth in the *SW* quadrant occurred on a mainly clear sky, those in the *SE* happened when the sky contained clouds.

If a linear relationship, in the range of *SW* values, can be defined for clear skies (reflected sunlight), a relationship for the remaining observations could be classified for intermediate skies. These results suggest that the intermediate linear relationship is in the same trend when the sun is in front (*NE*) or behind the building (*SE*). These situations could be a result of the sun being covered by clouds and the way these disperse the light. However, it is difficult to predict whether the sun is covered by clouds. Moreover, clouds in the sky can obstruct or reflect light to a greater or lesser degree, depending on their distribution, altitude and thickness. As an example, high clouds let through more light than low ones, see fig. 4.14, clouds with low aerosol[5] concentration allow more of the sunlight to pass through, whereas high concentrations can reflect up to 90% of visible radiation back into space. (webpage, 2004b) Therefore for the relationship that emerged for intermediate skies to be statistically significant would require a larger number of observations. This goes beyond the scope of the measurements obtained in this research.

Although the luminance of a clear sky still depends on the turbidity of the atmosphere, which may vary significantly, results obtained for a clear sky distribution can be predicted more easily, as the sun, being the main source of light, is uncovered, and its geometrical position is analytically known.

The third set of recordings made for the same location between 29$^{th}$ December 2000 and 2$^{nd}$ January 2001 showed a partially cloudy sky. See fig. 4.15.

The illuminance on a surface can vary significantly over a partially cloudy day. Similarly to the results obtained on 12$^{th}$ and 13$^{th}$ August, a linear relationship exists between the global horizontal and the total vertical illuminance for the period of 29$^{th}$ December 2000 till 2$^{nd}$ January 2001. See fig. 4.16.

A correlation analysis shows an acceptable fit between the predicted values and the real ones, with values for $R^2$ of 0.82 for the first floor and 0.85 for the fifth floor. Both lines show a clear relationship between total vertical illuminance and global horizontal illuminance, with very small P- values. However, the distribution

[5] Aerosols are tiny particles suspended in the air. i.e. volcanic dust, sea spray or pollution. They range in size from about $10^{-3}\mu m$ to 20 $\mu m$. They help cloud form by serving as nucleus where water droplets are formed.

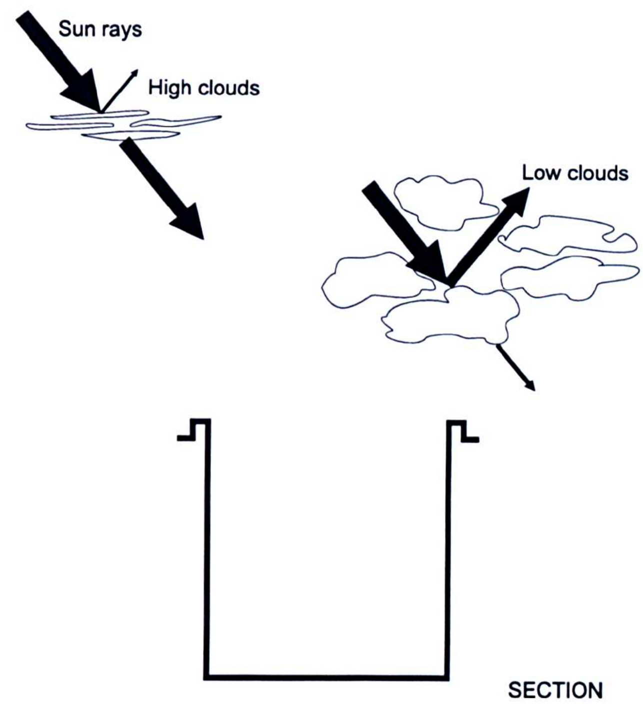



Figure 4.14: Different type of clouds can reflect or let through sunlight in different quantities.

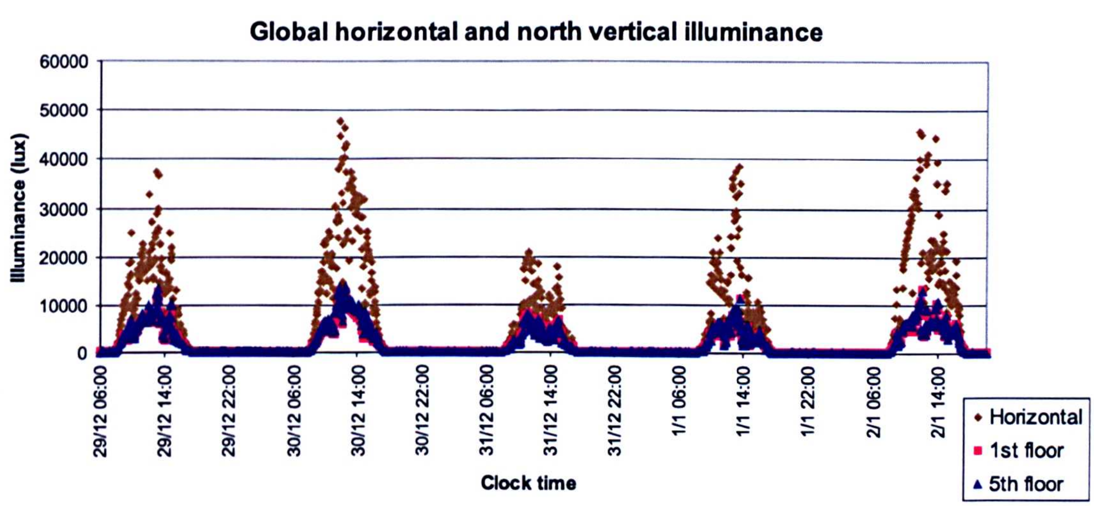
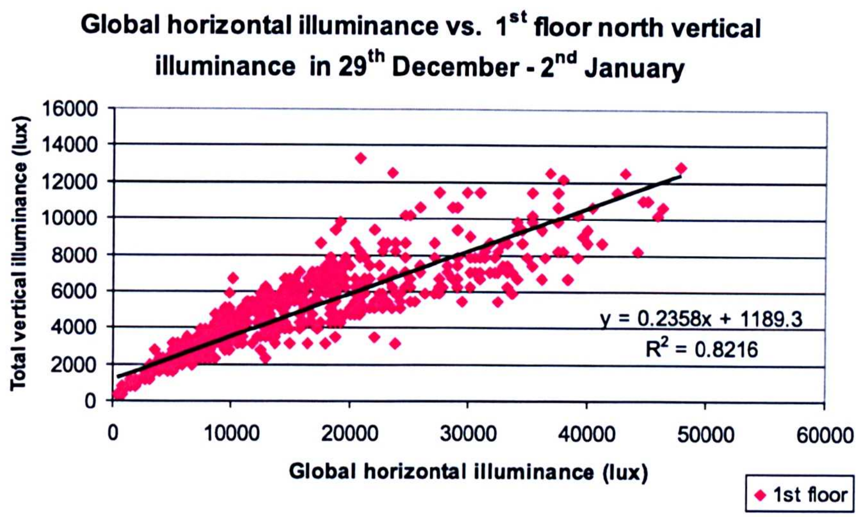



Figure 4.15: Global horizontal and north total vertical illuminance at first and fifth floor between 29th December 2000 and 2nd January 2001.



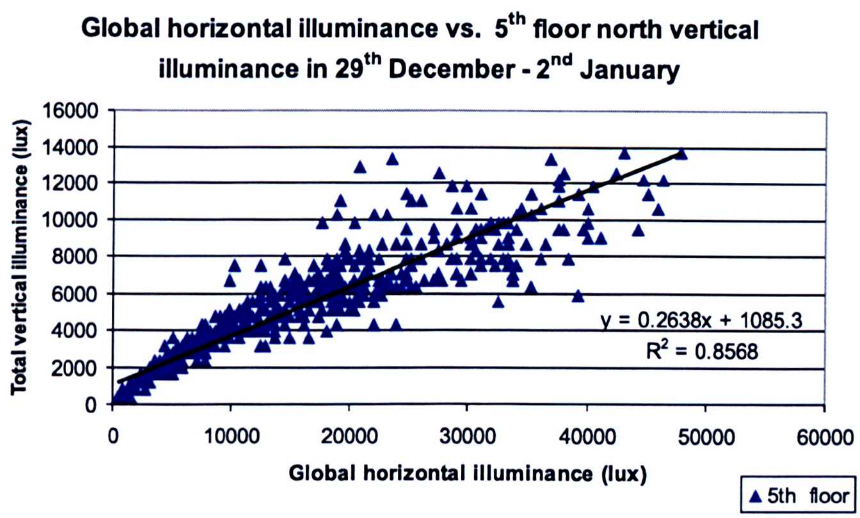
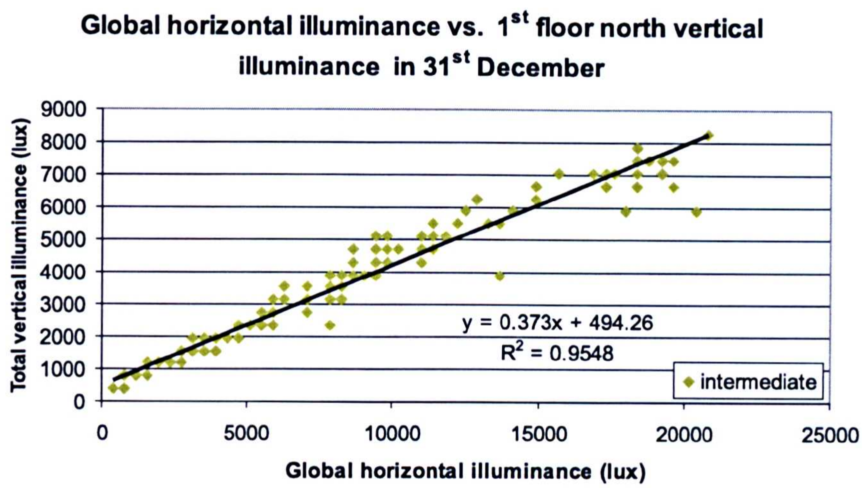




Figure 4.16: Global horizontal illuminance versus 1st and 5th floor north total vertical illuminance between 29th December 2000 and 2nd January 2001.

and thickness of clouds can vary greatly, so more data could be usefully collected to confirm the linear relationship for other conditions.



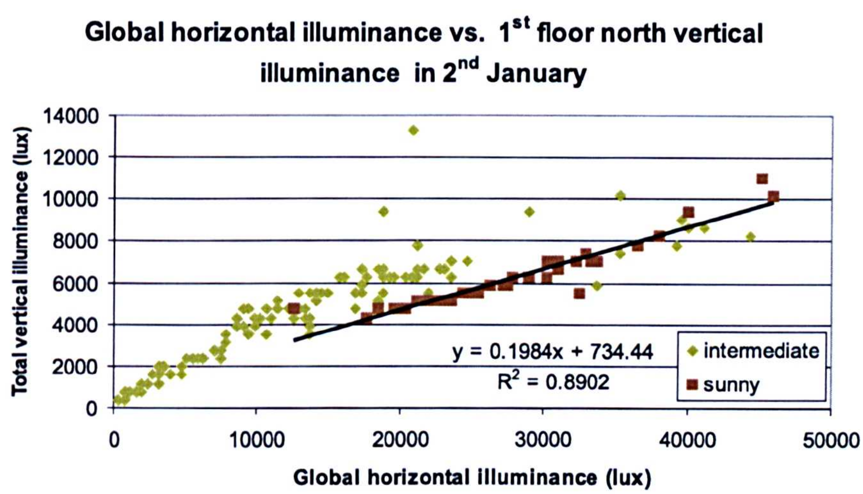
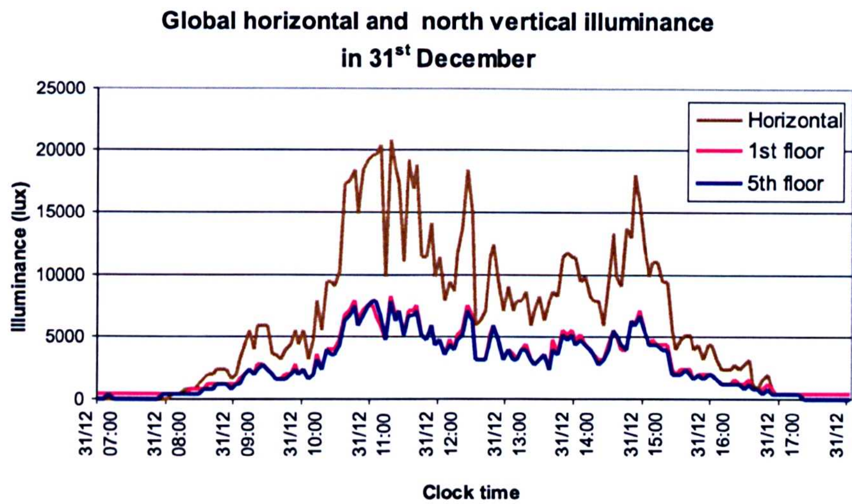




Figure 4.17: Linear relationship between the global horizontal illuminance to the north total vertical illuminance on the first floor window in 31st December 2000 and 2nd January 2001 in Lisbon.

Figure 4.17 shows the linear relationship between the horizontal and vertical illuminance at first floor, with the heaviest cloud cover, 31st December, and for the day with the lightest cloud cover, with a possible clear sky period in the morning of 2nd January. See fig. 4.18 for the global and vertical illuminance distribution over these two days.

The effect of the low resolution of the instrument's A/D converter is clear from the significant number of equal readings, particularly for lower values.

In the northern hemisphere, a building oriented north never receives direct sunlight in the facade in December. However, on a clear day, its illuminance can be



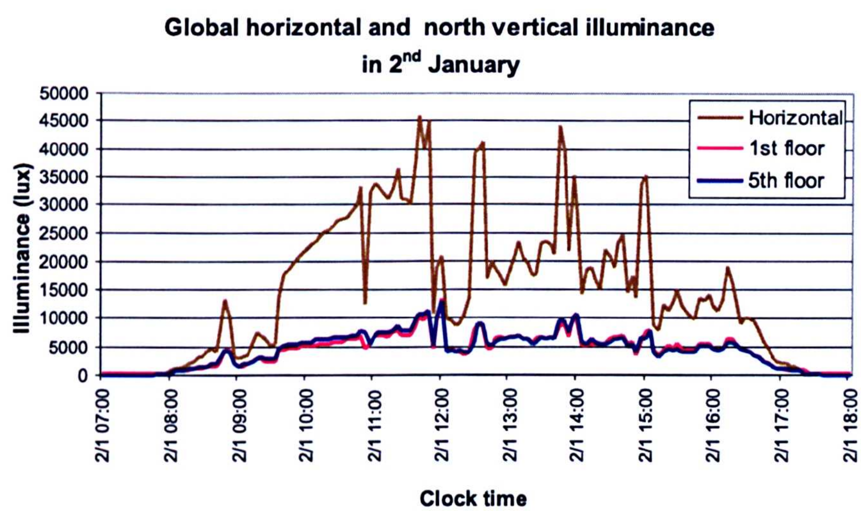




Figure 4.18: Global horizontal and north total vertical illuminance on first and fifth floor height in 31st December 2000 and 2nd January 2001 in Lisbon.

strongly increased by reflected sunlight, mainly from the obstruction. At this time of the year the low solar angles (in European latitudes) will favour light reaching vertical surfaces. The ground contribution will be reduced, as the geometry of the canyon is likely to prohibit sun access to the ground. Also as the sun altitude is low the vertical component of the light will be minimum. See fig. 4.19.

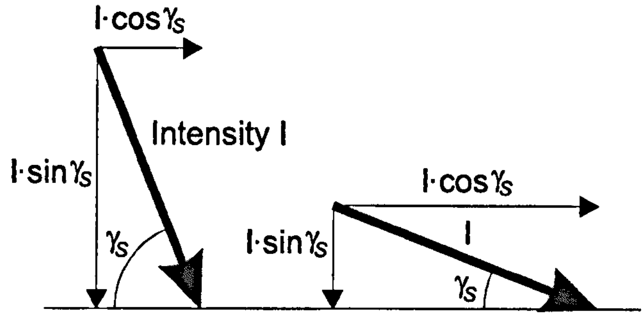



Figure 4.19: Horizontal and vertical vectorial components for different altitude angles.

On an intermediate day the sky component can be the main contribution to daylight in the facade, particularly if bright clouds, are in the visible angle of the sky.

Reduced differences between the 1st and 5th floor vertical illuminance during a cloudy period can be explained by bright clouds being visible on both floors. As sunlight reflected by these clouds can be the major contribution to daylight, there will be no significant difference on the various floors. Although the top floors see a wider angle of the sky, if the brighter patches are visible on both floors there will be no significant difference in the illuminance of the facade at different heights.

On 2nd January, there are two distinct sets of data. Both demonstrate a linear relationship between the global horizontal and vertical illuminance, but with different trends. The first one is a result of observations for the period between 9:40 and 11:48 am, considered a relatively clear sky period.

The second set covers the remaining daylight hours period, considered an intermediate sky period. These observations are in the same range as those obtained for the 31st of December.

During the clear sky period, the 5th floor illuminance is on average around 13% higher than the 1st floor illuminance. As the sun altitude angle is low a strong sunlight patch occurs at the top of the obstruction. This bright area in the obstruction is likely to produce more illuminance on the higher floors of the building. Considering a diffuse obstruction, the top floor has a higher illuminance due to the greater flux transfer between the sun patch and the 5th than there is for the 1st floor. The top floor has a small angle to the normal of the sun patch, therefore a higher cosine value than the lower floor and a higher illuminance. Also higher floors can benefit from the brighter band around the horizon of a clear sky.

### 4.3.2 South orientation

During the summer, a south facing facade will mainly be illuminated by direct sunlight incident on the facade. However, during early and late periods of the day, the sun azimuth promotes direct sunlight on the obstruction, then the building relies more on reflected sunlight.

Fig. 4.20 presents measurements of global horizontal illuminance and total vertical illuminance at a first floor south oriented facade collected during the 23rd August 2000.

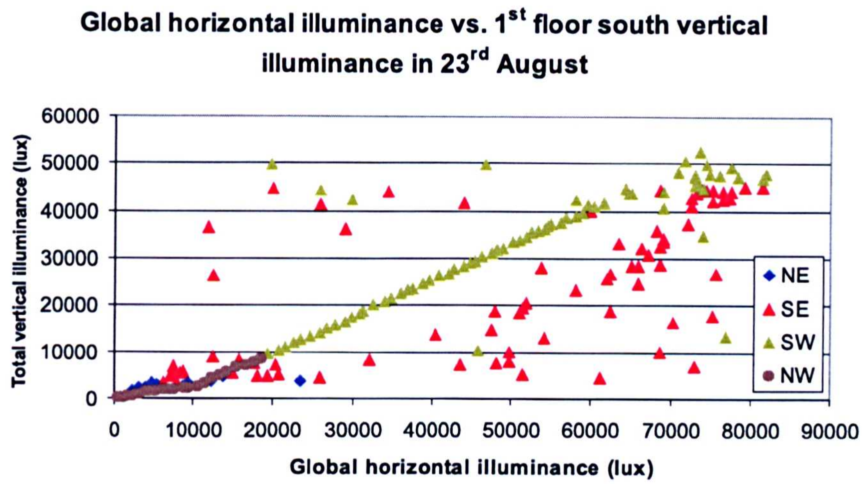



Figure 4.20: Relationship between the global horizontal illuminance and the total vertical illuminance on the first floor window of a south building facing an obstruction for real measurements collected on 23rd August 2000.

Clearly, for the time when the facade is receiving direct sunlight, a linear relation is confirmed for southwest (*SW*). However, for the period when the sun azimuth is southeast it is difficult to find that relationship. That fact could be explained by the different locations of the instruments for collection of the horizontal and vertical measurements. Although the instruments were not too far apart, and they were synchronised for readings every four minutes, under a sky with clouds, as shown in fig. 4.21 with the consequent sudden variations of the horizontal illuminance, the results can be different from one location to another.

Fig. 4.22 show the unobstructed horizontal illuminance against the total vertical illuminance for the early and late hours in the day when the south facade is not receiving direct sunlight, i.e. when the solar azimuth is in the *NE* and *NW* quadrants. It represents the illuminance on the facade due to reflected sunlight from a recently painted (high reflectance) and an old (low reflectance) obstruction.

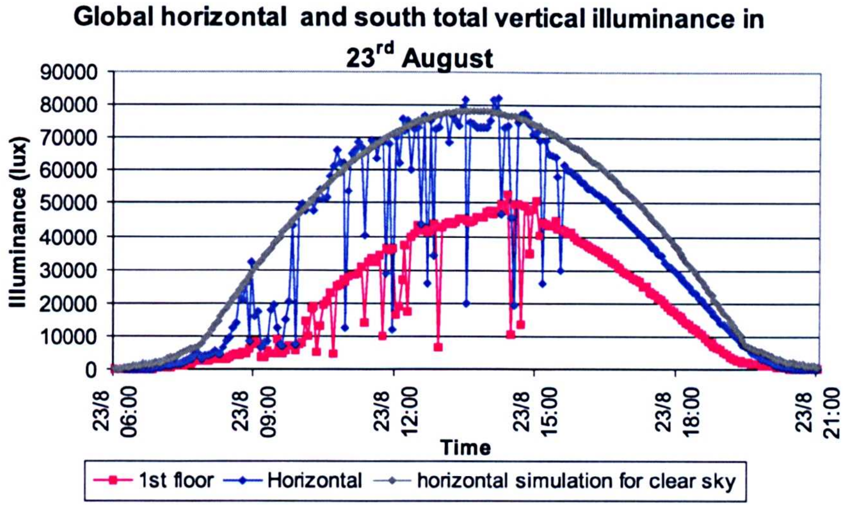



Figure 4.21: Plot of the total vertical illuminance on the first floor south window and the global horizontal illuminance for real measurements, as well as simulated with Radiance for a clear sky with the sun component over the period of a day in 23rd August 2000.

Some discrepancy in the values of the linear relation between the horizontal and the vertical illuminance can be a result of the horizontal readings having been taken under different cloud conditions and to the building and the obstruction not being a perfectly flat surface in regard to windows reveals, setbacks and balconies.

The sun is incident on the obstruction in early and late periods of the day. These correspond to low sun altitude angles, therefore the flux that reaches the vertical surface may be high.

The illuminance due to the high reflectance obstruction is on average 24% higher than the one due to the low reflectance obstruction.

### 4.3.3 East orientation

A building oriented east will have a period in the morning when sunlight will be incident on the facade if the sun is not covered by the obstruction. Although the sun altitude can be low, the resulting illuminance in the vertical facade can be high, due to a strong horizontal component (see fig. 4.19 on page 85). Also, as the sun can be frontal to the building (reduced HSA[6] and high cosine) its contribution can be higher.

In the afternoon the sun will be behind the building and its illuminance will depend on reflected sunlight from the obstruction and ground. Similarly, the illuminance on the obstruction can be high due to lower sun altitude angles late in the afternoon. The illuminance in the building due to light reflected from the obstruc-

[6]HSA is the horizontal angle between the sun's azimuth and the azimuth of the normal of the building.

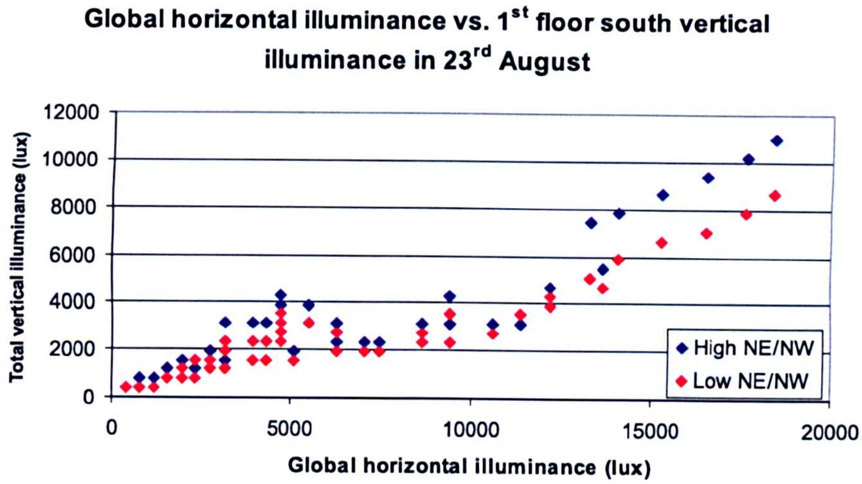



Figure 4.22: Global horizontal versus vertical illuminance in a building facing a high (recently painted) and low reflectance obstruction in 23rd August 2000.

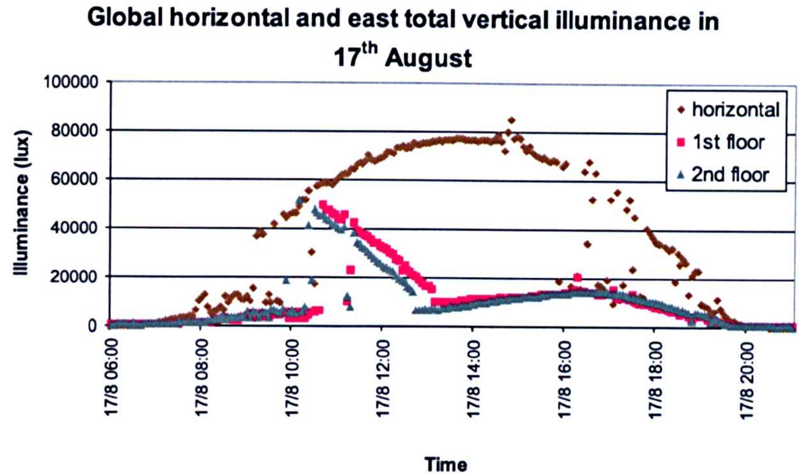
tion will depend on the reflectance of the obstruction and the position of the sun patch in regards to the point in the building.

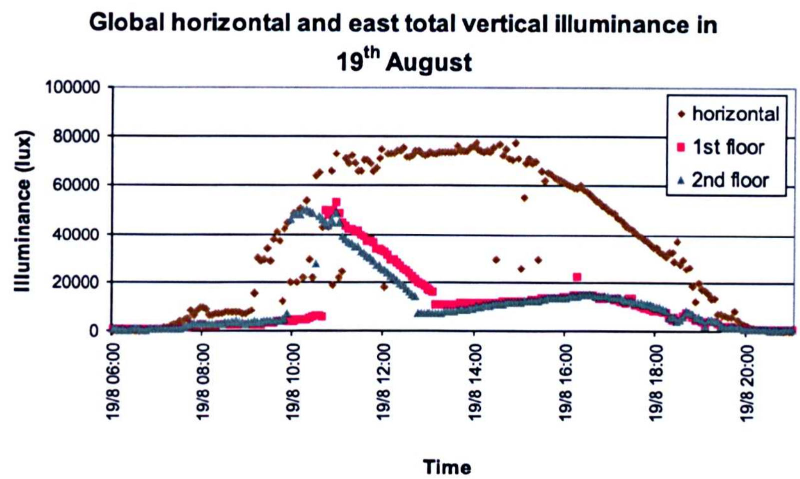
However, reflected sunlight from the ground can also be a significant contribution to the illumination of the building, particularly around midday as the the sun altitude is highest and the ground can be fully sunlit (solar azimuth is the same direction as the axis of the canyon).

Measurements taken on the first and second floor of an east facing building between 17th and 21st August 2001 are a good example of the contribution of reflected light from the obstruction and ground towards the illuminance of the building.

The sun is in the eastern half of the sky hemisphere in the morning, therefore in front of the building. In the early hours, the sun altitude is low and the obstruction is sufficiently high to obstruct direct sunlight to both floors. Understandably the second floor starts receiving sunlight earlier than the lower floor. Fig. 4.23 shows a period around 10 am until 1 pm for 17th and 19th August where there is direct sunlight on the facade. However, the first floor shows higher illuminance than the second, probably due to reflected sunlight from the ground. The illuminance in the lower floors can be high due to their proximity to the source (sun patch on the ground). In that period the illuminance in the first floor is at least 10% higher than that in the second floor, but it can be as much as 50% higher. These differences are due to the ground contribution contributing more to the overall illuminance on the facade when the ground is more widely sunlit and the direct component from the sun is reduced for larger angles of incidence.

However, the contribution from the ground to the illuminance of the building will depend on the reflectance of the surface. It can be significantly enhanced by a



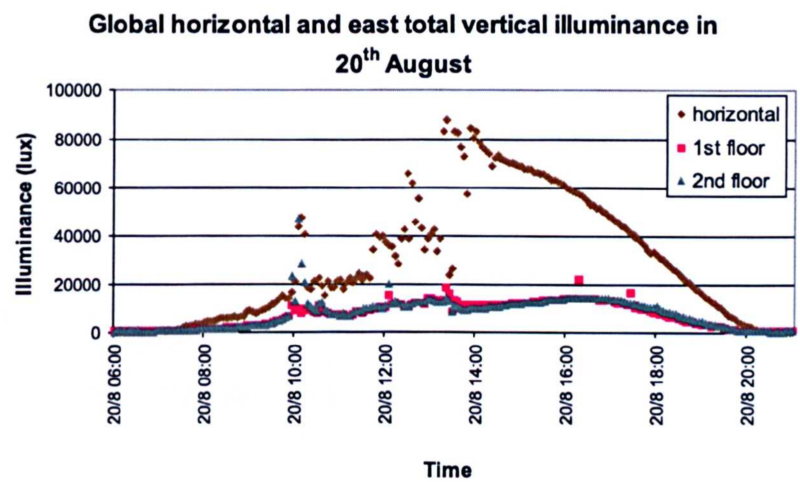
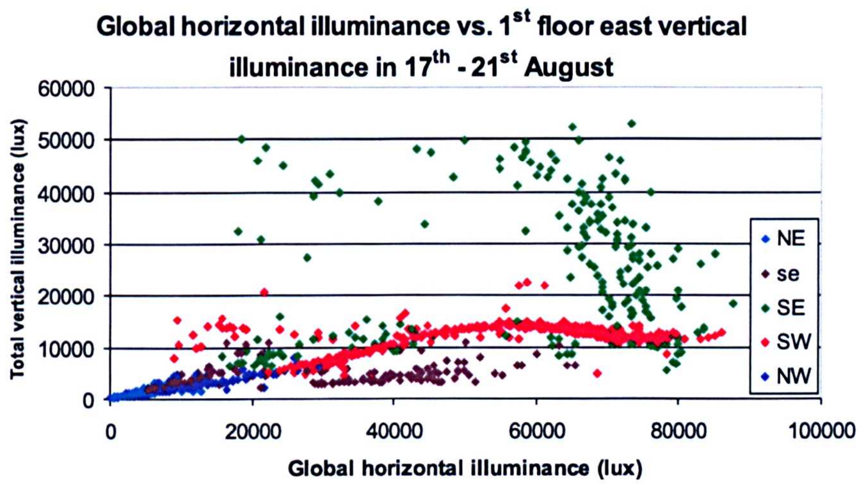




Figure 4.23: Global horizontal and east total vertical illuminance in first and second floor in 17th, 19th and 20th August 2001 in Lisbon.

highly reflective ground. This is the case for this particular canyon, which has the typical pedestrian limestone floor, see fig. 4.2 on page 70. Also, it depends on the position and size of the sun patch with respect to the building. In the morning, the sunlit ground is closer to the building, therefore it will have more influence. In the afternoon, it is closer to the obstruction, and further away from the building, therefore its contribution to the illuminance of the building is less significant.

Fig. 4.23 on the page before also shows a period when reflected light from the obstruction contributes to the illuminance of the building. This is clearly shown in the hourly graphs for the period between around 2 pm and 5 pm, where the sun is behind the building (no direct sunlight). During this period the horizontal illuminance is decreasing and there is an increase in the illuminance on the building.



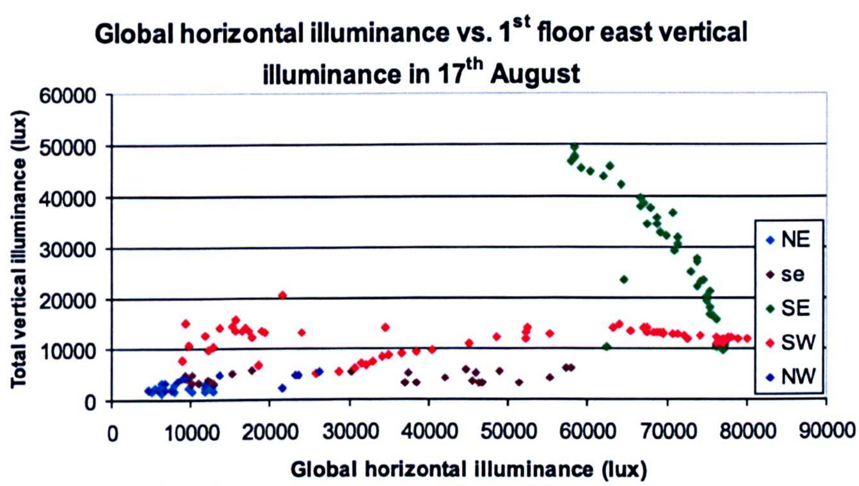




Figure 4.24: Global horizontal versus east total vertical illuminance in $17^{th}$ till $21^{st}$ August 2001.

Fig. 4.24 presents the global horizontal illuminance versus the east total vertical illuminance for different solar azimuths. There are two distinctive results when the sun is in the eastern side: - sunlight is incident in the facade (*SE*); - sunlight is blocked by the obstructions (*se*).

A comparison between the illuminance on the facade for symmetrical solar azimuths, in *se* (between 90 and 110°) and *SW* (between 250 and 270°) for the same horizontal illuminance, between 30 000 and 50 000 lx, confirms the contribution of reflected sunlight in the latter azimuths. For the same sun altitude, similar intensity and angle of incidence, higher illuminance in the afternoon periods (azimuth *SW*) is due to a bright sun patch on the obstruction that reflects light into the building. In the morning period (azimuth *se*) the contribution of sunlight to the illuminance on the facade will be reduced, as at least two interreflections in the canyon take place before the light reaches the facade.

Fig. 4.25 represent results for illuminance on the facade for *SW* and *NW* sun azimuths in Lisbon. These are periods when there is no direct sunlight incident on the building. The linear relationship between the horizontal and vertical illuminance is initially positive but then changes to a negative value. This feature may be related to some reveal at the obstruction or the angle of incidence of the sunlight on the obstruction.

High horizontal illuminance corresponds to high solar altitudes. This occurs around 1pm when the sun's azimuth is near south (northern hemisphere). The flux reaching the obstruction is small due to the high sun altitude and high HSA. The ground near the obstruction may be sunlit, but the configuration factor between a distant sun patch on the ground and a point in the facade is reduced. Towards sunset the solar altitude angle reduces, as does the HSA in the obstruction, until the sun is due west, increasing again until sunset. This results in an increase of illuminance in the obstruction and consequently in the building, while the horizontal illuminance is reducing. Hence the negative slope in the graph.

There is a time when the angle of incidence will be a minimum, therefore the vertical illuminance will be highest. Towards sunset this angle will increase again, reducing the contribution to the illuminance on the obstruction. As the illuminance in the horizontal plane also reduces, the slope of the graph will be positive.

A sun patch in the obstruction contributes to higher illuminance on the second than on the first floor. Conversely, a sun patch on the ground contributes more to the illuminance in the first than in the second floor. See the graph for 20$^{th}$ August in fig. 4.25. For a global horizontal illuminance of around 20 000 to 40 000 lx the vertical illuminance is higher on the second floor. This corresponds to lower solar altitudes and azimuths around west, therefore greatly affecting the facing vertical surface. The bright sun patch on top of the obstruction will contribute more to the illuminance on higher floors in the building. Higher solar altitudes corresponding to

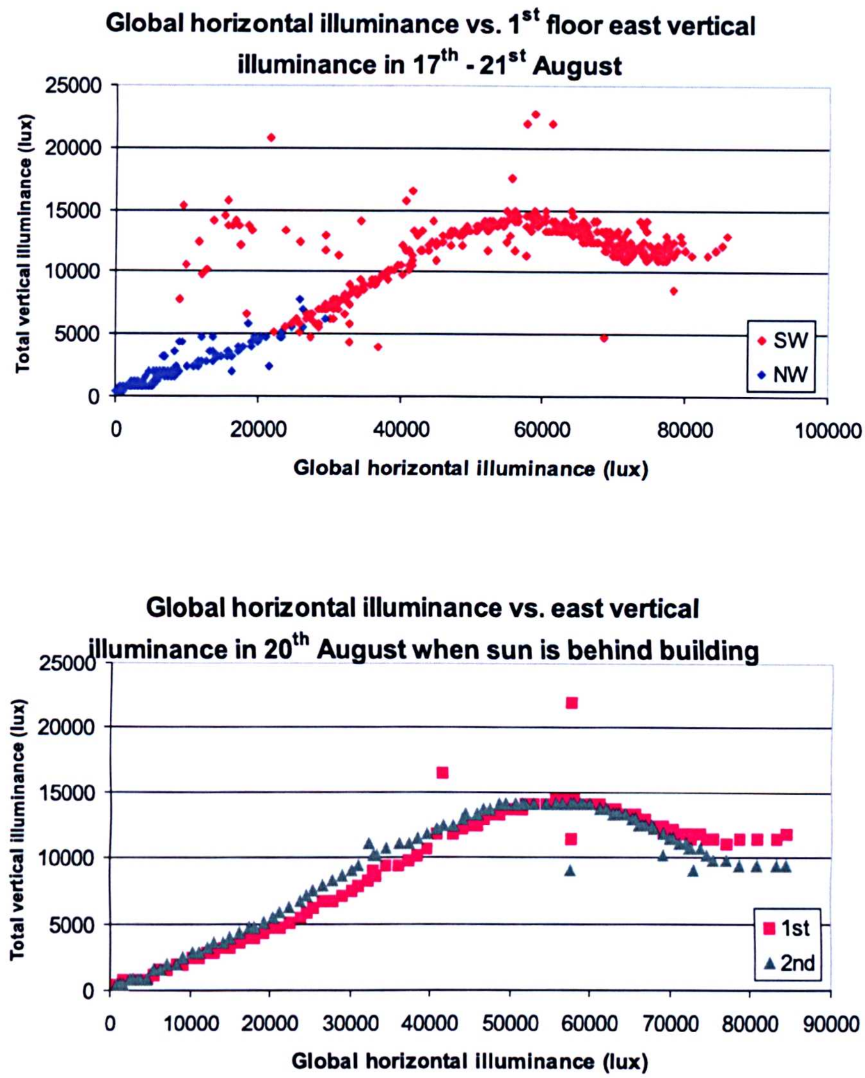



Figure 4.25: Relationship between the global horizontal illuminance and the east total vertical illuminance for the period between 17$^{th}$ and 21$^{st}$ August 2001 when the sun azimuth direction is behind the building.

a horizontal illuminance of around 70 000 lx and higher, may result in bright sun patches on the ground which contributes more to the illuminance on the first than on the second floor.

## 4.4 Conclusions

This survey was limited to a few days. The purpose was not to obtain enough data to develop a statistically sound model but to confirm a hypothesis on the importance of reflected light in the illumination of buildings. Although it was not possible to quantify the contributions from reflected light from buildings or ground, it clearly showed the significance of reflected light for light levels on a facade.

The discovery of a simple relationship between the global horizontal and the total vertical illuminance is an interesting result and should give the basis for further studies with other methods to explore the validity of that relationship.

The difficulties of obtaining accurate readings in an urban canyon emphasise the need for a more extensive data survey, in order to get results with a higher statistic significance for a full year.

# Chapter 5

# Computer simulations and analysis

## 5.1 Introduction

Computer simulations can be powerful tools for daylight analysis. Different scenarios may be modelled by varying parameters of interest for the daylight analysis instead of these being dependent on limitations imposed by the real conditions, namely the weather condition, scene geometry or material characteristics. On the other hand, computer simulations can be of limited accuracy, considering factors such as user input error and model simplifications, program analytical limitations and computation time to perform the calculation. Furthermore, the learning process needed in order to work with simulation programs can be time consuming. Computer simulations should therefore be used sparingly. Sometimes it is better to rely on widely accepted rules, even of reduced accuracy than on potentially unreliable results taken as reliable because they were obtained with a software package that can be accurate. Nowadays, several CAD[1] and lighting system's produce visual renderings of a scene. However, most are just a visual image and not a physically realistic representation of a lit environment. RADIANCE, see section 2.5.5, is widely accepted as one of the few programs that can qualitatively and quantitatively create reliable representations of a scene. Several studies have been produced to confirm its validity and accuracy against real data and other lighting simulation programs (Mardaljevic, 1999; webpage, 2003b; Ubbelohde and Humann, 2003; Altmann and Apian-Bennewitz, 2001).

Taking all this into consideration, it was decided to use RADIANCE to perform the lighting analysis. (webpage, 2000) However, the results are as much as possible questioned and taken as relative, giving a trend rather than an absolute result.

Simulations were performed to extend the reach of the physical measurements to different conditions, define the influence of some variables to the overall result and to extend results to a sample assumed representative of a full year. The simu-

[1]Computer Aid Design

lations allowed for a modification of the canyon geometry, the building orientation and reflectance of surfaces. With RADIANCE it was also possible to look at the separate contributions from the sky, ground and obstruction to the illuminance on the building for overcast and clear skies in Lisbon and in London.

The hypothesis formulating the importance of reflected light in the illuminance of buildings in urban canyons is discussed for overcast and clear skies. Facing buildings act as obstructions, but can also be an important source of reflected light from other parts of the sky. By varying the canyon aspect ratio or the reflectance of the obstruction, the amount of light reaching a point in the facade can be significantly enhanced and may compensate for a reduction in daylight due to the facing obstruction blocking sunlight and skylight access to the building.

Figure 5.1: View of the urban canyon generated with Radiance.

## 5.2 Scene geometry and properties

Initially a daylight analysis was undertaken for an urban canyon with a west-east axis (buildings facing north). The analysis was later extended to south, east and northeast orientations for clear skies.

The geographical coordinates of the location considered in the simulations for Portugal are those of Lisbon: latitude $38.73° N$ and longitude $9.15° W$. For the United Kingdom, the coordinates are those of London: latitude $51.53° N$ and longitude $0.8° W$.

The geometry of the urban canyon considered is a six storey block, 18 m in height, facing an obstruction of the same dimensions, see fig. 5.1. The length of the canyon is 55 m. The width of the canyon is 18.0 m and 34.3 m for the Portuguese and English location respectively. The aspect ratio of the urban canyon was selected according to the 45° or 25° rule in these countries, see sections 2.8.1.3 and 2.8.2.3. The ground was modelled as a horizontal plane enclosing the lower side of the canyon.

The reference points are located outside, at the centre of the facade, in the mid point of the windows (height 1.5, 4.5, 7.5, 10.5, 13.5 and 16.5 m). No window setbacks and reveals were modelled.

The opaque surfaces of building and ground are defined as perfectly diffusing materials, they have uncoloured highlights, no transmission, roughness or specular reflection. Vertical surfaces were defined considering a variation of reflectance, $\rho$, of 0, 0.2, 0.3, 0.5 and 0.7. Very few diffuse materials have a reflectance value grater than 0.8. Also it was assumed that the pollution of the cities and reduced maintenance of the facade paint reduces the reflectance of the surfaces. It is very unlikely for an external surface to have a reflectance of more than 0.7. The ground plane was assumed to have 0.2 reflectance.

The reflectance of transparent materials was calculated using RADIANCE according to different angles of incidence between the surface and the sun. (Ward, 1997; Ward, 1992)

## 5.3 Results for CIE overcast skies

Traditionally, standard daylight calculations are based on overcast skies. In the following daylight analysis, the sky is considered to have an overcast CIE distribution, see section 2.2 on page 8. The main characteristic of this sky distribution is it's relative gradient between the zenith and the horizon with the luminance at the zenith being three times as bright as that at the horizon.

The diffuse horizontal illuminance is a function of the zenith luminance which changes with solar altitude, the horizontal illuminance is different during the day and around the year for the different locations, see figure 5.2. Absolute values of the sky luminance vary with the sun's altitude and therefore with latitude, which also causes different day lengths throughout the year. Lisbon has longer periods of daylight during the winter solstice but London benefits from more daylight hours during the summer season. However, as daylight analyses are usually based on the ratio between indoor and outdoor illuminance, clearly constant for different illuminance as only depends on the same source, the sky, a single horizontal illuminance is sufficient for daylight calculations. Mardaljevic defines a realistic illuminance by a bright overcast sky as 10 000 lx. (Larson and Shakespeare, 1998)

The orientation of the buildings is irrelevant for a CIE overcast sky as its luminance distribution is independent of solar azimuth.

As the CIE overcast distribution is representative of a heavily overcast sky, not

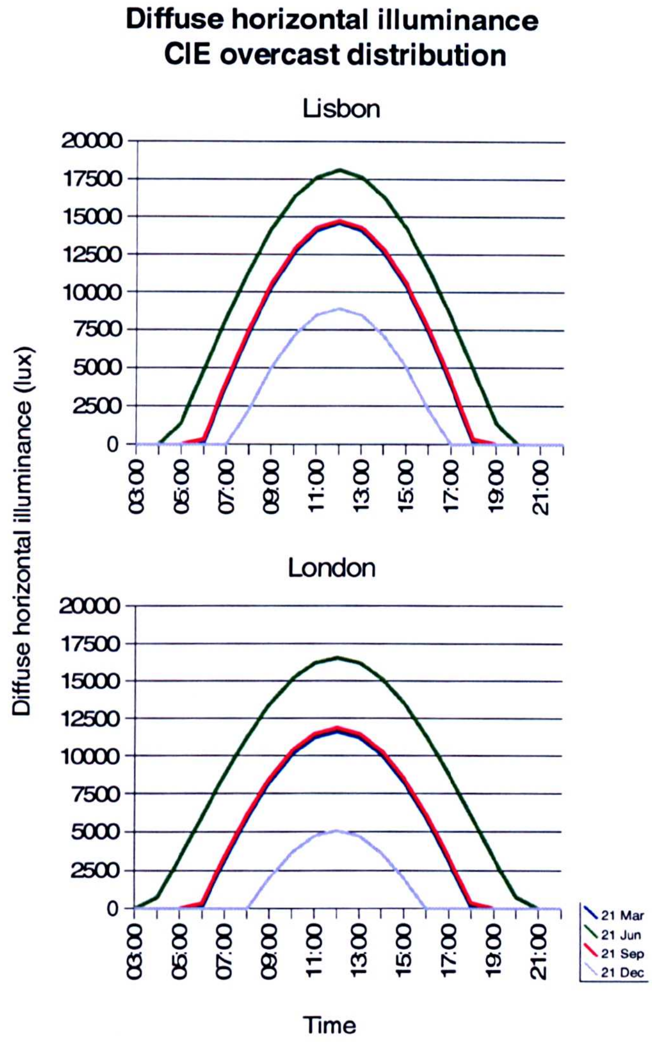



Figure 5.2: Diffuse horizontal illuminance generated by RADIANCE for a CIE overcast distribution for the solstice and equinox days in Lisbon and in London.

always the most frequent condition, orientation factors can be applied to take into consideration different sky luminance for the cardinal points. However, they were not used in these analyses. They are presented in appendix H. (CIBSE, 1999)

Research was undertaken to characterise a more realistic overcast distribution, considering the relative luminance of the sky element not only dependent on the zenith luminance but also on the sun's position and the atmospheric scattering. The CIE has recently defined 2 overcast sky distributions that take into consideration these variables (CIE, 2002). A RADIANCE sky generator for the new CIE model is now available, but came too late for the research presented in this thesis. However, the significant difference between the old CIE overcast distribution and the new one occurs for sky elements near the horizon (angles below 20°), which are obstructed for the lower floors in a canyon. The error between the two distributions for the remaining sky elements is less than 3%. (CIE, 2002)

Under an overcast sky the building illuminance depends on the sky as the primary light source. Three distinct contributions to the amount of light reaching the point of interest on a facade of an urban canyon may be defined:

- direct light from the sky - sky contribution;
- light reflected off the obstruction - obstruction contribution;
- light reflected of the ground - ground contribution.

Six interreflections between the surfaces of the canyon are calculated for the last two cases. (Ward et al., 1988)

At this stage, as the reference points are external, no window area, glass transmittance or interreflections within the internal surfaces of the room have been considered yet.

### 5.3.1 45° rule

This section presents results for a vertical facade in an urban canyon with a 45° obstruction angle[2] to comply with the Portuguese regulation, see section 2.8.1 on page 41.

Fig 5.3 shows the three contributions: sky, ground and obstruction, to the diffuse vertical illuminance at the lowest window in an urban canyon with a 45° angle. Table 5.1 presents those percentages for the several window heights considered. Under an overcast sky the building illuminance will be mainly dependent on the diffuse light direct from the sky. For a canyon with a 1:1 aspect ratio, the minimum

[2]A canyon angle is sometimes defined as the obstruction angle. It is the angle between the horizontal at the reference point and the tilted plane above the height of the obstruction measured at the vertical plane perpendicular to the facade.

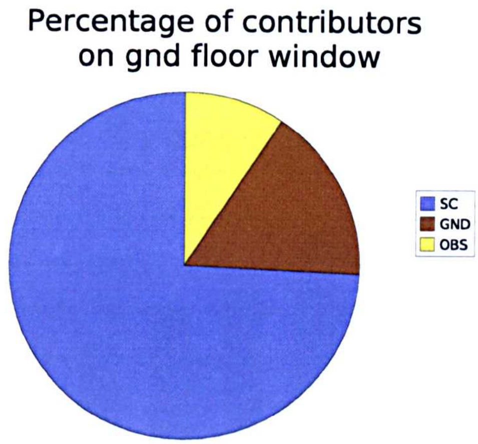



Figure 5.3: Percentage of the sky, ground and obstruction contribution to the diffuse illuminance at the ground floor window of a 45° rule geometry. All surfaces have 0.2 reflectance.

sky contribution will be 75% for the lowest floor, up to 91% in the highest. The ground contribution is higher than the obstruction contribution up to the middle floor height. For the higher floors the latter contribution is higher.

Table 5.1: Percentage of the sky, ground and obstruction contribution to the diffuse vertical illuminance at mid of the window for several floors of a building in an urban canyon with a 45° rule. All surfaces have 0.2 reflectance.

| | sky contribution | ground contribution | obstruction contribution |
|---|---|---|---|
| gnd | 75 | 16 | 9 |
| $1^{st}$ | 78 | 13 | 9 |
| $2^{nd}$ | 81 | 10 | 9 |
| $3^{rd}$ | 85 | 7 | 8 |
| $4^{th}$ | 88 | 5 | 7 |
| $5^{th}$ | 91 | 3 | 6 |

Fig 5.4 on the next page represents the vertical sky, ground and obstruction components at several floors in a 1:1 urban canyon (45° rule). The higher the window, the higher the vertical sky component (section 2.5.3 on page 22). This is due to a larger solid angle of the visible sky hemisphere between the zenith and the horizon. The vertical sky component at the highest window is 38% and on the lowest one 19%. On the top floors the sky component is closer to one occurring on an unobstructed facade.

The illuminance on a vertical surface for an unobstructed overcast sky is equal to the horizontal unobstructed illuminance under the same sky times a constant 0.3955 ($(3\pi + 8)/14\pi$). (Walsh, 1961) The maximum sky component for a vertical surface is therefore 39%.

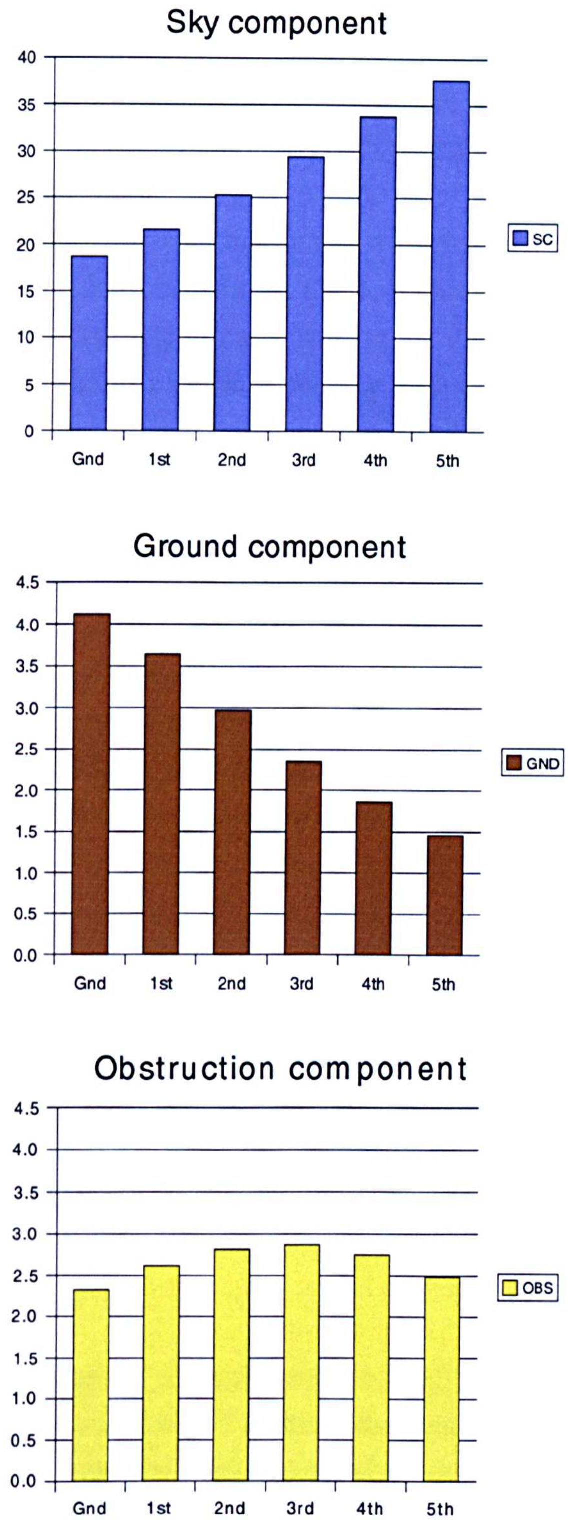



Figure 5.4: Sky, ground and obstruction components at several window heights in a canyon for a 45° rule.

The ground contribution is highest for lower floors. The flux transfer between a ground surface and a lower point in a perpendicular facade is higher than the flux between the same emitter and a more distant point in the same perpendicular. Considering a 'vertical ground component', as the ratio of the illuminance that reaches the centre of the window reflected from the ground to the unobstructed horizontal illuminance, this component varies between 4% on the lowest window to 1.4% on the top window.

The sky component doubles from bottom to top window. The ground component reduces to around a third from bottom to the top window.

The variation of the obstruction contribution for different window heights is far less significant in comparison to those of the sky and ground. The obstruction contribution increases from the ground floor window to the third one. It then decreases for the higher floors.

The highest configuration factor, CF, between the obstruction and the point on the facade occurs at the mid point of the facade. If the luminance of the obstruction was uniform for all floors the highest illuminance on the facade would occur in the middle and it would decrease similarly to bottom and top floor. However, for the overcast sky, the top floor has a higher illuminance than the bottom one, therefore the illuminance at the facade is higher at the top than at the bottom floor.

The 'vertical obstruction component', defined as as the ratio of the illuminance that reaches the centre of the window reflected from the obstruction to the unobstructed horizontal illuminance, is 2% for the first and fifth floor and 3% for the floors in between.

For a canyon with a 1:1 ratio and a reflectance of 0.2 of all the external surfaces, the ground contribution is higher than the obstruction contribution at the lower floors, and lower than the obstruction contribution for high floors. Both contributions are about the same in between the second and third floor of the building, which corresponds to the middle height of the facade.

### 5.3.2 25° rule

This section presents results for a canyon with a 1:1.9 aspect ratio to conform with the English recommendation of a 25° obstruction angle measured at the centre of the lowest window. Although this recommendation was derived for United kingdom latitudes and weather conditions predominant for those locations, it should be noticed that such wide canyons are unlikely to exist in cities, where the price of land makes such a low density construction prohibitive.

Fig 5.5 shows that the percentage of the three contributions on the ground floor window. Table 5.2 presents those percentages for the several window heights considered. The highest contribution is from the sky, being 81%. The ground contribution

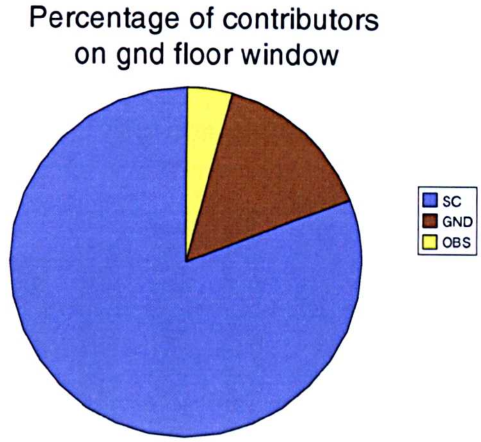



Figure 5.5: Percentage of the sky, ground and obstruction contribution to the diffuse illuminance at the ground floor window of a building within a 25° angle geometry.

is 15% and the obstruction is only 4%.

Table 5.2: Percentage of the sky, ground and obstruction contribution to the diffuse illuminance at several floor windows at a building within a 25° angle geometry. All surfaces have 0.2 reflectance.

| | sky contribution | ground contribution | obstruction contribution |
|---|---|---|---|
| gnd | 81 | 15 | 4 |
| 1st | 81 | 15 | 4 |
| 2nd | 83 | 13 | 4 |
| 3rd | 85 | 11 | 4 |
| 4th | 87 | 10 | 4 |
| 5th | 89 | 8 | 3 |

Fig 5.6 on the next page represents the sky, ground and obstruction components at several window heights for the 25° rule for a CIE overcast sky. The vertical sky component is higher for higher floors. It is 30% at the lowest window and 39% at the highest one. There is an increase of the sky component of 130% from the lowest to the highest window.

The ground component is smaller for higher up windows. It is 5.7% on the ground floor window. At the top floor window, the 'vertical ground component' drops to 61% this value.

The variation of the obstruction component for different window heights is nearly constant and is always smaller than the ground or sky components. This canyon is quite wide so the obstruction is too distant to significantly affect the illuminance on the facade and to influence one or another floor more than the others.

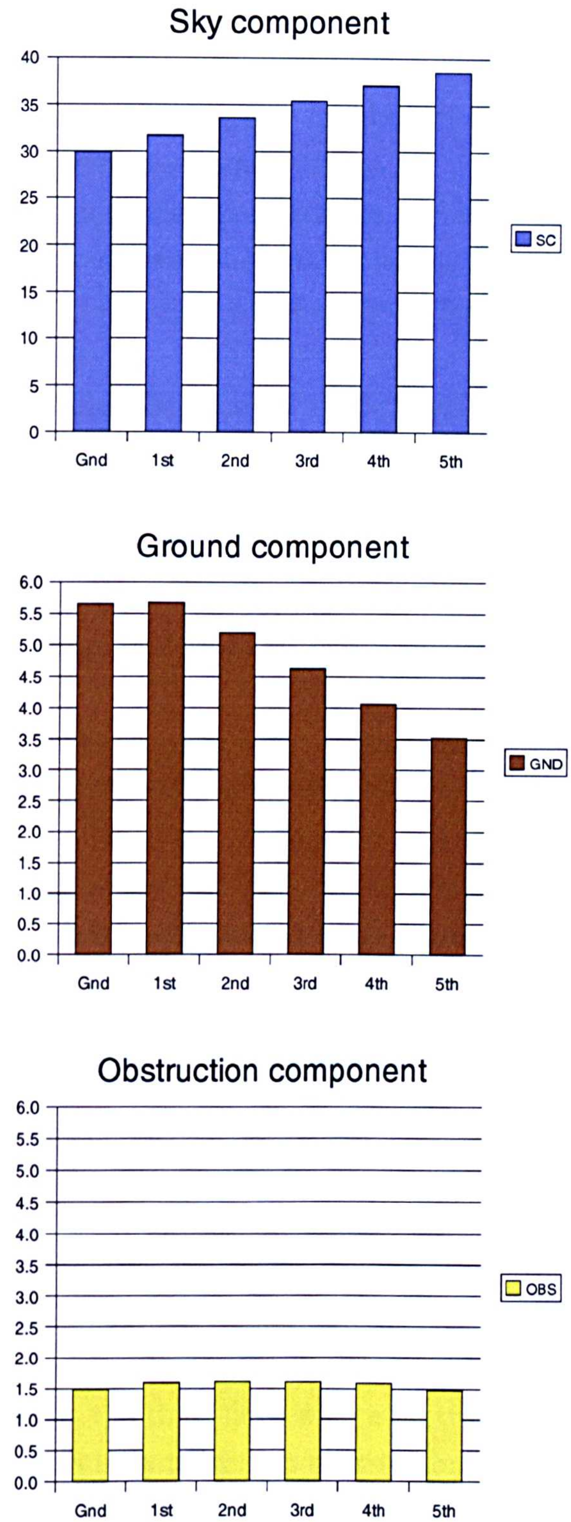



Figure 5.6: Sky, ground and obstruction components (%) at several window heights in a canyon for a 25° rule.

### 5.3.3 Variation of the canyon geometry

For the definition of the urban canyon geometry the 45° angle measured at the street level for the Portuguese rule (PT45) corresponds to a 42° angle measured in the middle of the lowest window (in existing buildings) for the United Kingdom approach (UK42). Similarly, the 25°angle for the UK (UK25) corresponds to a 28° angle at the Portuguese reference point (PT28).

Fig. 5.7 on the following page presents the variation of the sky, ground and obstruction components at different heights on facade for different canyon angles of 25, 28, 35, 40, 45 and 50°, measured according to the Portuguese approach (reference point at street level).

The sky component varies significantly at the lower windows for different canyon angles but it tends to be the same on the top window. Wider canyons (the obstruction is further distant) will allow higher sky components at lower floors. They are 15% for the PT50 (narrow) and 32% for the PT25 (wide) canyon. At the top window the sky component is between 37% for narrow canyons and 39%, for wide ones. The wider the canyon the lower the variation between components on the bottom and top floor level.

The ground component increases with wider canyons, but maintains the same relative variation at the different heights considered. The ground component decreases for higher floors, but for the 25° and 28° canyon angles, it is highest at the first floor, instead of the ground floor. This can be explained by the ground reference point (1.5 m) being too close to the ground plane where a further distant increase of the ground area is less noticeable than at a higher level. From the narrowest to the widest canyon, the vertical ground component is between 3.7 to 5.6% at the lowest window and between 1.5 to 3.8% at the highest.

The obstruction contribution is higher for narrow canyons than for wide ones, and higher for highly reflective surfaces.

For narrow canyons, PT50, the obstruction component is higher on the middle of the facade whereas for wide canyons, PT25, it tends to be roughly equal for all the floors. At PT50, for reflectance 0.2 in the surfaces of the canyon, the lowest obstruction component is at the ground floor level, with a vertical obstruction contribution of 2.4% and the highest at the third floor with a vertical contribution of 3.1%. For vertical surfaces with a 0.5 reflectance this obstruction component triples, with the lowest component being 7.2% and the highest one 9%. At PT25, when the surfaces have a reflectance of 0.2 the obstruction component is about 1.3% for all the heights. For a higher reflectance of 0.5 on the vertical surfaces (the ground remains with a 0.2 reflectance) it is 3.5%.

For an equal reflectance at the vertical and horizontal surfaces of the canyon the ground contributes more to the illuminance on the facade than the obstruction for

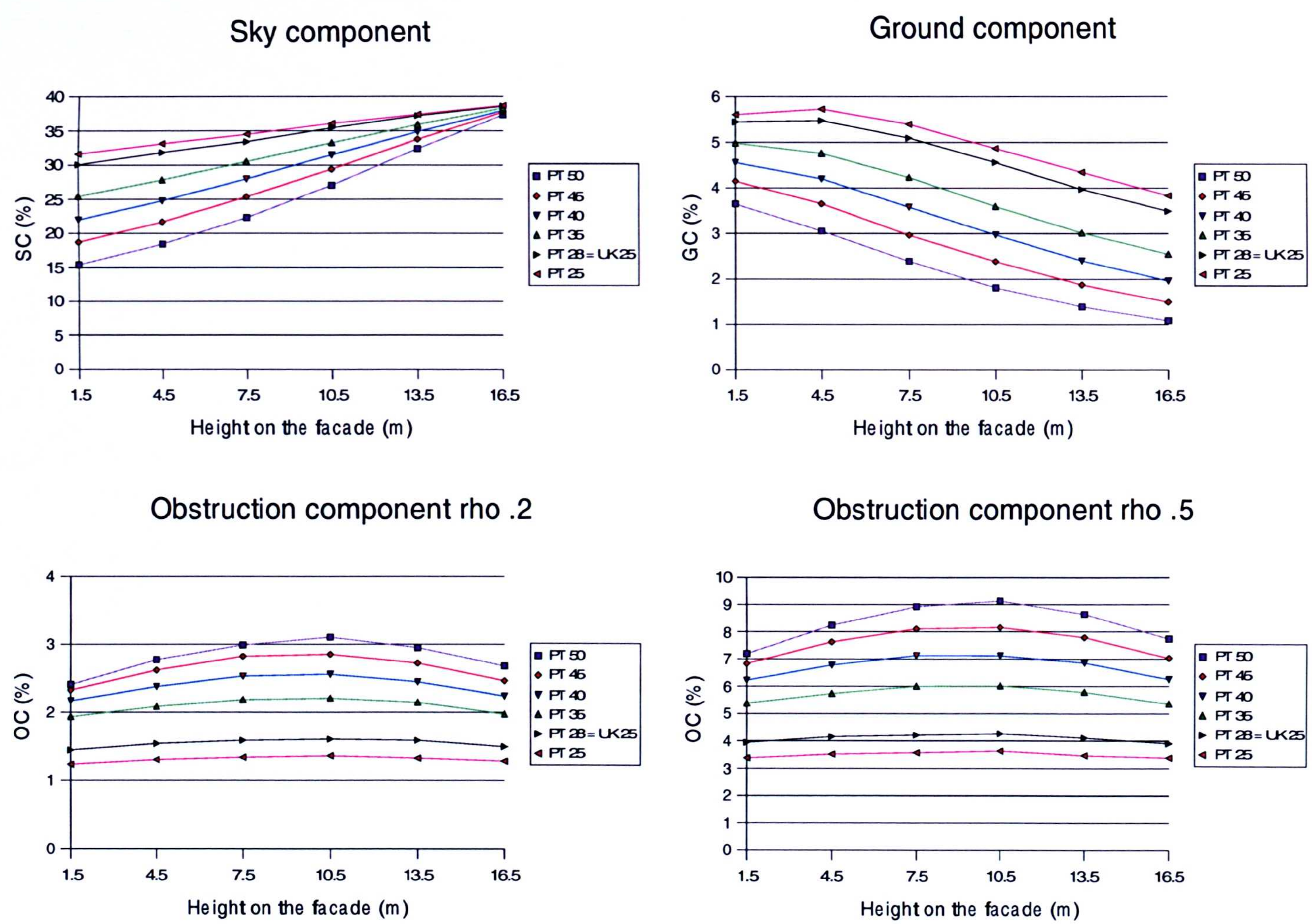



Figure 5.7: Variation of the contributions of the sky, ground ($\rho$ 0.2) and obstructions ($\rho$ 0.2 and 0.5) on a 18 m height facade (6 floors) for section canyon angles of 25, 28, 35, 40, 45 and 50°, under overcast sky distribution.

larger canyons (PT35 - PT25). On narrow ones the ground component will be less than the obstruction on higher floors.

Narrow canyons will result in a higher obstruction component at the facade, but a small sky and ground components.

Table 5.3: Ratio $E_{dv}/E_{dh}$ at various points in the facade for different canyon aspect ratios

| | 1:0.5 (PT64) | 1:1 (PT45) | 1:1.5 (PT34) | 1:2 (PT27) |
|---|---|---|---|---|
| Gnd | 12 | 25 | 33 | 38 |
| $1^{st}$ | 14 | 28 | 36 | 40 |
| $2^{nd}$ | 17 | 31 | 38 | 41 |
| mid point | 20 | 33 | 39 | 41 |
| $3^{rd}$ | 23 | 35 | 40 | 42 |
| $4^{th}$ | 30 | 38 | 41 | 43 |
| $5^{th}$ | 39 | 42 | 43 | 44 |

Table 5.3 presents the diffuse vertical component, ratio of the illuminance at the facade from the sky, ground and obstruction to the diffuse horizontal illuminance, at various points in the facade for different canyon aspect ratios. The reflectance of the surfaces is 0.2.

The illuminance on the facade on a given floor is always lower that the one on the above floor for narrow and wide canyons. However, the illuminance on the lower floor will be significantly reduced on narrow canyons, whereas on wide canyons will be marginally lower. The illuminance on the lowest floor is around 30% of the illumination on the top window, in a narrow canyon (1:0.5). It is around 61% in a equal canyon. For an one and a half wide canyon is 78% and a double wide one is 87%.

### 5.3.4 Variation of the obstruction reflectance

Fig. 5.8 on the next page presents the percentage of 3 different contributions to the overall diffuse vertical illuminance at different floor with different diffuse reflectance ($\rho$ 0.2, 0.3, 0.5 and 0.7) at the vertical surfaces, for an urban canyon with a 1:1 aspect ratio. The ground has a constant reflectance of 0.2.

The obstruction contribution is relatively constant for lower floors and slightly decreases for higher floors. However, its influence on the overall illuminance increases significantly for highly reflective surfaces. At the lowest point, for surface reflectance of 0.2, the obstruction contribution is 9% of the overall illuminance at the facade. It increases to 14, 23, 32% for a reflectance of 0.3, 0.5 and 0.7, respectively. At the highest point, the obstruction contribution is 6, 9, 15 and 21% for reflectance of 0.2, 0.3, 0.5 and 0.7, respectively.

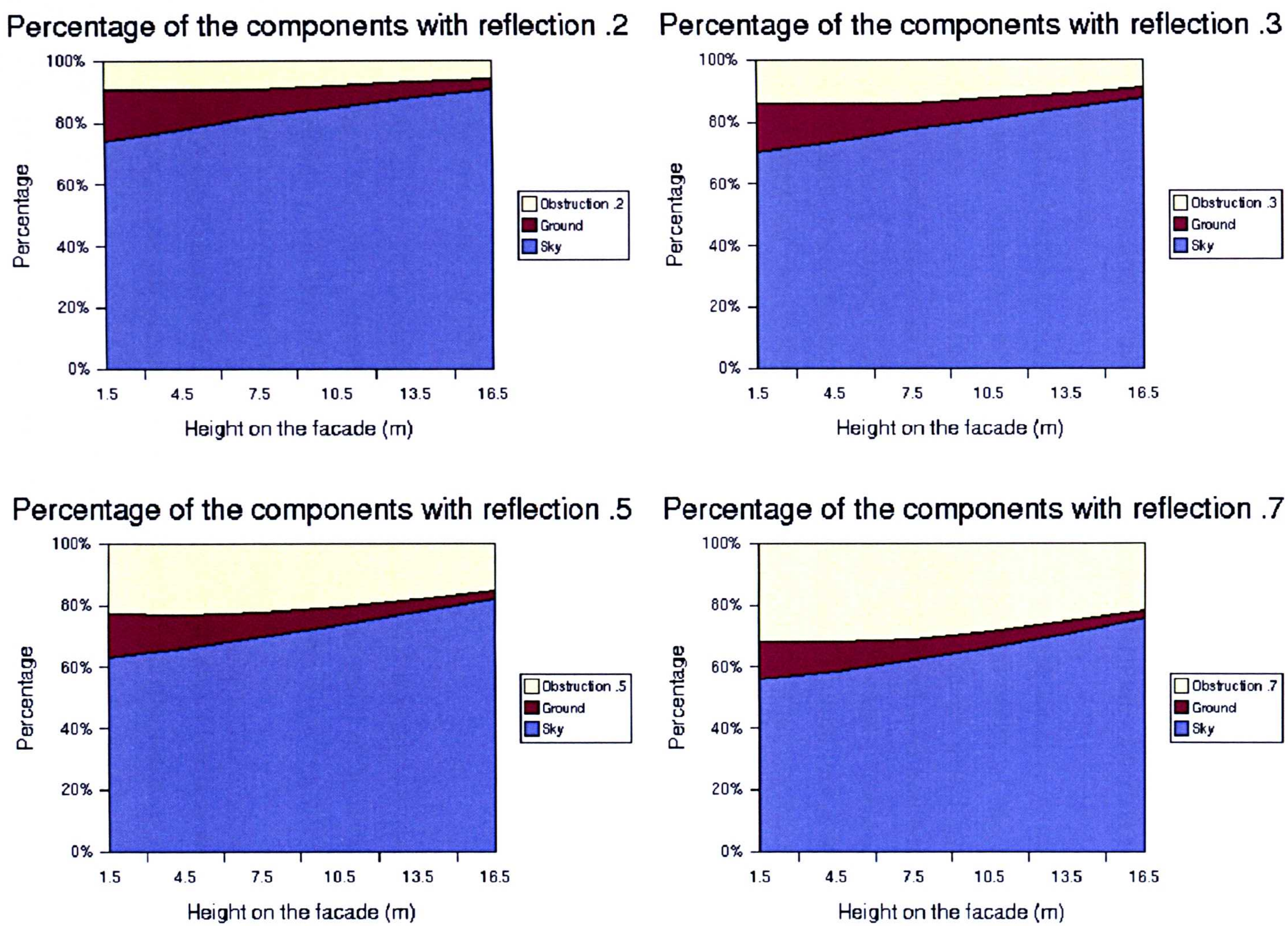



Figure 5.8: Percentage of the contributions of the sky, ground and obstructions to the diffuse vertical illuminance, for different window heights on a 18 m height facade and different diffuse reflectance ($\rho$ 0.2, 0.3, 0.5 and 0.7) at the vertical surfaces for an urban canyon with a 1:1 aspect ratio, under overcast conditions.

The ground contribution decreases for higher floors. It is 16% at the lowest floor and 3% at the highest for a model with obstruction reflectance of 0.2. With 0.7 reflectance on the obstruction, the ground contribution reduces by 75% its former values at the lowest and highest floor, becoming 12 and 3%, respectively.

The sky contribution increases for higher floors. The higher floor 'sees' more sky than the lowest one. For an obstruction of 0.2 reflectance the lowest floor has a sky contribution to the diffuse illuminance of 75%. In the highest floor that contribution is 91%. With higher reflectance in the obstruction the percentage of the sky contribution to the overall illuminance decreases by 75% for an obstruction reflectance of 0.7.

The illuminance in the facade is directly proportional to the reflectance of the obstruction. Therefore an increase of 150, 250 and 350% of the reflectance of the obstruction (0.2 to 0.3,0.5 and 0.7) corresponds to an equal increase of the obstruction contribution in the facade. As both ground and sky components remain unaltered, an increase of the the obstruction component percentage proportionally reduces those percentages. The increase of ground luminance due to a higher flux transfer between the obstruction and ground with higher obstruction reflectance is considered to be part of the obstruction contribution.

### Summary

- The luminance of the CIE overcast sky is independent in azimuth, with the zenith being three times brighter than the horizon. The zenith brightness depends on solar altitude so sky luminance is variable throughout the day and the year and for different latitudes;
- As all the three components sky, ground and obstruction depend only on the light from the sky, the proportionality of light received between the components remains constant for different sky brightness; It will vary for different canyon geometries and reflectance of the surfaces;
- The sky component increases for higher floors. This is due to a larger solid angle of the visible sky between the zenith an the horizon;
- Wider canyons increase the sky component, particularly on lower floors;
- The direct component from the sky is higher than the reflected components from ground and obstruction;
- The ground component is highest for lower floors;
- The ground component increases for wider canyons, but maintains relatively the same variation between heights on the facade;

- The obstruction contribution is higher for narrow canyons than it is for wider ones and it is higher for high surface reflectances;

- The difference of the obstruction component between points on the facade are less significant in comparison with those of the sky and ground. For narrow canyons the obstruction component is higher at the middle of the facade. For wider canyons it tends to be the same for all floors;

- In a canyon with a 1:1 ratio and 0.2 reflectance on all the external surfaces, the ground component is higher than the obstruction component at the lower floors, and lower than the obstruction contribution for high floors. Both contributions are about the same in the middle height of the facade;

- Light reflected from the obstruction and ground is around 18% on the mid of the facade of a 1:1 canyon with 0.2 reflectance on the surfaces. With higher reflectance of the vertical surfaces (obstruction and facade) of 0.3, 0.5 and 0.7, the light reflected increases to 21, 29 and 36%, respectively.

## 5.4 Results for clear skies

In locations where the clear sky distributions are predominant, daylight analysis should be based on a sky model that includes the component from the sun. The following simulations consider a CIE clear sky luminance distribution described in section 2.2 on page 8.

Initially, hourly simulations were run with the buildings in the canyon having windows areas of 15% the floor area (see view 5.1). The opaque surfaces were defined Lambertian diffusers with 0.5 reflectance for the obstruction and 0.2 for the ground. The glazing surfaces were considered to have a specular reflection and transmittance, depending on the angle of incidence of the light. The frequency of the results was later increased to 4 minutes interval. All surfaces were modelled as perfect diffusers without windows. Their reflectance will be stated depending on the model. The canyon has a 45° angle for Lisbon, and a 25° angle for London, accordingly to the planning regulations and recommendations, respectively. Unless stated otherwise, a CIE clear sky distribution is used, whether with or without the sun component, or as sunlight and skylight considered separately.

Simulations of a building in an urban canyon were made for four orientations, north, east, south and northeast.

Simulations are usually presented for the spring equinox (21$^{st}$ March), summer solstice (21$^{st}$ June) and winter solstice (21$^{st}$ December) for the north hemisphere. The autumn equinox (21$^{st}$ September) gives identical results to the spring equinox and is therefore omitted. The $21^{st}$ day of the remaining months is also presented for the north oriented building. Time was set to local solar time.

## 5.4.1 Lisbon

### 5.4.1.1 Percentage of sunlight and skylight

On a clear sky day when no direct light is incident on the fachade, reflected sunlight from ground and obstructions is an important source of light.

Fig. 5.9 on the next page presents the percentage of sunlight and skylight contributions to the daylight of a north facade in an urban canyon with a 1:1 ratio in Lisbon for the equinox and solstice days. Both sun and sky light contributions include the direct and indirect component (reflected from surfaces). However, a north facade only receives direct sunlight in the early (between sunrise and around 8am) and late period (between around 4pm and sunset) of the summer solstice graph.[3]

As seen from the graphs, reflected sunlight from obstruction and ground weighs significantly as a contribution to the illuminance of the building.

Except early and late in the day of the summer solstice, the highest sunlight contribution to the facade illuminance occurs at midday, when the sun's altitude is highest and directly opposite in azimuth to the obstruction. On the $3^{rd}$ floor, the reflected sunlight contributes to 64, 58 and 55% of the daylight that reaches the floor, in March, June and December, respectively, at midday.

The highest sunlight contribution is 67% on the ground floor in March, at midday. The lowest is 42%, occurring on the $5^{th}$ floor in June.

When the sun altitude is above 10°, the lowest sunlight contribution occurs on the $5^{th}$ floor in March, as 12%.

Clearly, the percentage of sunlight reflected from ground and/or obstruction may differ for other latitudes (different solar altitudes), different canyon geometries and reflectances of surfaces. These results may therefore apply only to similar conditions. However, they are representative of the importance of reflected sunlight in the illumination of buildings.

### 5.4.1.2 Percentage of contributions

Fig. 5.10 presents the percentage of the contributions from the sky and light reflected from obstruction and ground to the illuminance on the third floor of a north facade.

[3]By definition sunlight is the direct contribution from the sun and skylight is the diffuse contribution from the sky. However, to make clear when there is sunlight on the surface it is mentioned as 'direct' sunlight and as 'indirect' after interreflections. The same applies in regard to skylight. 'Direct' skylight will be the light that arrives directly from the sky and the 'indirect' after being reflected by surfaces.

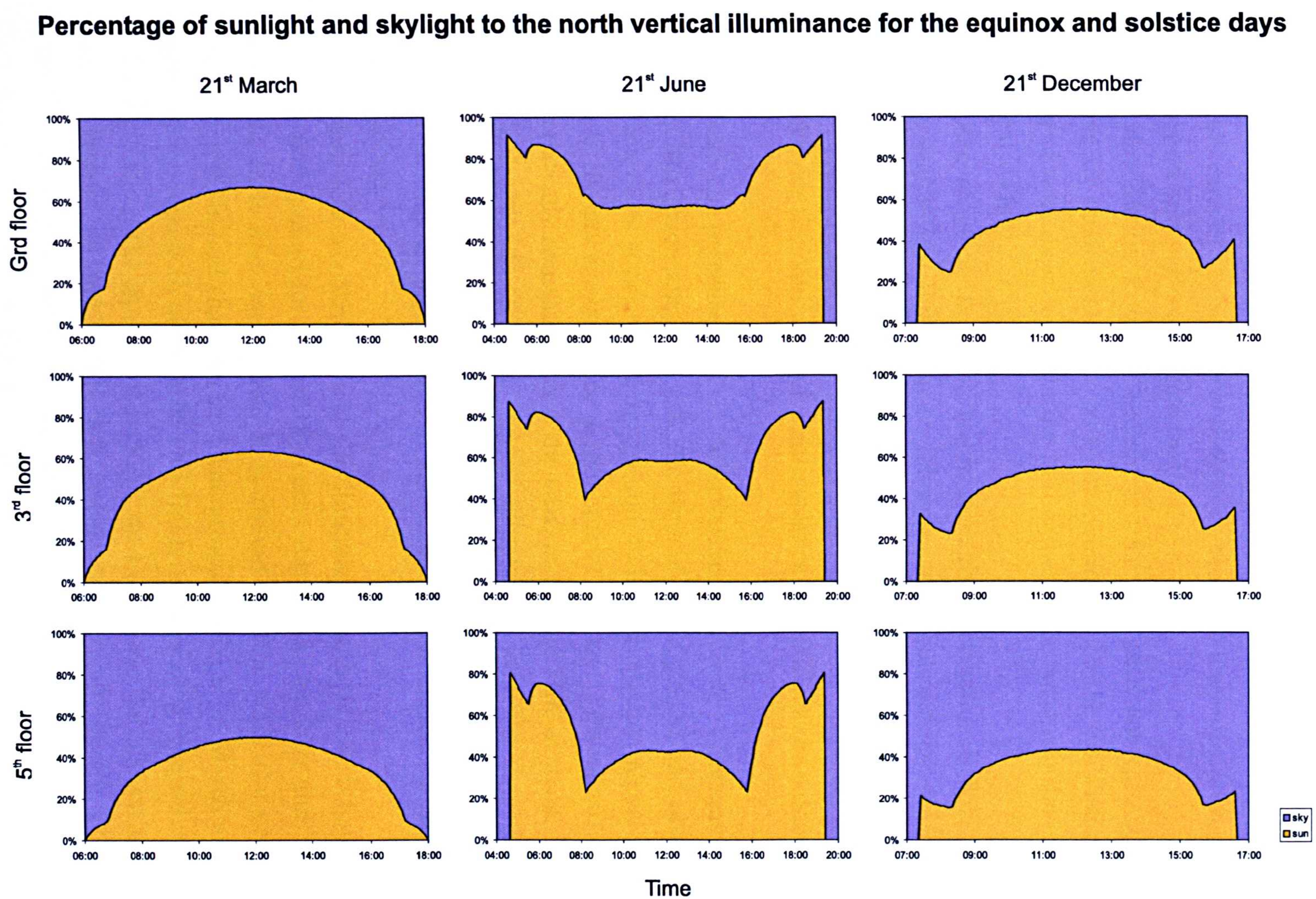



Figure 5.9: Percentage of sunlight and skylight to the illuminance on the north gnd, $3^{rd}$ and $5^{th}$ floor in an urban canyon ratio 1:1 in Lisbon on the spring equinox, summer and winter solstice days. All external surfaces have 0.2 reflectance.

The ground is the contribution that varies most during the year, from an average 10% in March to 40% in June and 3% in December. This is a result of different solar altitudes during the year. During the summer, when the sun is incident on the ground, the solar altitude can be high with a maximum of 75° in Lisbon, therefore a high flux will reach the horizontal plane. Inversely, during the winter, low solar altitude angles with a maximum of 28° result in a higher flux to the vertical surface. During this time of the year, the canyon dimensions may also prevent solar access to the ground and part of the obstruction.

The contribution from the ground is relatively constant throughout the day. Exceptions are early and late hours at the equinox when the sun's azimuth is around the east and west direction resulting in a higher contribution to the ground than to the vertical surface.

The percentage of the contribution from the obstruction is 65% in March and December and 30% in June, at noon. However, those percentages are lower when the solar azimuth is around the west-east axis, as a large angle of incidence of the sunlight on the obstruction reduces its contribution significantly. The sky contribution is around 33% for the equinox and winter solstice and 26% at the summer solstice, at noon.

Although the percentage of the contributions may vary significantly throughout the day (obstruction and sky) and the time of year (ground and obstruction), the contribution of reflected light from ground and obstruction is higher than the contribution of the sky except in the early hours of the day. This reflected contribution remains relatively constant during the year, at around 60% at noon.

Fig. 5.11 presents the total vertical illuminance from the sky, obstruction and ground on the third floor window of a north facade in an urban canyon for a clear sky when the sun is not incident at the facade in the spring equinox and solstice days in Lisbon.

The obstruction contribution to the illuminance on the facade is higher than those from sky and ground for almost the entire day at the equinox and winter solstice (except for early and late hours). It is around 4500 lx, while the sky contribution is around 1800 lx and that one from the ground is 600 lx in March at noon. These contributions reduce to 3000, 1500 and 100 lx in December, respectively.

In June when the sun is not incident on the facade the highest contribution is from the ground, around 3100 lx, followed by the sky contribution, 2700 lx and that from the obstruction with 2400 lx. For the 3 days considered, the total vertical illuminance is highest at the summer solstice (8200 lx) and lowest at the winter equinox (4700 lx), while 6900 lx are incident at the equinox at noon.

The contribution that varies most throughout the day is the one from the obstruction. The sky and ground contribution are relatively constant excluding the

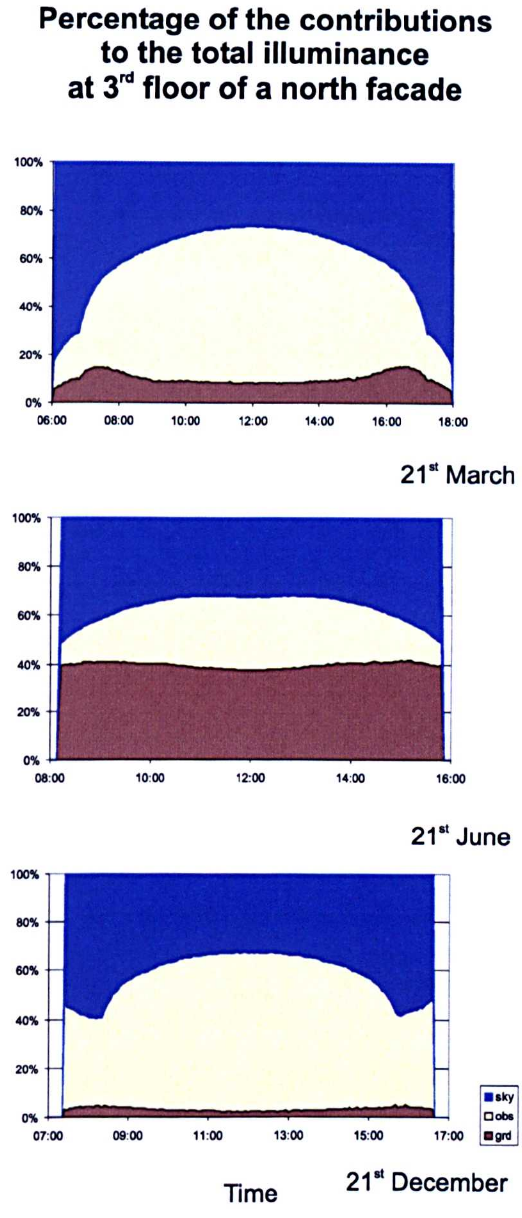



Figure 5.10: Percentage of the sky, obstruction and ground contribution to the total illuminance on the 3rd floor of a 6 storey building with a north facing facade under clear skies at the spring equinox and summer and winter solstice in Lisbon. The reflectance of the obstruction, building and ground surfaces is 0.2. The graph for 21st June only covers the time of the day when the sun is not incident on the facade. Early and late hours of daylight are omitted.

early and late hours.

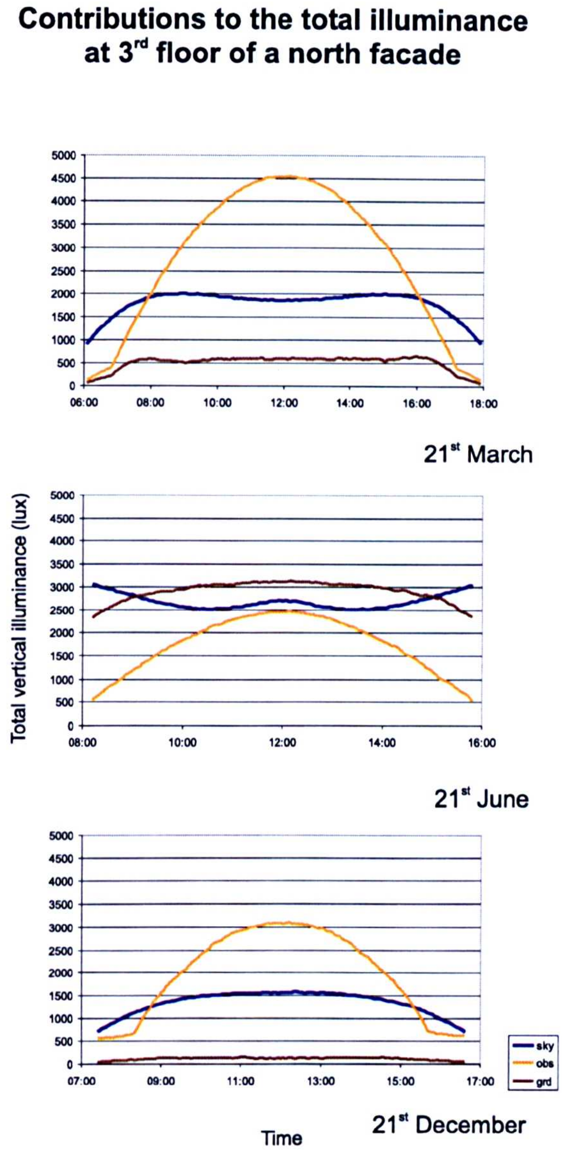



Figure 5.11: Illuminance at the third floor of a north facade from the sky, obstruction and ground on a clear sky day in the spring equinox and summer and winter solstice in Lisbon. All the surfaces have 0.2 reflectance. The graph for 21st June only covers the time of the day when the sun is not incident on the facade. The early and late hours of the day are omitted.

#### 5.4.1.3 Global horizontal illuminance versus total vertical illuminance

Previous results from measurements taken in Lisbon showed a linear relationship between the global horizontal illuminance and the total vertical illuminance when sunlight is not incident on the facade, see chapter 4.

This section presents results which show that a similar linear relationship holds for different building orientations and times of year.

Results are presented for an urban canyon with a 1:1 ratio. Simulations were made for 4 minutes interval from sunrise to sunset.

#### 5.4.1.3.1 North orientation

In the building oriented north, fig. 5.12 on the following page, at the summer solstice, there are two distinctive results: - solar azimuth *NE* and *NW* quadrants, which causes direct sunlight on the facade; - remaining solar azimuths, when the sun is behind the building. These latter results (azimuth *SE* and *SW* quadrant) present a linear relationship between the horizontal and the vertical illuminance. Results for the equinox and winter solstice also show a linear relationship.

The illuminance on the $5^{th}$ floor tends to be higher than on the $1^{st}$ floor. However, at summer solstice, when sunlight is not incident on the facade (*SE-S-SW*) the results are similar for both floors. This might be a result of the ground contribution being high (due to high solar altitudes) therefore compensating the lower floor against the sky contribution on the top floor.

**For the summer and winter solstice and spring equinox days**

Fig. 5.13 presents the global horizontal illuminance versus the total vertical illuminance at the ground floor, $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ and $5^{th}$ floor of a north facade in an urban canyon for the spring equinox and summer and winter solstice in Lisbon when the sun is not incident on the facade.

There is a linear relationship between the global horizontal and the total vertical illuminance on a north facade at the equinox and solstices.

During the summer on the lower floors (gnd and $1^{st}$), the values tend to deviate from the trendline. In those periods the sun's altitude is high while its azimuth is in the east/west, so that direct sunlight is incident mainly on the ground. This results in a high illuminance on lower floors due to the higher ground contribution. However, they are not significant for the overall relationship between the estimated values of the trendline and the simulated ones. The coefficients of determination for all the floors considered are between 0.89 and 0.99. All the results are significant at the 1% level.

The apparent linear relationship can be described by the equation

$$E_{tv} = k \cdot E_{gh} + C \qquad (5.1)$$

previously defined as eq. 4.1 on page 73, where $k$ is a factor dependent on the reflection of obstructions, the geometry of the canyon and the position on the facade. $C$ is mainly the contribution of the diffuse sky and is therefore more significant for higher floors.

Fig. 5.14 presents results for the equinox and solstices considering only the sun as

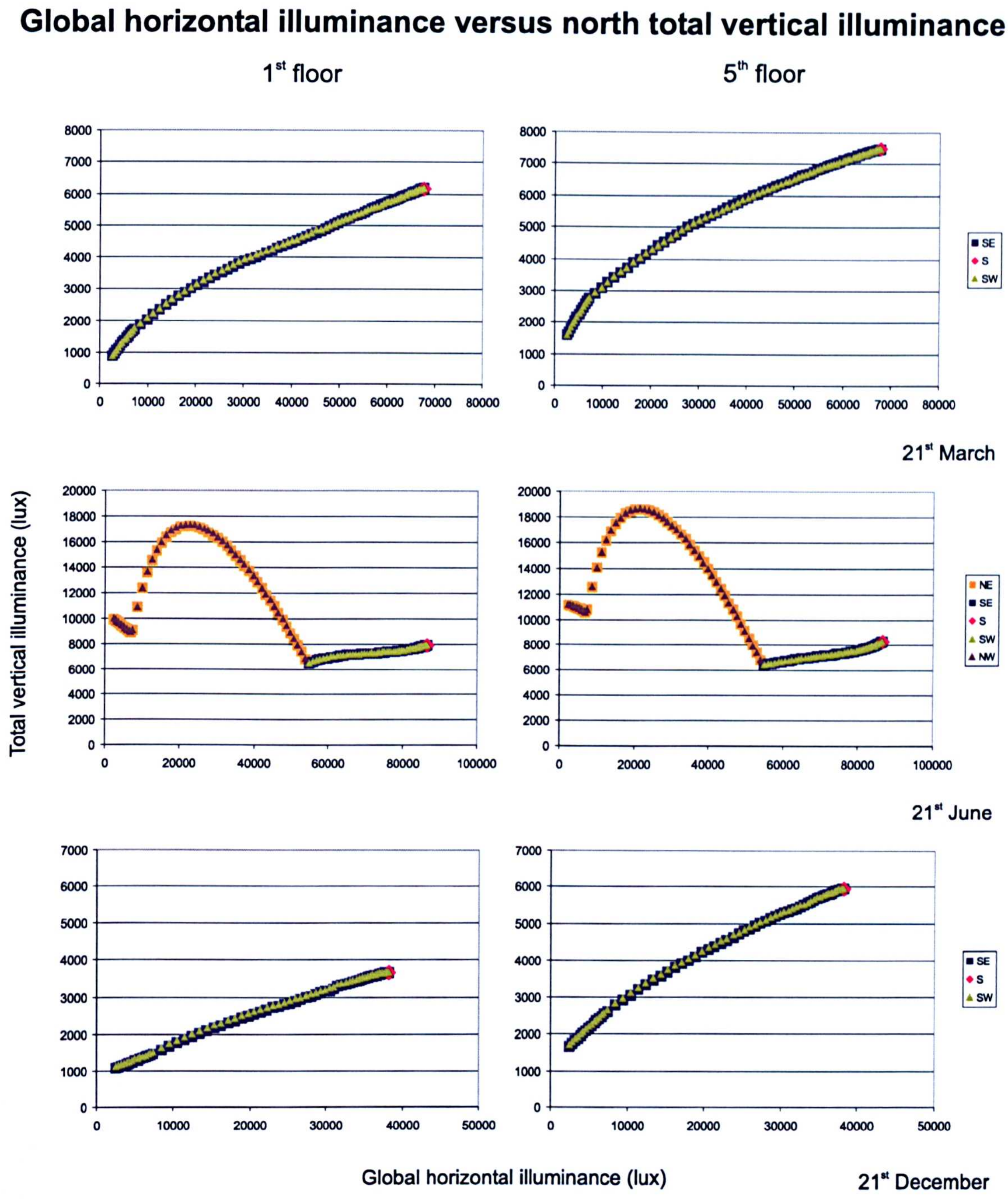



Figure 5.12: Results of the simulations for two points located externally in the middle of the window, at the first and fifth floor, on a north facade in an urban canyon for the summer and winter solstices and equinox days (considering those days a good representation for the effects of interest to be detected).

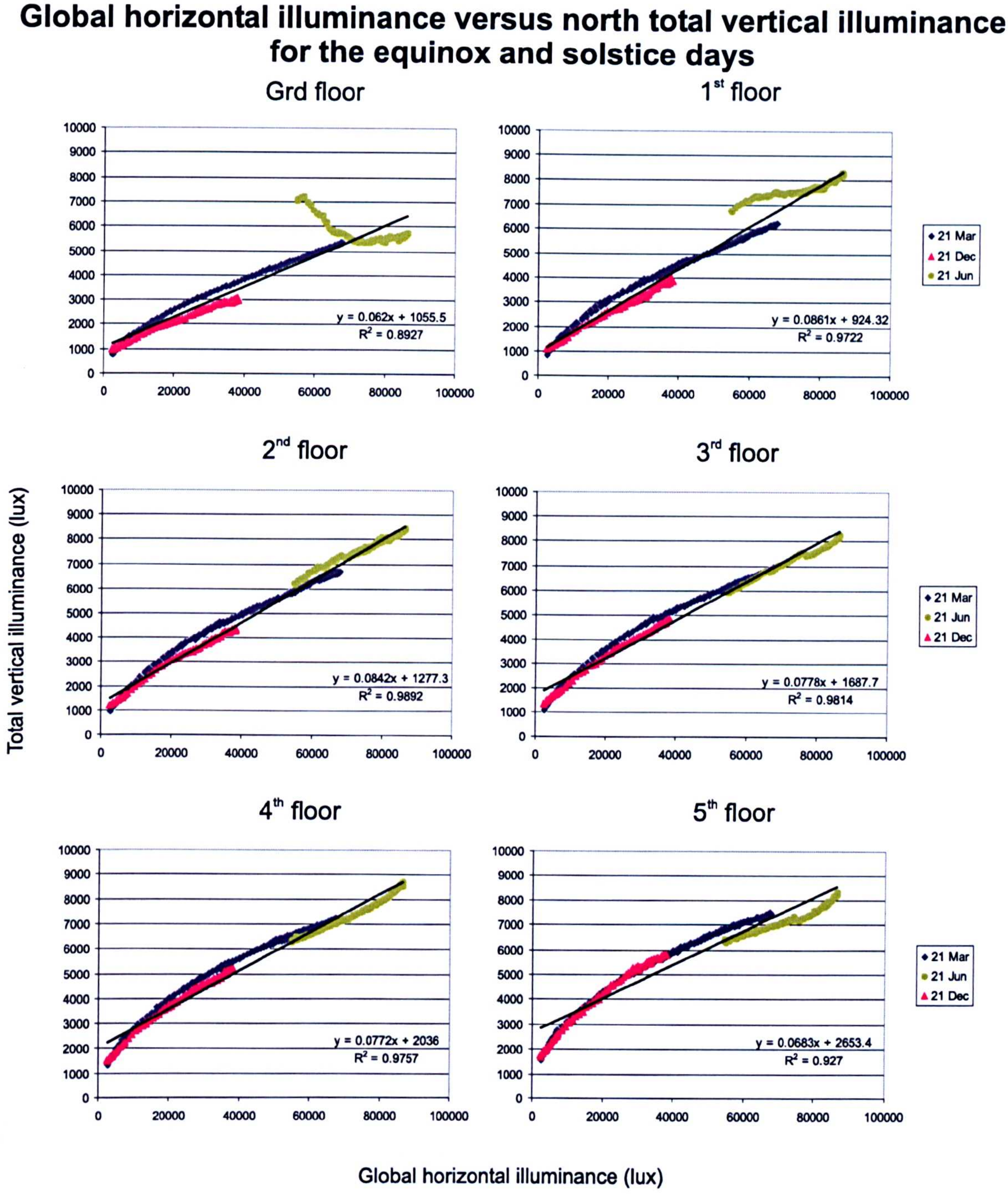



Figure 5.13: Relationship between the global horizontal illuminance and the total vertical illuminance at different heights of a building facing north in an urban canyon in Lisbon when sunlight is not incident on the facade for the summer and winter solstice and the spring equinox days.

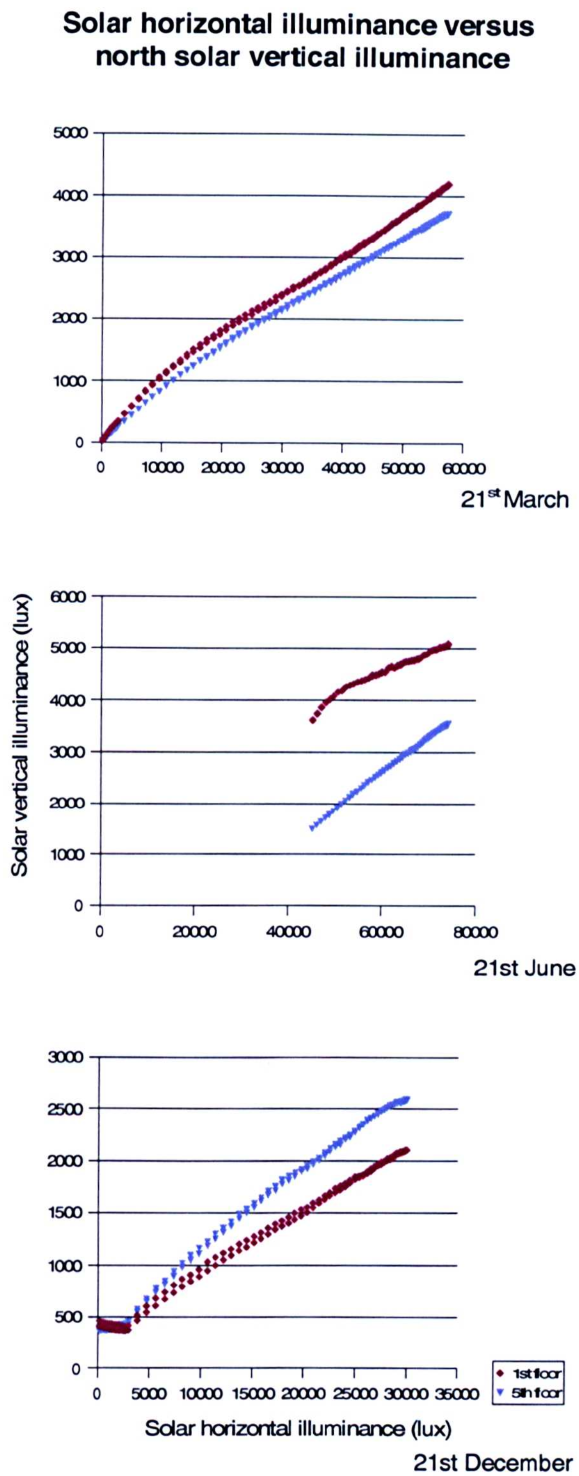



Figure 5.14: Relation between the solar horizontal illuminance and the vertical illuminance on the 1st and 5th floor of a building facing north in a 1:1 canyon ratio when the sun is behind the building on a equinox and solstice days. The sky contribution is excluded in these values. The horizontal illuminance is only the direct component of the solar illuminance while the vertical includes the interreflections from sunlight in the canyon.

a light source. The equinox day shows a linear relationship between the unobstructed solar horizontal illuminance and the solar vertical illuminance which can be defined as $E_{sv} = s \cdot E_{sh}$ (without a constant). It shows that when the diffuse sky is excluded from the simulation, the illuminance on the facade displays a direct proportionality to the unobstructed solar horizontal illuminance.

However, at the summer solstice a linear correlation between the solar horizontal and vertical illuminance exists but a constant $B$ cannot be excluded. Furthermore, this constant might be of negative value. This may be due to the sun's high altitude, where sunlight is mainly incident on the ground floor, resulting in a high horizontal illuminance against a reduced vertical illuminance. Reflected sunlight will affect the lower floors more than it does the top one, so the $5^{th}$ floor presents a significant difference compared to the $1^{st}$ one at summer solstice.

At the winter solstice, a linear correlation between the solar horizontal and vertical illuminance can be observed without a constant. Results below around 10° in the graph should be ignored as RADIANCE assumes a constant solar brightness when $\sin \gamma_s < 0.16$, see formulae in appendix I.

Given these results, it can be assumed that in the linear relationship between the global horizontal and the total vertical illuminance defined as $E_{tv} = k \cdot E_{gh} + C$ the constant $C$ is mainly due to the sky contribution. An exception occurs in the summer period when the sun's altitude and azimuth promote sunlight on the ground and a reduced contribution from the obstruction.

The linear relationship may be rewritten as

$$E_{tv} = s \cdot E_{sh} + B \tag{5.2}$$

assuming $E_{tv}$ is a function of the solar illuminance, $E_{sh}$, plus a constant $B$. Then

$$\begin{aligned} E_{tv} &= s \cdot E_{sh} + B \\ & s \cdot [E_{gh} - E_{dh}] + B \\ & s \cdot E_{gh} - s \cdot E_{dh} + B \end{aligned} \tag{5.3}$$

As the diffuse contribution from the sky, $E_{dh}$, is fairly constant, and both $s$ and $B$ are constants, $D = -s \cdot E_{dh} + B$ and

$$E_{tv} = s \cdot E_{gh} + D \tag{5.4}$$

as previously defined as eq. 5.1 where $D$ is mainly the contribution from the diffuse sky and $s$ depends on the solar illuminance.

### Calculation of the coefficients $k$, $s$, $C$ and $D$

Given the previous theory and the relationship between the global horizontal and total vertical illuminance derived from results, two slightly different approaches to obtain the coefficients for eq. 5.1 can be taken.

The first one is based on the assumption that the slope $k$ in eq. 5.1 is derived from the solar illuminance and that the diffuse sky contribution is fairly constant (except early and late hours during the day). The approach is defined as eq. 5.2.[4]

The constant $k$ renamed $s$ is derived as the slope of the regression line that best fits (proportion of the variance in Y attributable to the variance in X) the relationship between the solar horizontal illuminance and the solar reflected vertical illuminance. The constant $D$ as the diffuse contribution is derived as the interception with the y-axis that allows the best fit of the solar linear equation in the relationship between the global horizontal and the total vertical illuminance.

As the coefficient of determination, $R^2$, is insensitive to constant proportional deviations, the Nash and Sutcliffe model-efficiency measure, $NS$[5], is used to derive $D$ from the best fit of the solar linear model in the global data. (Mulligan and Wainwright, 2004)

Table 5.5 presents the slope $s$ and constant $D$ and the correlation between the estimated and calculated results $NS$ according to this approach. Values for solar altitude below 10° were omitted. Fig. 5.15 shows the variation of $s$ with different canyon ratios and obstruction reflectances.

The second approach derives the slope $k$ and constant $C$ from the linear regression that best fits the relationship between the global horizontal illuminance and the total vertical illuminance defined by the eq. 5.1[6]. $R^2$ is the indicator that reveals how closely the estimated values for the trendline correspond to the actual data.

Table 5.7 presents the slope $k$ and constant $C$ and the correlation between the estimated and calculated results, $R^2$, according to this approach. Fig. 5.16 shows the variation of $k$ with different canyon ratios and obstruction reflectances.

Both approaches are valid, and the coefficients are fairly similar for a reflectance of 0.2. However, significant differences can be seen for higher reflectances. The solar best fit approach underestimates the slope of the equation in comparison to the one derived for the global best fit. Although the difference between the two values is reduced for a 0.2 reflectance it increases substantially with higher reflectance. On the other hand the constant is higher for the solar approach and significantly increases to almost three times the constant of the global approach for higher reflectance.

Clearly the global best fit approach presents $R^2$ closer to the unit than the $NS$

[4]It will be addressed later as the solar best fit approach.

[5]$NS$ is a measure of the mean square error to the observed variance. If the error is zero, $NS$ equals 1 and the model represents a perfect fit.

[6]It will be addressed later as the global best fit approach.

calculated for the solar best fit one. The lower coefficient for the former method is 0.70, for the latter 0.48. They occur on the top floor of a narrow canyon with reflectance 0.5 and may be explained by a reduced illuminance reaching the top floor on the summer solstice. Nevertheless, the remaining floors and canyon ratios present much higher coefficients, representative of a close estimation to the actual data.

The solar approach presents more consistent results in terms of the diffuse contribution compared to the negative values obtained on lower floors of narrow canyons with the global approach. However, very high values obtained for higher reflectance and wider canyons may be unrealistic. If the maximun diffuse horizontal illuminance on an urban canyon in the equinox is around 10 300 lx it would be expected to verify much reduced levels on a vertical surface. Assuming a uniform sky distribution the vertical illuminance (without an obstruction) would be 50% of the horizontal illuminance. However, the obstruction allows into the canyon light from other parts of the sky. Higher reflectances of surfaces, the interreflections within the canyon, as well as wider canyons with a large sky solid angle may cause a considerate increase of the iluminance on the facade and justify high values.

The main discrepancies between the two methods may be the dependence on theoretical models of a sky to obtain the solar reflected component in an urban canyon in the solar best fit method. The global approach may be simply taken with measurements obtained in an urban canyon with two illuminance meters. See 4.2.1 for details of real measurements taken in an urban canyon. The solar best fit approach is limited in practical terms to scale models under an heliodon, computer simulations or analytical calculations to derive results for the reflected and interreflection contributions within a canyon exclusively from the sun.

### Variation of the canyon geometry

Table 5.5 and fig. 5.15 and table 5.7 and fig. 5.16 present the slopes and constants, as well as the indicator of the good estimation of the calculated results to the actual data for different canyon ratios and obstruction reflectances, for the two approaches. The slope $s$ tends to be higher on the $2^{nd}$ and $3^{rd}$ floors, whereas $k$ is higher on the $1^{st}$ and $2^{nd}$ . Both are similar for reflectance 0.2 and will be higher for higher reflectances of the obstruction. While the coefficient $s$ varies significantly from a narrow to a wider canyon (it is higher in the former due to a close proximity to the sun patch), the coefficient $k$ remains relatively constant for the different canyon ratios. This may be a result of the skylight reflected from the ground being considered in the coefficient $k$. It is also consistent with higher illuminance on lower floors for $k$. Coefficient $s$ tends to be higher on higher floors for narrow canyons and on the mid and lower floors for equal and wide canyons, consistent with a sun patch on top of the obstruction on narrow canyons and extended downward for wider ones, mainly

| canyon ratio | 1:0.5 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $\rho$ | 0.2 | | | 0.5 | | | 0.7 | | |
| coefficients | s | D | NS | s | D | NS | s | D | NS |
| Gnd | 0.04 | 410 | 0.70 | 0.10 | 2565 | 0.63 | 0.15 | 5895 | 0.60 |
| $1^{st}$ | 0.06 | 390 | 0.83 | 0.13 | 2580 | 0.74 | 0.19 | 5720 | 0.69 |
| $2^{nd}$ | 0.06 | 645 | 0.91 | 0.14 | 2470 | 0.87 | 0.22 | 5110 | 0.84 |
| $3^{rd}$ | 0.06 | 1100 | 0.82 | 0.15 | 2650 | 0.83 | 0.23 | 4850 | 0.86 |
| $4^{th}$ | 0.06 | 1815 | 0.68 | 0.15 | 3245 | 0.64 | 0.23 | 5120 | 0.73 |
| $5^{th}$ | 0.05 | 3060 | 0.66 | 0.13 | 4305 | 0.48 | 0.19 | 5820 | 0.58 |
| canyon ratio | 1:1 | | | | | | | | |
| $\rho$ | 0.2 | | | 0.5 | | | 0.7 | | |
| coefficients | s | D | NS | s | D | NS | s | D | NS |
| Gnd | 0.06 | 1480 | 0.85 | 0.11 | 5080 | 0.80 | 0.16 | 8845 | 0.78 |
| $1^{st}$ | 0.07 | 1460 | 0.95 | 0.13 | 5800 | 0.83 | 0.19 | 9790 | 0.80 |
| $2^{nd}$ | 0.08 | 1725 | 0.98 | 0.14 | 6005 | 0.88 | 0.20 | 9680 | 0.84 |
| $3^{rd}$ | 0.07 | 2145 | 0.99 | 0.13 | 6055 | 0.90 | 0.19 | 9240 | 0.87 |
| $4^{th}$ | 0.07 | 2615 | 0.97 | 0.11 | 6220 | 0.90 | 0.18 | 8940 | 0.88 |
| $5^{th}$ | 0.06 | 3490 | 0.94 | 0.11 | 6520 | 0.87 | 0.16 | 8770 | 0.87 |
| canyon ratio | 1:1.5 | | | | | | | | |
| $\rho$ | 0.2 | | | 0.5 | | | 0.7 | | |
| coefficients | s | D | NS | s | D | NS | s | D | NS |
| Gnd | 0.05 | 2265 | 0.76 | 0.09 | 5610 | 0.76 | 0.12 | 9305 | 0.73 |
| $1^{st}$ | 0.07 | 2185 | 0.88 | 0.12 | 6485 | 0.79 | 0.15 | 10675 | 0.73 |
| $2^{nd}$ | 0.07 | 2380 | 0.92 | 0.12 | 6780 | 0.81 | 0.15 | 10935 | 0.75 |
| $3^{rd}$ | 0.07 | 2685 | 0.96 | 0.12 | 6880 | 0.85 | 0.15 | 10810 | 0.78 |
| $4^{th}$ | 0.07 | 3075 | 0.97 | 0.11 | 6935 | 0.87 | 0.14 | 10510 | 0.81 |
| $5^{th}$ | 0.06 | 3605 | 0.96 | 0.10 | 6990 | 0.87 | 0.13 | 10150 | 0.82 |

Table 5.5: Slope $s$ and constant $D$ for eq. and Nash and Sutcliffe model-efficiency measure, $NS$, for different canyon ratio (narrow, equal and wide), different surface reflectance ( 0.2, 0.3, 0.5 and 0.7) at different window heights (gnd, $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ and $5^{th}$) on a north facade.

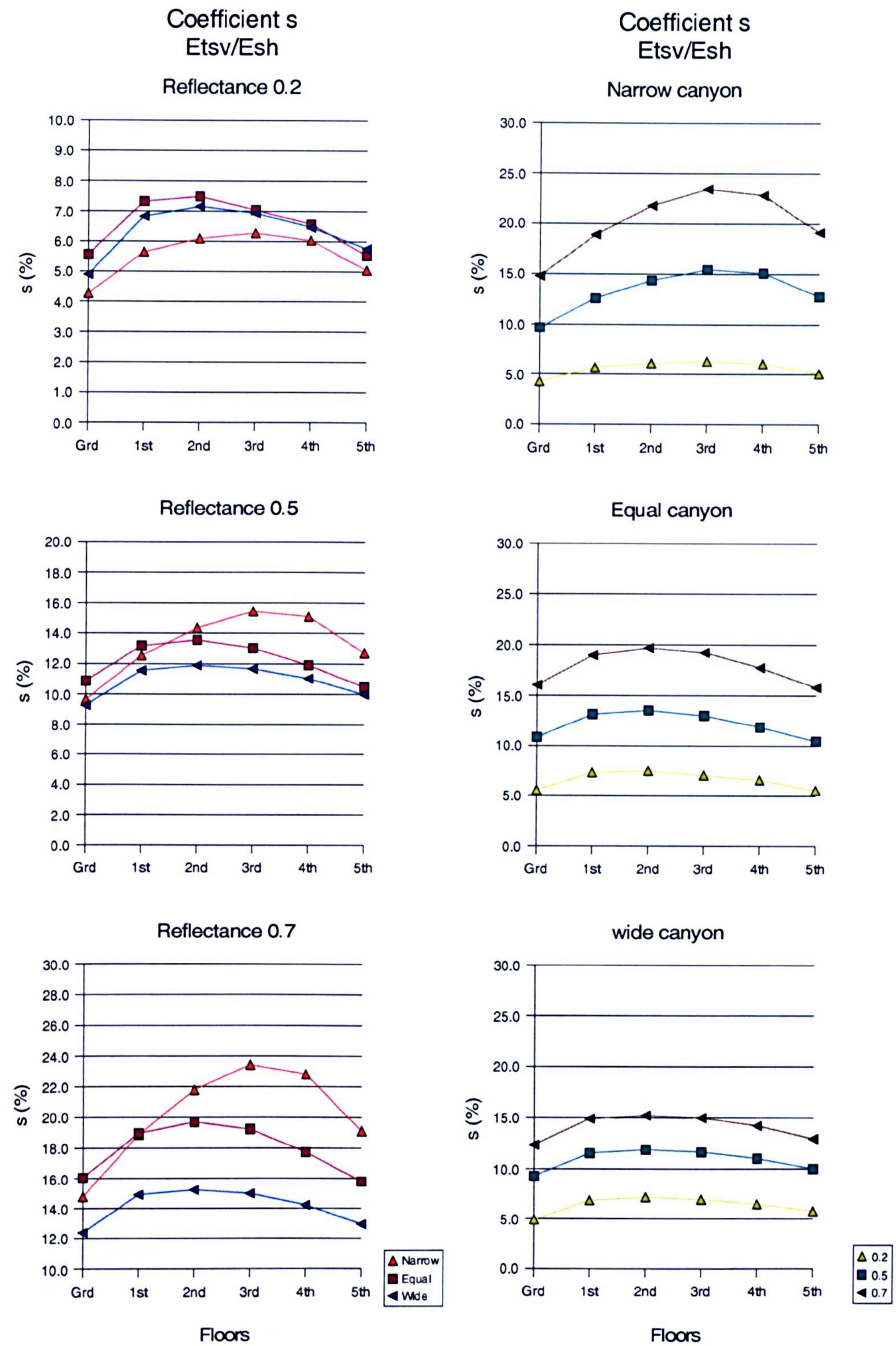



Figure 5.15: Coefficient $s$ ratio of total solar vertical illuminance to solar horizontal illuminance for different canyon ratio (narrow, equal and wide), different surface reflectance (0.2, 0.5 and 0.7) at different window heights (gnd, $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ and $5^{th}$) on a north facade.

| canyon ratio | 1:0.5 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\rho$ | 0.2 | | | 0.3 | | | 0.5 | | | 0.7 | | |
| coefficients | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ |
| Gnd | 0.05 | -10 | 0.78 | 0.08 | -152 | 0.79 | 0.16 | -506 | 0.82 | 0.29 | -951 | 0.85 |
| $1^{st}$ | 0.07 | -66 | 0.89 | 0.10 | -256 | 0.89 | 0.19 | -703 | 0.89 | 0.33 | -1219 | 0.90 |
| $2^{nd}$ | 0.07 | 314 | 0.95 | 0.10 | 285 | 0.95 | 0.19 | 197 | 0.95 | 0.31 | 107 | 0.96 |
| $3^{rd}$ | 0.07 | 902 | 0.88 | 0.10 | 1103 | 0.88 | 0.17 | 1507 | 0.89 | 0.29 | 1949 | 0.92 |
| $4^{th}$ | 0.06 | 1643 | 0.80 | 0.09 | 2062 | 0.77 | 0.15 | 2908 | 0.78 | 0.25 | 3824 | 0.83 |
| $5^{th}$ | 0.06 | 2554 | 0.77 | 0.08 | 3060 | 0.72 | 0.12 | 4086 | 0.70 | 0.20 | 5168 | 0.75 |
| canyon ratio | 1:1 | | | | | | | | | | | |
| $\rho$ | 0.2 | | | 0.3 | | | 0.5 | | | 0.7 | | |
| coefficients | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ |
| Gnd | 0.06 | 1095 | 0.90 | 0.09 | 1338 | 0.91 | 0.17 | 1942 | 0.93 | 0.28 | 2729 | 0.95 |
| $1^{st}$ | 0.08 | 978 | 0.97 | 0.12 | 1146 | 0.98 | 0.21 | 1531 | 0.99 | 0.34 | 2068 | 0.99 |
| $2^{nd}$ | 0.08 | 1283 | 0.99 | 0.12 | 1513 | 0.99 | 0.21 | 2008 | 0.99 | 0.33 | 2635 | 0.99 |
| $3^{rd}$ | 0.08 | 1691 | 0.98 | 0.11 | 2002 | 0.98 | 0.19 | 2666 | 0.98 | 0.30 | 3445 | 0.98 |
| $4^{th}$ | 0.07 | 2148 | 0.96 | 0.10 | 2516 | 0.96 | 0.17 | 3288 | 0.95 | 0.27 | 4161 | 0.96 |
| $5^{th}$ | 0.07 | 2660 | 0.93 | 0.09 | 3073 | 0.91 | 0.15 | 3805 | 0.92 | 0.23 | 4797 | 0.93 |
| canyon ratio | 1:1.5 | | | | | | | | | | | |
| $\rho$ | 0.2 | | | 0.3 | | | 0.5 | | | 0.7 | | |
| coefficients | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ |
| Gnd | 0.06 | 1656 | 0.85 | 0.08 | 2024 | 0.86 | 0.14 | 2859 | 0.89 | 0.23 | 3870 | 0.91 |
| $1^{st}$ | 0.08 | 1471 | 0.93 | 0.12 | 1694 | 0.94 | 0.20 | 2220 | 0.96 | 0.30 | 2906 | 0.97 |
| $2^{nd}$ | 0.09 | 1609 | 0.96 | 0.12 | 1818 | 0.97 | 0.21 | 2319 | 0.98 | 0.30 | 2970 | 0.99 |
| $3^{rd}$ | 0.08 | 1889 | 0.98 | 0.12 | 2152 | 0.98 | 0.20 | 2734 | 0.99 | 0.29 | 3459 | 0.99 |
| $4^{th}$ | 0.08 | 2216 | 0.98 | 0.11 | 2516 | 0.98 | 0.18 | 3170 | 0.99 | 0.27 | 3930 | 0.99 |
| $5^{th}$ | 0.08 | 2542 | 0.97 | 0.10 | 2846 | 0.97 | 0.17 | 3503 | 0.98 | 0.24 | 4259 | 0.98 |

Table 5.7: Slope $k$ and constant $C$ for eq. and coefficient of determination $R^2$ for different canyon ratio (narrow, equal and wide), different surface reflectance ( 0.2, 0.3, 0.5 and 0.7) at different window heights (gnd, $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ and $5^{th}$) on a north facade.

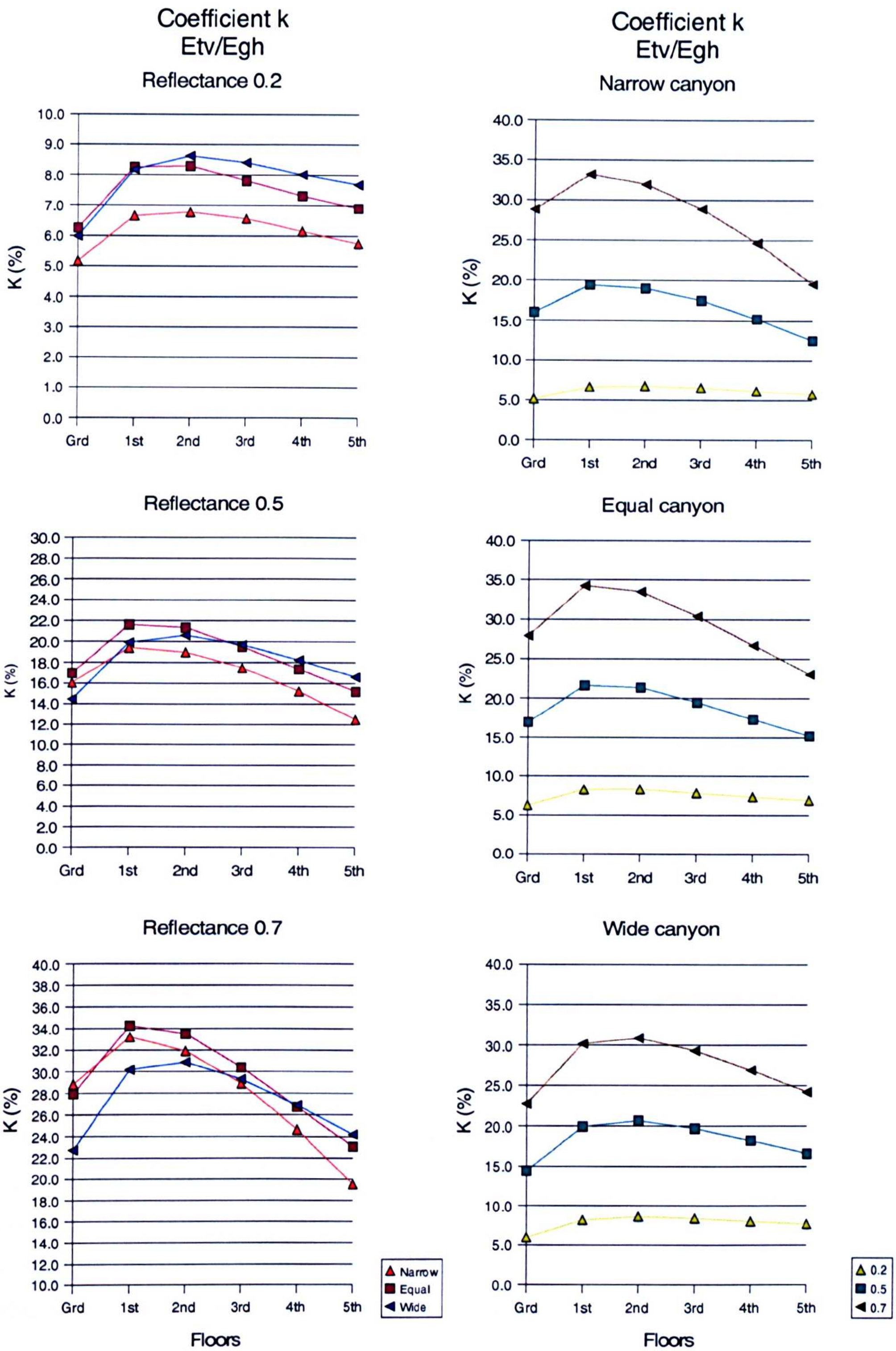



Figure 5.16: Coefficient $k$ ratio of total vertical illuminance to global horizontal illuminance for different canyon ratio (narrow, equal and wide), different surface reflectance (0.2, 0.5 and 0.7) at different window heights (gnd, 1$^{st}$, 2$^{nd}$, 3$^{rd}$, 4$^{th}$ and 5$^{th}$) on a north facade.

affecting the opposite area.

The constants $C$ and $D$ tend to increase for higher floors with both methods. However, they are higher on the ground floor against the $1^{st}$ one due to a higher contribution from the ground plane to the lower floor. Both floors present negative values on narrow canyons for the global approach due to a reduced illuminance on lower floors when the horizontal illuminance may be high.

**For every $21^{st}$ day of the month**

Previous simulations were presented for the summer and winter solstice and a day at the equinox. This can be considered a fair representation for the yearly daylight distribution. However, a more detailed analysis can be made if more days are included in the sample. The $21^{st}$day of each month are included in the analysis in the following paragraphs.

Fig. 5.17 presents those results in terms of the relationship between the global horizontal illuminance and the north total vertical illuminance on the gnd, $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ and $5^{th}$ floors of a building in an urban canyon in Lisbon. It shows that results for the $21^{st}$ day of each month follow a similar trend. This linear relationship can thus be representative of the whole year. The coefficients of determination for all floors are between 0.86 and 0.98, considered a good index of a reduced error between the values calculated and the estimated values. The results for all the floors are statistically significant at 1%. The lowest correlation occurs at the lowest floor (1.5 m) where the influence of the ground is more significant. Second comes the top floor where the influence of the sky is higher and more significant when the global illuminance is low, at early and late hours in the day. The highest correlation occurs in the middle floors of the building where the influence of the obstruction is higher.

Although some values deviate from the trendline, particularly in the lower floors in the summer period, they do not weight significantly on the year average.

Except for the lower floor where the light reflected from the ground increases the illuminance on the facade and for the higher floors where the diffuse sky contribution is dominant, $k$ is fairly constant for all floors. The constant tends to increase for higher storeys due to a higher contribution from diffuse skylight and a reduced contribution from the light reflected from obstruction and ground.

#### 5.4.1.3.2 South orientation

Fig. 5.18 presents results for a south oriented facade in an urban canyon with a 1:1 ratio in Lisbon.

The graphs for the equinox day present values when the sun altitude is above 10° and its azimuth is within 90° of due south. Direct sunlight reaches all the floors in the south facade at the equinox day, the illuminance at the first floor is therefore

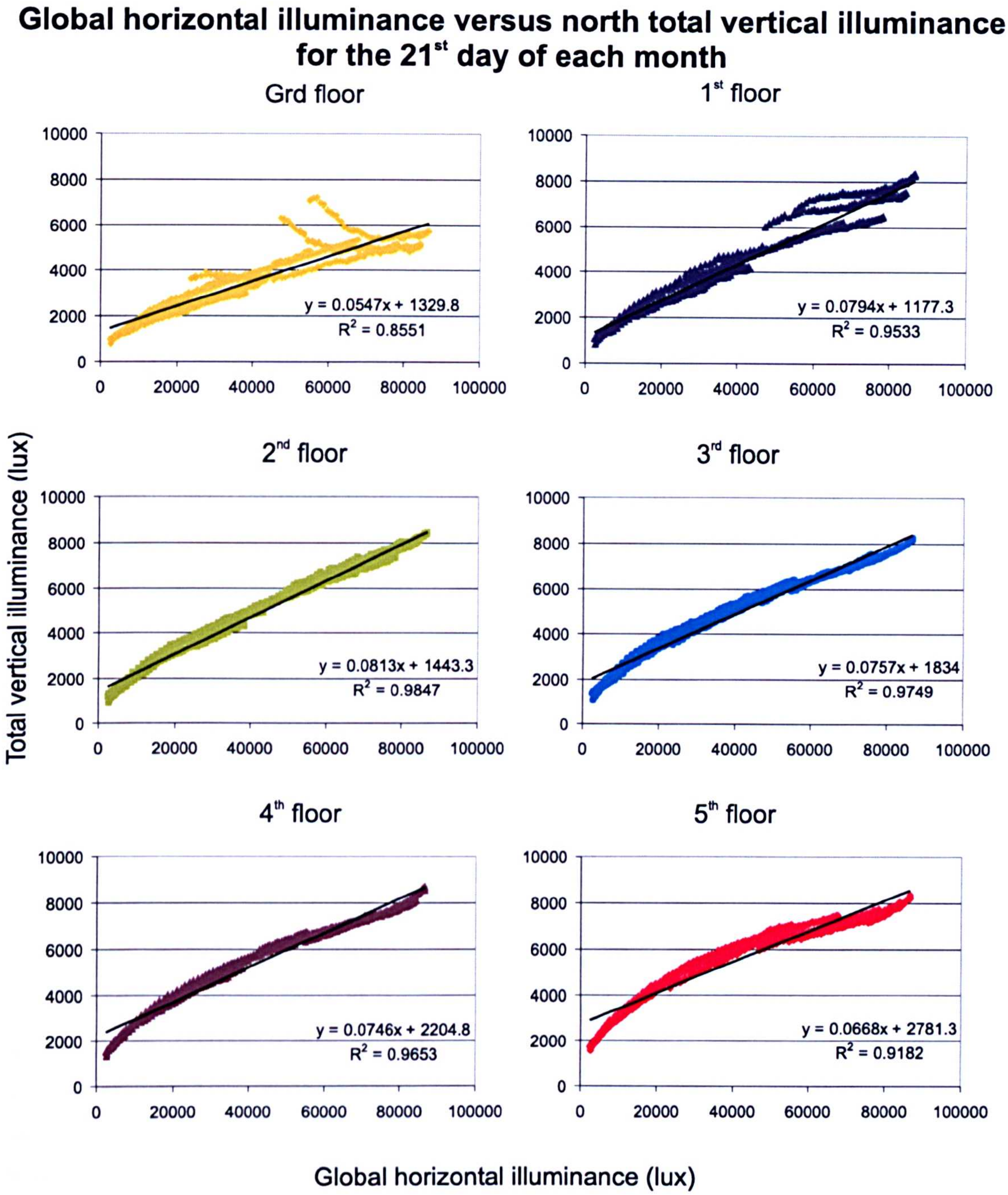



Figure 5.17: Global horizontal illuminance versus total vertical illuminance at different heights on a north facade in an urban canyon of 1:1 ratio for $21^{st}$ the day of each month in Lisbon.

similar to that at the fifth floor. They are around 53 000 and 56 000 lx, respectively, at noon. Also, as the sun's maximum altitude is 51°, the vertical illuminance is about the same as the horizontal illuminance, being around 68 000 lx, at noon.

There is a linear relationship between $E_{gh}$ and $E_{tv}$ on both floors.

At the summer solstice day there are two different scenarios: the first one occurs when the sun is in the south half of the sky hemisphere thereby promoting direct sunlight while the second occurs when the sun is behind the building (solar azimuth *NE* and *NW* quadrants) where the direct component of the sun is excluded. Both scenarios present a linear relationship but with different slopes. In the first one the illuminance on the vertical facade is high due to direct sunlight. However, as the sun's altitude is relatively high, the horizontal illuminance is much higher than the vertical illuminance (around 88 000 lx horizontal illuminance compared to 30 000 lx vertically on both floors, at noon).

At the winter solstice, there is a clear difference in the illuminance for the first floor and the top one. At the first floor the facing building obstruct direct sunlight while the top floor is unobstructed. At noon the illuminance at the lower floor is around 5% of that of the top one. The vertical illuminance on the top floor is much higher than the horizontal unobstructed value, mainly because the sun's altitude is lower, creating a higher horizontal component in comparison to a low vertical one. Also, the sun's azimuth between sunrise and sunset is close to the normal of the obstruction therefore creating a higher contribution towards the obstruction.

For all days considered, a linear relationship between $E_{tv}$ and $E_{gh}$ occurs but with different slopes. However, when the sun is behind the building or blocked by the obstructions, the linear relationship have relatively a similar slope. At noon, when the sun is due south and the geometry of the street does not obstruct the sun, the highest vertical illuminance occurs in the winter solstice (when not obstructed) followed by the equinox and summer solstice days. In a building oriented due south, the vertical illuminance is directly proportional to the cosine of the sun altitude, which is smaller for higher altitude angles. For other times of the day it is also proportional to the cosine of the angle between the horizontal projection of the solar azimuth and the normal of the facade. Small illuminance values occur when the sun is in front of the building but is blocked by the obstruction. Sunlight is reflected at least twice before it reaches the point in the facade.

#### 5.4.1.3.3 East orientation

In the east orientation, fig. 5.19, there are two distinct sets of results: - the first when the sun is in the northeast and southeast quadrant, and is not obstructed; - the second when the sun is behind the building or obstructed by the facing facade. The linear relationship between the global horizontal and vertical illuminance previously

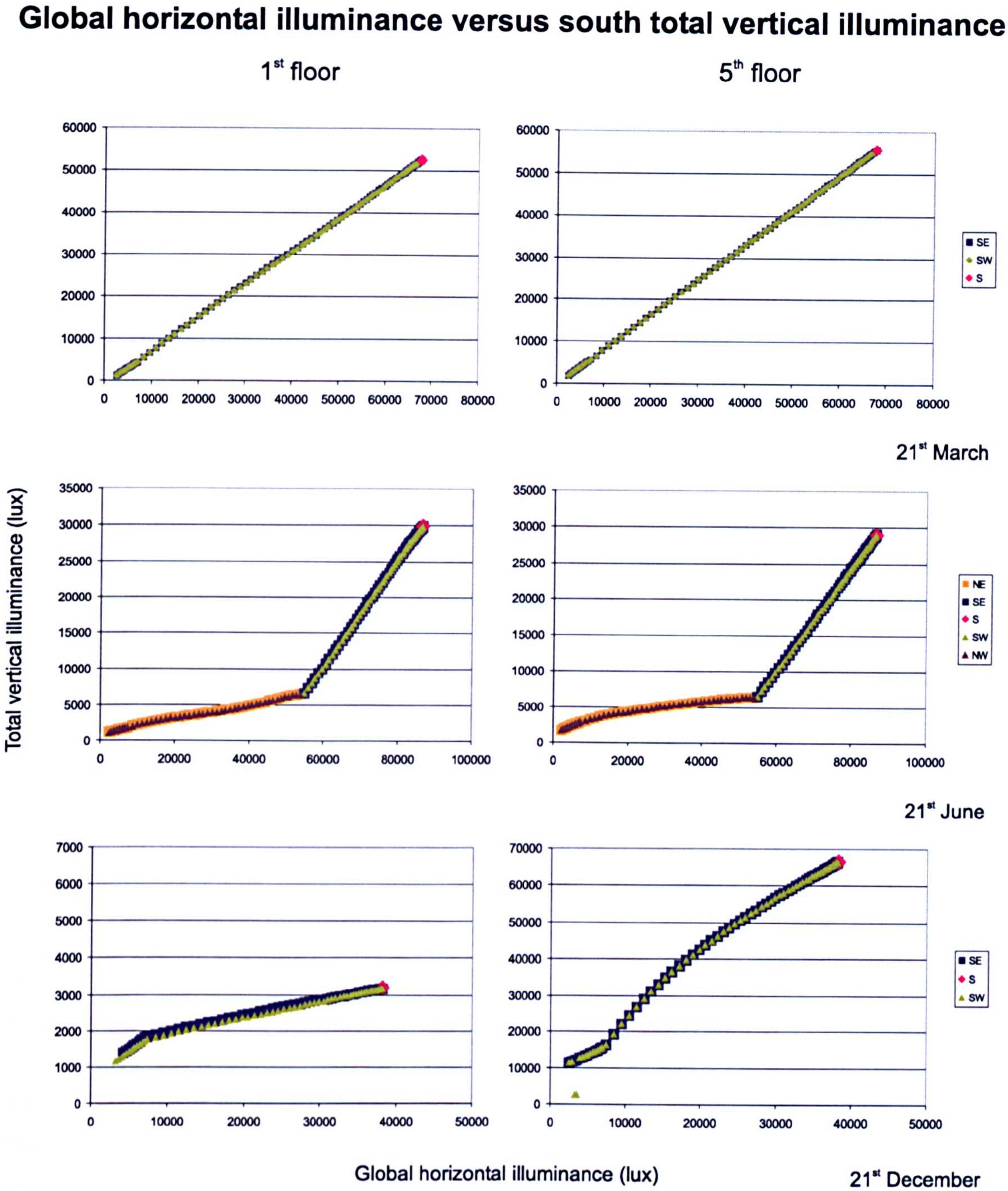



Figure 5.18: Results of the simulations of two points located in the first and fifth floor of a south facade in a urban canyon, for the summer and winter solstices and equinox days.

described stands for this last occurrence. A building facing west produces similar results though mirrored in relation to the *N-S* axis.

An east facing building can have direct sunlight between sunrise and noon solar time. For the remaining period the building daylight relies on the diffuse light from the sky and reflected light from the obstruction and ground.

Fig. 5.20 shows the relation between the global horizontal illuminance and the total vertical illuminance on the $1^{st}$, $3^{rd}$ and $5^{th}$ floors of an east facade for time of day when there is no sunlight incident (sun's azimuth in the *SW* and *NW*).

The total vertical illuminance increases with an increasing global horizontal illuminance, but the rate of increase falls off when the angle of incidence on the obstruction is large, thereby reducing its light contribution to the building. This is visible when the horizontal illuminance is between around 60 000 lx and the 80000 lx at the summer solstice. However, when the sun's azimuth is closer to south, the trendline increases sharply, particularly on lower floors, as the sun's altitude is higher and the ground is almost fully sunlit, resulting in a high ground contribution to the building illuminance.

In an urban canyon with axis north-south, around midday, the flux that reaches the ground floor is higher than that reaching the obstruction. This influences most the lower floors where the ground contributes more to the vertical illuminance of the building.

On the $1^{st}$ floor the highest total vertical illuminance occurs at midday when the ground floor is almost fully sunlit. As the sun moves towards the west, the sun patch in the ground is reduced in size and moves further away from the building. This causes a descending curve in the relationship between global and total vertical illuminance, down to a lowest point when the flux reaching the ground is still high, but the sun patch is furthest away from the building. When the sun altitude reduces to a point where the flux that reaches the obstruction is higher than that reaching the ground, the relationship between global and total vertical illuminance becomes linear.

On higher floors, the ground contribution is less significant. For the periods when the ground receives higher illuminance than the obstruction, the illuminance reaching the point in the facade is low, therefore reducing the slope of the linear relationship.

Overall, the relationship between the horizontal and vertical illuminance is strong with a coefficient of determination between 0.93 and 0.97 for the floors considered.

#### 5.4.1.3.4 Northeast orientation

A building facing *NE* can have sunlight incident in the morning period between sunrise and a solar azimuth 135°.

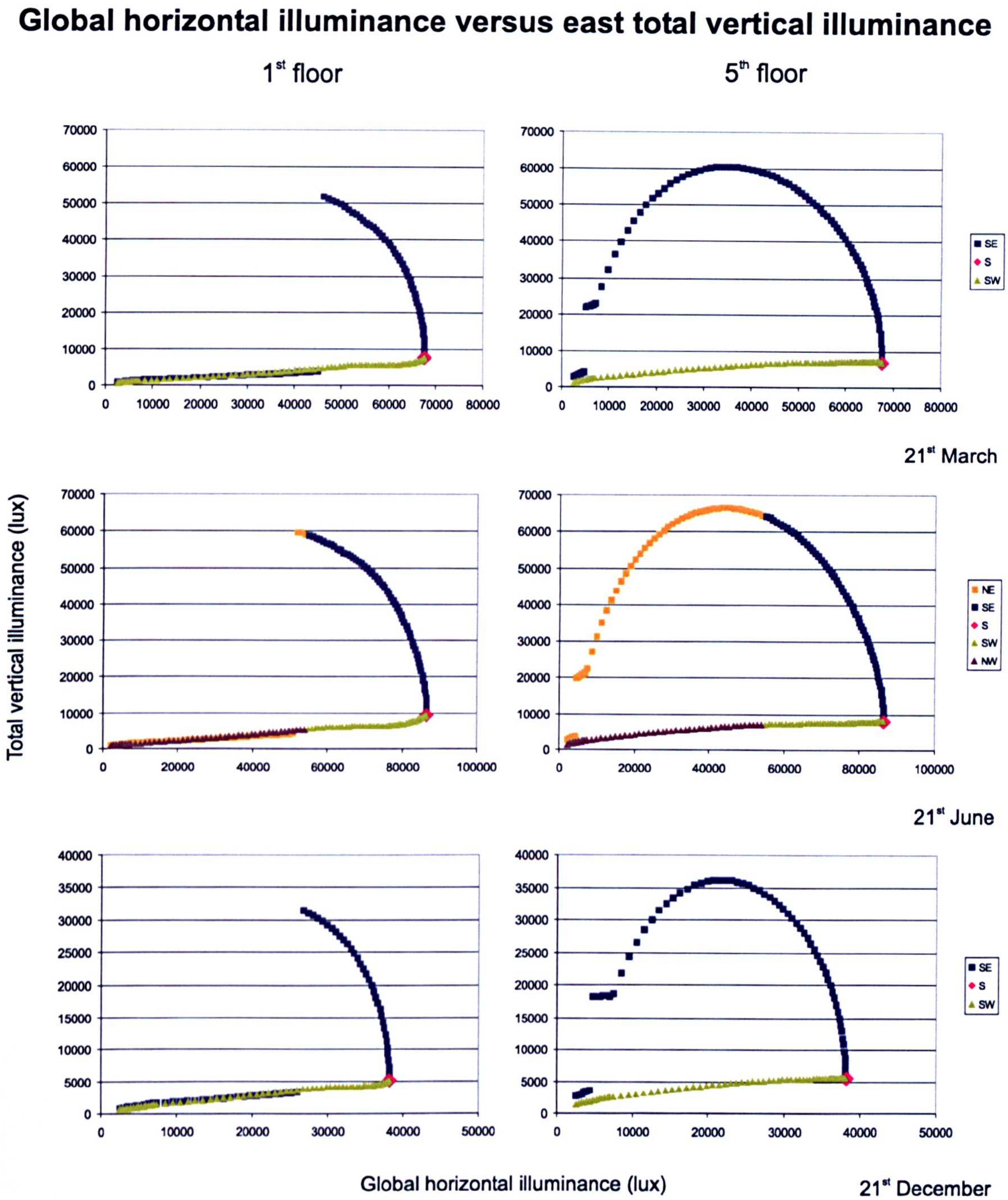



Figure 5.19: Results of the simulations for an east facade at the first and fifth floor in a urban canyon where the distance to the obstruction equals its height, for the summer and winter solstices and equinox days.

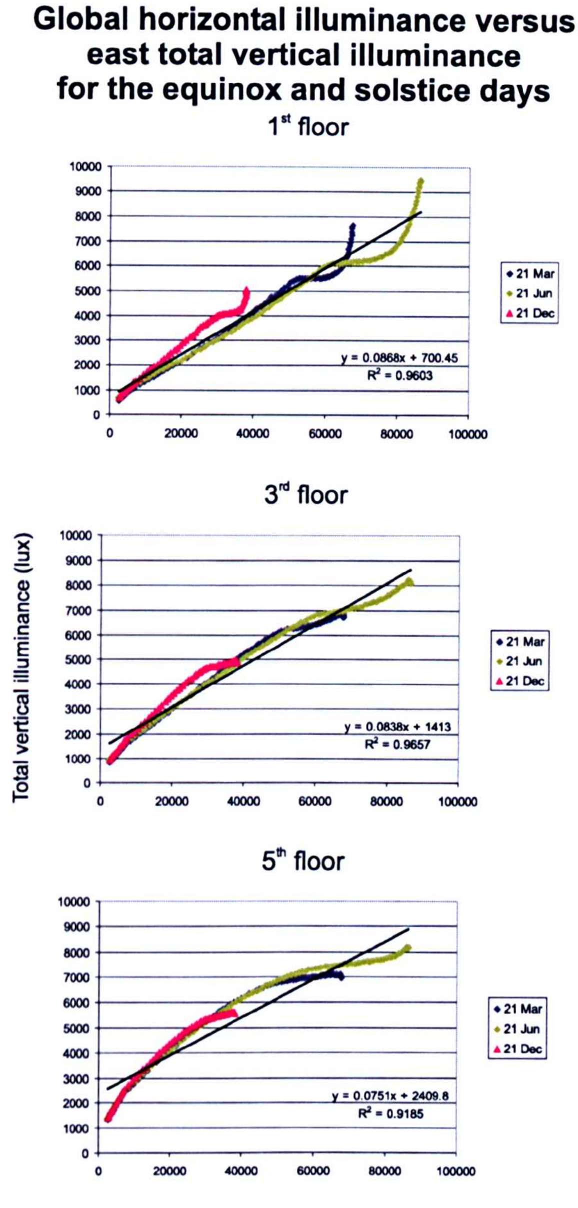



Figure 5.20: Global horizontal illuminance versus east total vertical illuminance on the 1st, 3rd and 5th floor in an urban canyon ratio 1:1 in Lisbon on the equinox and summer and winter solstice days.

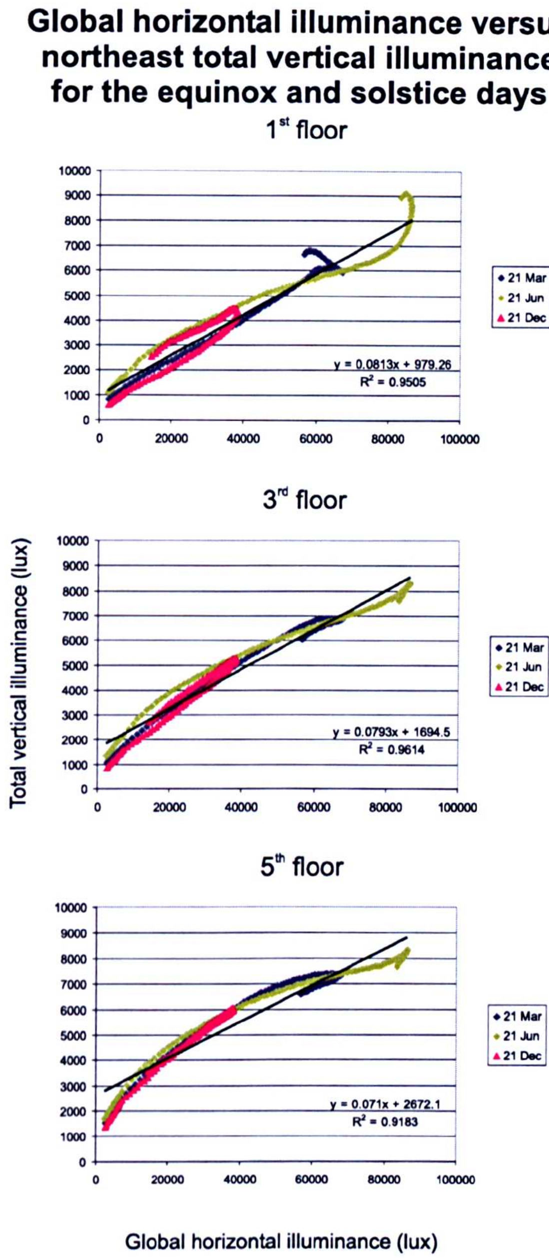



Figure 5.21: Global horizontal illuminance versus east total vertical illuminance on the 1st, 3rd and 5th floor in an urban canyon ratio 1:1 in Lisbon on the equinox and summer and winter solstice days.

Fig. 5.21 presents the global horizontal illuminance versus northeast total vertical illuminance on several floors in an urban canyon with a 1:1 ratio in Lisbon at the equinox, summer and winter solstice. Although the results present some deviation from the linear trendline, they mainly occur when the sun's altitude is relatively high and its azimuth is parallel to the axis of the canyon. This sun's position can reduce significantly the contribution to the vertical illuminance, whereas the ground can be fully sunlit, making a strong contribution to the illuminance on the facade. As the ground contribution mostly affects the lower floors, the graphs show a sharp increase in the vertical illuminance. However, the overall results still indicate a significant correlation between the global horizontal and the total vertical illuminance, with a minimum $R^2$ of 0.9.

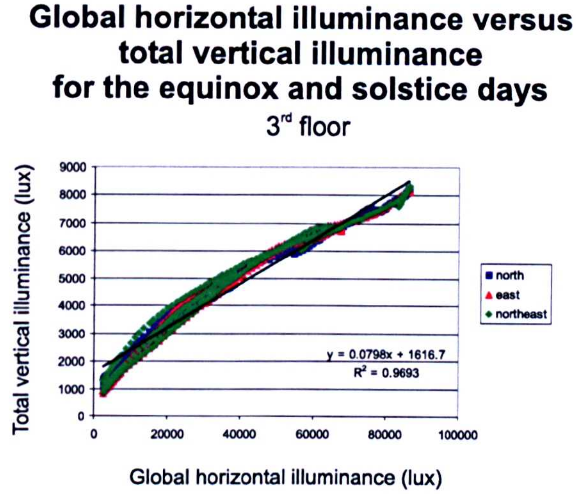



Figure 5.22: Global horizontal illuminance versus north, east and northeast total vertical illuminance on the 3rd floor in an urban canyon ratio 1:1 in Lisbon on the equinox and summer and winter solstice days.

#### 5.4.1.3.5 Combination of orientations

Fig. 5.22 presents the combination of the vertical illuminance on the north, east and northeast facade in an urban canyon, when the sun is behind the building. The linear relationship between the global and the vertical illuminance does not change significantly with orientation. The relatively constant diffuse light from the sky, the diffuse materials of the canyon that disperse the light and the following interreflections within the canyon may explain the uniformity of the results obtained with the three orientations. Although this is beyond the scope of this thesis, if this hypothesis is confirmed, particularly with specular and combined reflective material, it may minimise the importance of orientation when designing buildings for reflected sunlight.

### 5.4.2 London

London is situated further north than Lisbon in the Northern hemisphere.

Summer days are longer than in Lisbon, while winter days are shorter.

The higher latitude will also result in lower maximum solar altitude angles. They are 38, 62 and 15° for the equinox, summer and winter solstice, respectively, at noon.

Lower altitude angles may result in a higher flux of light reaching the vertical facade against the horizontal one. However, it may also extend the periods when the sun is obstructed by the buildings. For the given geometry (height of obstruction is 18 m), this canyon has a 1:1.9 ratio.

#### 5.4.2.1 Global horizontal illuminance versus total vertical illuminance

##### 5.4.2.1.1 North orientation

Fig. 5.23 shows the global horizontal illuminance versus the total vertical illuminance at the 2 m hight, $3^{rd}$ and $5^{th}$ floor of a north facing building in an urban canyon in London with an obstruction below the 25° angle to the horizon.

There is a linear relationship between the global horizontal and the vertical illuminance at the facade. As before in the results for Lisbon, those for the summer solstice tend to deviate from the trendline observed during the winter solstice and the equinox. As this canyon is wider, the influence of the obstruction is reduced. The extended area of the ground will make a significant contribution to the illuminance on the facade. It is still noticeable on higher floors. However, the coefficient of determination for the floors considered are between 0.85 and 0.97.

##### 5.4.2.1.2 East orientation

Results for the east oriented building within a 1:1.9 canyon ratio for London present a similar trend to those in Lisbon. As the canyon is wider, the contribution from the ground reflected light to the vertical illuminance is higher.

## 5.5 Conclusions

**Overcast skies**

Under an overcast sky, the main contribution to the illuminance of the building is from direct skylight. In a 1:1 aspect ratio canyon with 0.2 reflectance on all surfaces, lower floors will have a higher ground component than the obstruction component. They will be around the same on the mid point of the facade, and higher floors will have a higher obstruction contribution. Nevertheless, both ground and obstruction contribute a maximum of 25% of the illuminance on the facade, at ground floor. The lowest contribution of 9% occurs at the top floor.

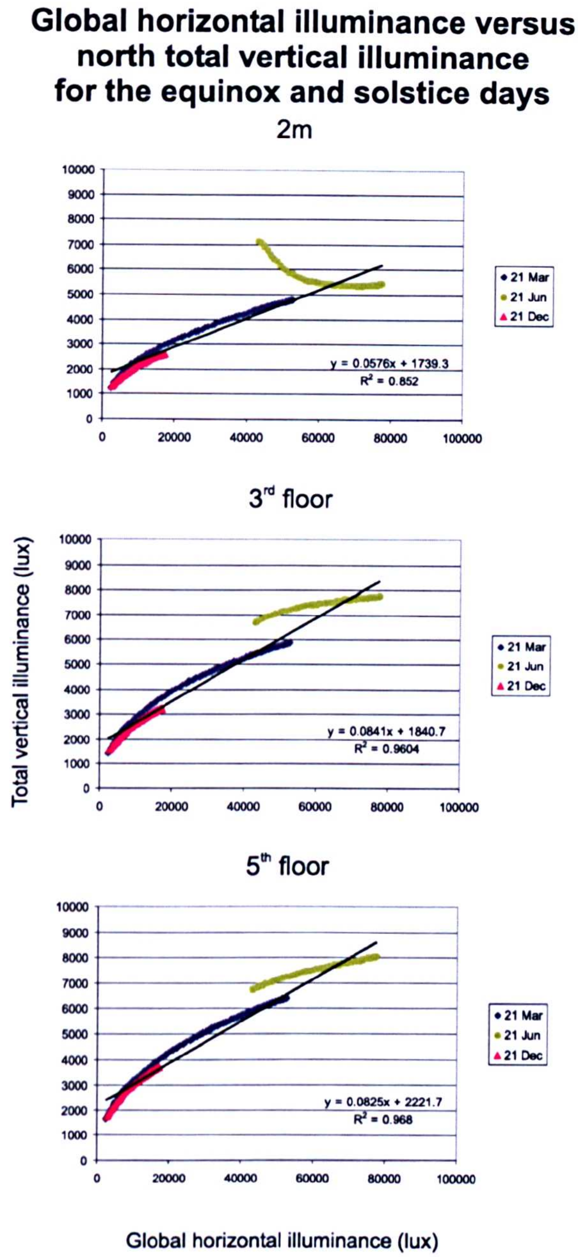



Figure 5.23: Global horizontal illuminance versus north total vertical illuminance on 2 m hight, 3$^{rd}$ and 5$^{th}$ floors in an urban canyon for the 25° rule in London on the equinox and summer and winter solstice days.

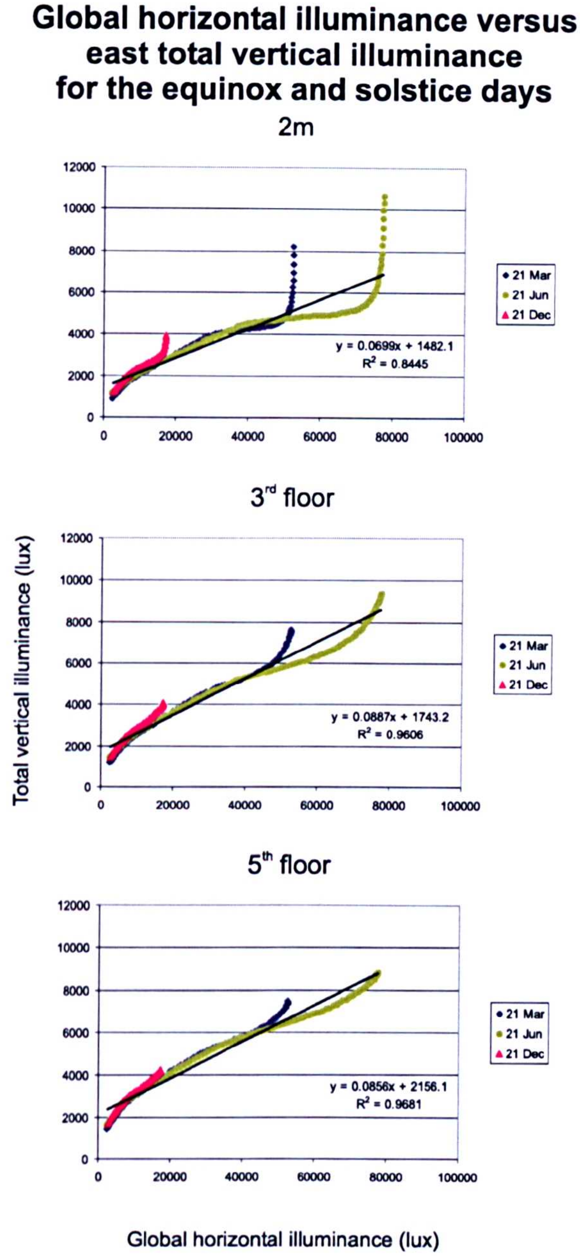



Figure 5.24: Global horizontal illuminance versus east total vertical illuminance on 2 m hight, 3rd and 5th floors in an urban canyon for the 25° rule in London on the equinox and summer and winter solstice days.

The sky contribution increases with the height due to a higher sky visibility. The ground contribution decreases on higher floors, as the distance to the ground plane is bigger. The obstruction contribution is highest in the mid of the facade and reduces at the top and bottom floors.

The sky component doubles from bottom to top floor in a 1:1 ratio canyon, being around 19% on the lowest floor. The ground contribution reduces to a third for the same conditions. It is around 4% at the ground floor. The obstruction component is the one that varies least with window height. For this equal ratio canyon, the obstruction component is below 3% on all floors.

A variation of the canyon geometry strongly affects the illuminance on the facade, particularly on lower floors. Ground floor windows receive a lower illuminance than top floor ones for narrow and wide canyons. However, this reduction is significant in a narrow canyon (1:0.5), where the illuminance on the bottom floors is less than one third of the value on the top floors. In wide canyons (1:2), the difference in the illuminance between floors is reduced and illuminance at the bottom floor is around 90% that of the top floor. Likewise, the variation of sky component for different ratios is significant at lower floors but is reduced at the top floor. The ground component increases with wider canyons but remains relatively proportional for different floor heights. The obstruction component increases for narrow canyons. However, large canyons tend to smooth out the contribution (higher in the mid floor for narrow canyons) for all floors.

A highly reflective obstruction may significantly increase the illuminance at the building facade. While the contribution from reflected skylight from obstructions and ground is around 18% on the middle of the facade for a 0.2 reflectance of the obstruction, it increases to 21, 29 and 36% for 0.3, 0.5 and 0.7 reflectance, respectively. It can be argued that the reflectance of the building facade may be reduced. Sporadic facade maintenance, low diffuse reflectance (around 14%) of the glazing materials, dark colour and roughness of the surfaces all result in a reduction of the facade reflectance. Theoretical values traditionally used in simulations and scale models may overestimate the reality.

### Clear skies

Reflected sunlight from obstructions and ground can have a significant contribution to the illuminance of buildings when there is no sunlight incident on the facade.

Although the percentage of the contributions may vary significantly throughout the day (obstruction and sky) and year (ground and obstruction), the contribution of reflected light from the ground and obstruction is higher than the contribution of the sky, except in the early hours of the day. This reflected contribution remains relatively constant during the year, being around 60% at noon.

With a clear sky distribution, sunlight availability will be significantly affected by the orientation of the building and position of the sun in the sky. There are clearly two results, one when the sun is incident on the buildings and the other when the sun is reflected by obstructions and ground.

Just like the results from the physical measurements in the urban canyon, those from the RADIANCE simulations demonstrate a linear relationship between the global horizontal illuminance and the total vertical illuminance when the facade is not receiving direct sunlight, except under specific conditions occurring mainly in the summer when the street is sunlit. This correlation may be expressed in terms of $E_{tv} = k \cdot E_{gh} + C$ where $k$ and $C$ are constants.

Initial results analysed for the equinox and solstice days, later verified for the $21^{st}$ of each month, confirmed that this relationship does not change significantly during the year. Exceptions occur in the summer but do not appear to weigh significantly in the overall calculation. In fact, a single trendline still presents significantly high coefficients revealing a close estimation to the actual data. A general equation can therefore be the basis of a simplified calculation, representative for the whole year with a reduced error.

The reflectance of the surfaces strongly affect the illuminance of the buildings. The coefficients of the equation increase significantly with higher reflectances. Even with highly reflective paint in the opaque areas, the effective reflectance may be reduced, particularly considering that window reveals and setbacks or balconies may cast shadows. A conservative value of 0.2 may be a realistic value to consider in daylight studies.

The variation of the canyon ratio from narrow to wide may affect the slope of the equation for solar illuminance but remains relatively uniform considering the global illuminance.

In the 6 storey canyon, the coefficient $k$ remains relatively constant on all the floors, particularly for lower reflectances. An adoption of a single value may then be sufficient for simple calculations. In the initial design stages such simplifications may be useful to provide quick results without significantly compromising future stages of design.

The constant $C$ is mainly the contribution of the diffuse sky and is higher for high floors.

Analysis of results for the north, east and northeast orientation confirms that the linear relationship occurring when sunlight may be reflected from obstructions and or ground does not change with orientation.

This linear relationship applies when the facade is not receiving direct sunlight, which corresponds to a significant part of the daylight period on a north facade and half of the daylight hours for the east or west orientation. In the remaining periods, when the sun is incident on the facade, the relationship between the global and the vertical illuminance will be linearly dependant on the angle of incidence of sunlight.

# Chapter 6

# Analytical method - analysis of data

## 6.1 Introduction

This chapter presents results calculated with the analytical method described in chapter 3. The solar normal illuminance and the diffuse horizontal illuminance used in the calculation were derived with RADIANCE from a CIE clear sky with turbidity 2.75.

Sunlight reflected from the obstruction and ground is analysed separately and the relationship between solar horizontal and vertical illuminance is discussed.

The effects of a variation of the reflectance of the obstruction and ground as well as results for different latitudes are presented.

Although this analytical calculation has limitations on accuracy compared to a simulation with RADIANCE or to real measurements, as explained in chapter 3, section 6.6 makes a comparison of results between both methods. The main advantage of this calculation is the possibility of obtaining rapid results. It allows quick alterations of parameters in a spread sheet instead of performing a time consuming simulation.

## 6.2 Reflected sunlight

Fig. 6.1 presents the contribution of sunlight reflected from an obstruction or ground to the solar reflected vertical illuminance on the north gnd, $1^{st}$,$2^{nd}$,$3^{rd}$, $4^{th}$ and $5^{th}$ floors in an 1:1 urban canyon with 0.2 reflectance on all surfaces, in Lisbon on the equinox, summer and winter solstice days. The graphs show a direct proportionality between the solar horizontal and solar reflected vertical illuminance at the equinox and winter solstice days. On the summer solstice day there is still a linear relationship between the solar horizontal and the solar vertical illuminance but it is offset by a constant. Furthermore, this constant is negative when the contribution is from the obstruction. This may be due to the sun's angle of incidence on the surfaces

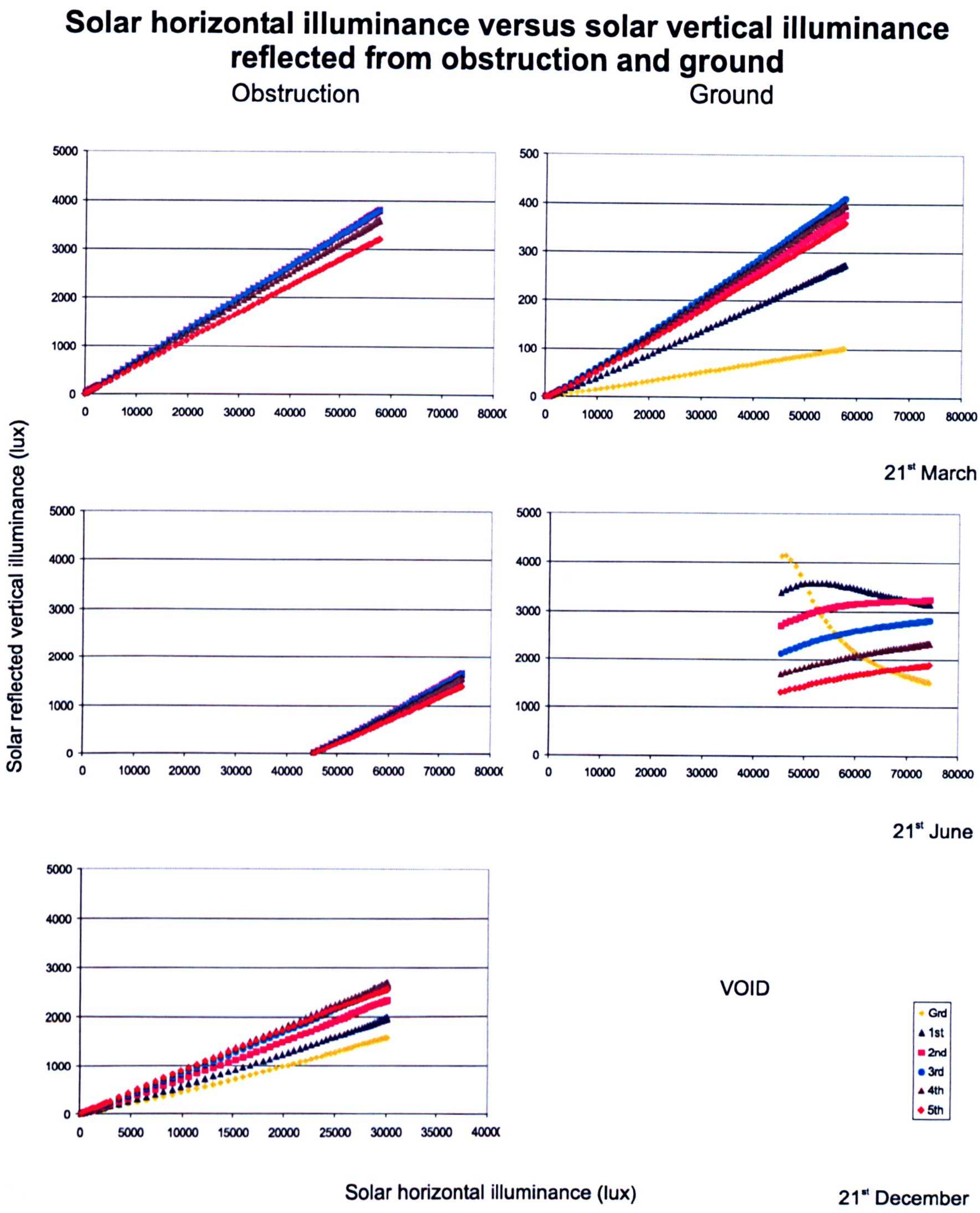



Figure 6.1: Solar horizontal illuminance, $E_{sh}$, versus solar vertical illuminance, $E_{sv}$, for sunlight reflected from obstruction or ground on a north gnd, $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ and $5^{th}$ floors in an urban canyon ratio 1:1 in Lisbon on the equinox, summer and winter solstice days with the analytical calculation. All surfaces (ground, obstruction and building) have 0.2 reflectance.

of the canyon. During the summer, when the sun is in front of the obstruction its altitude can be high, therefore it's mainly incident on the horizontal plane. This results in a high horizontal illuminance and a reduced vertical one. The solar vertical illuminance is zero when the solar azimuth is parallel to the canyon axis, because the cosine of the horizontal projection of the angle of incidence (HSA) is zero.

When the ground plane is almost fully sunlit, it's reflected sunlight contribution to the building may be high, particularly on lower floors. Occasionally, these lower floors may present a smaller illuminance on the facade due to reflected sunlight from ground than higher ones. See the ground contribution on the ground and first floor at the summer solstice in fig. 6.1. This may occur when the sun patch on the ground is more distant from the building and the angle to the point in the facade is too oblique. This results in a reduced configuration factor between the sun patch and the lower points on the facade and a bigger one on higher floors, resulting in lower illuminance on the lower floors than on the higher ones. See fig. 2.13 on page 32 for areas of the ground likely to contribute to the illuminance on the facade. In a canyon with equal height/width ratio and equal surface reflectance (ground, obstruction and building), the light reflected from the ground is around 10% of the light reflected from the obstruction that reaches the vertical facade at the equinox. There is no contribution from reflected sunlight from the ground during the winter as the geometry of the canyon obstructs the sun's access to the ground. With the exception of the summer period, where the ground contribution can be high, vertical surfaces contribute more to the illuminance of the building in comparison to the ground. Clearly, this conclusion applies for this latitude and canyon geometry and may vary for other situations. On one hand, higher latitudes will effectively enforce this conclusion as the sun's maximum altitude will be lower therefore more light will be incident on the vertical surface whereas the chances of reflected light reaching the ground plane will be lower. On the other hand, wider canyons may invert the effects of the contributions of the obstruction and ground to the building illuminance. Firstly, the illuminance on the facade due to reflected light from the obstruction may be reduced as the emitting surface is further away. Secondly, a wider canyon will have a wider ground sunlit area, increasing its contribution to the illuminance of the building.

When sunlight is incident on the obstruction its highest contribution is to the middle floors or the top ones when the sun patch on the obstruction is of reduced size as a result of low solar altitude angles and narrow canyon geometries. This applies for Lambertian surfaces where a higher reflected component is normal to the surface therefore affecting the opposite area of the facade. A specular component may contribute more to the illuminance of lower floors and ground as a result of the downward redirection of the sunlight after reflection on the obstruction.

## 6.3 Daylight

Fig. 6.2 presents results from the analytical calculation in terms of global vertical illuminance versus north total vertical illuminance on the gnd, 1$^{st}$, 2$^{nd}$, 3$^{rd}$, 4$^{th}$ and 5$^{th}$ floors in an urban canyon ratio 1:1 in Lisbon on the equinox and summer and winter solstice days. In a similar way to results presented on the previous chapters, there is a linear relationship between the global horizontal and vertical illuminance at several heights on the facade.

Although results from the calculation tend to be higher than those obtained with the computer simulation, see fig. 6.2 on the next page and fig. 5.13 on page 117, they follow a similar trend. Therefore they are sufficient to provide general guidelines, although not to predict values. Besides, even the simulations should not be assumed as an absolute prediction of what the reality may be.

As before, the slope $k$ does not change significantly for different floors and the constant $C$ tends to be higher for higher floors. An exception again occurs on the ground and first floors, where the lower floor exhibits a constant than in the higher floor due to a higher contribution from an almost fully sunlit ground in the summer period.

## 6.4 Variation of ground and obstruction reflection

Fig. 6.3 on page 146 represents the global horizontal illuminance versus the total vertical illuminance for various combinations of the reflectance of the ground and obstruction between 0.2 and 0.6 in a 1:1 urban canyon in Lisbon.

The higher the reflectance of the ground and obstruction the higher the illuminance on the facade. Nevertheless, a high ground reflectance mainly increases the illuminance during the summer period whereas a high obstruction reflectance significantly increases the illuminance on the facade during the winter and equinox days.

When the reflectance of the obstruction and ground doubles there is an increase of around 180% in the illuminance on the facade. However, when the obstruction reflectance doubles but the ground reflectance remains constant the illuminance increases by 130% at the summer solstice and by around 160% on winter solstice and equinox days. If the ground reflectance doubles and the obstruction remains constant there is an increase of 145% for the summer and around 115% for the winter solstice and equinox days. When the reflectance of both surfaces triples the illuminance in the facade increases by around 280%.

The decision to increase the reflectance of the ground and or obstruction may be based on the season for which a higher illuminance is desired. Nevertheless, an increase in reflectance of both surfaces will result in an higher illuminance due to a

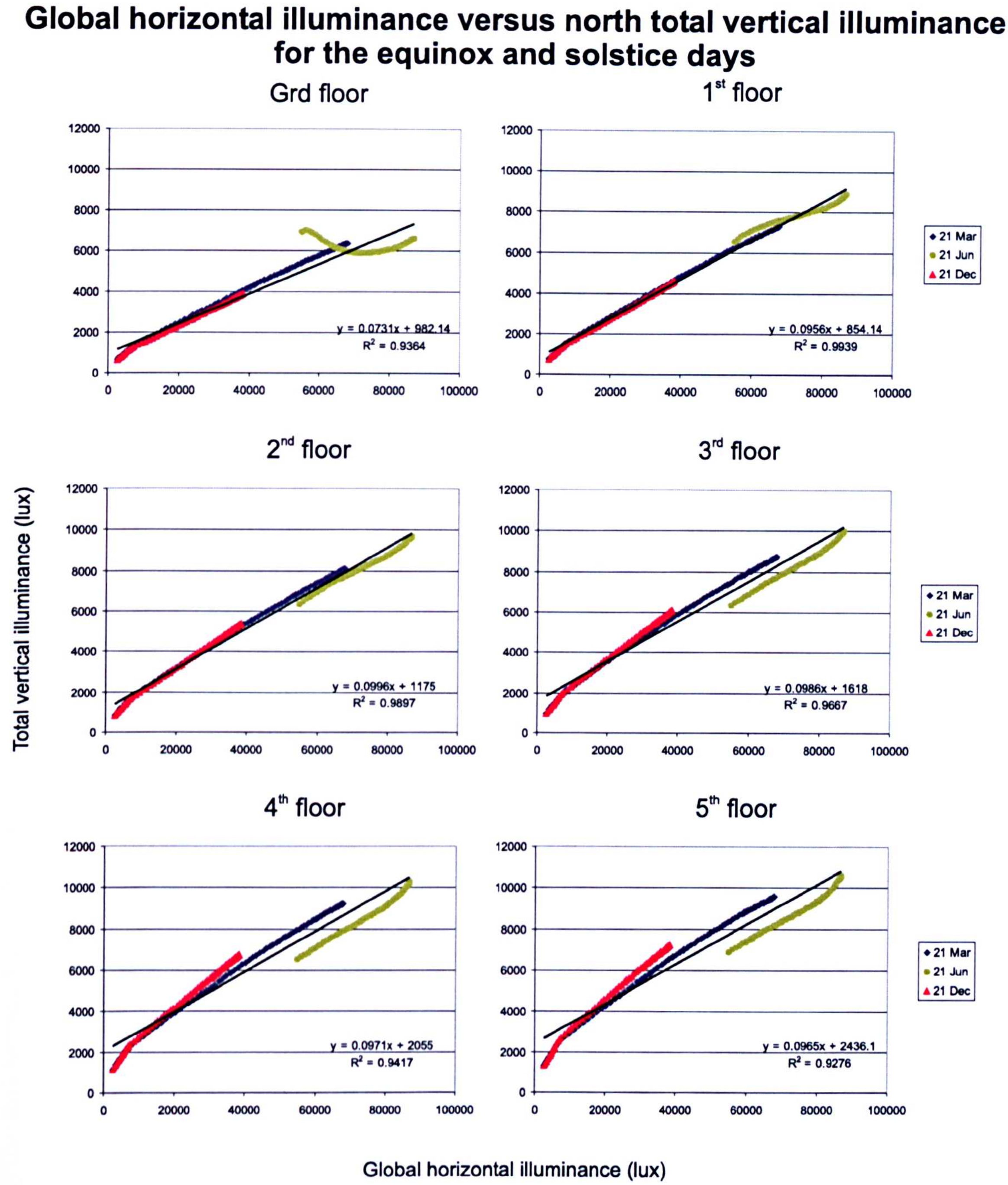



Figure 6.2: Global vertical illuminance versus north total vertical illuminance on the gnd, 1st, 2nd, 3rd, 4th and 5th floors in an urban canyon ratio 1:1 with 0.2 surface's reflectance in Lisbon on the equinox and summer and winter solstice days with the analytical calculation.

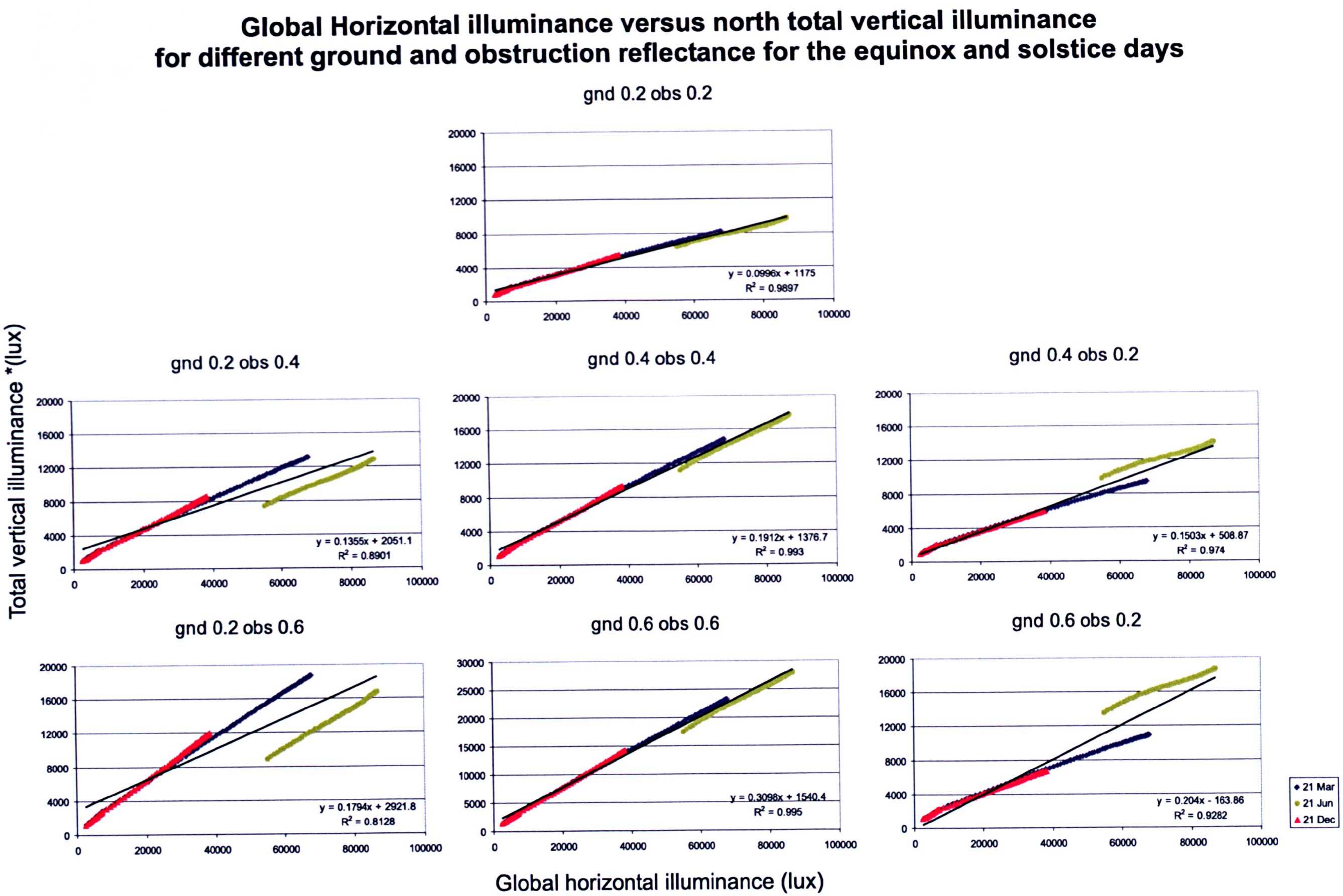



Figure 6.3: Global horizontal illuminance versus $2^{nd}$ floor north total vertical illuminance with variation of the ground and obstruction reflectance on a urban canyon ratio 1:1 in Lisbon on the equinox and summer and winter solstice days.

greater interreflected contribution in the canyon.

## 6.5 Variation of the latitude

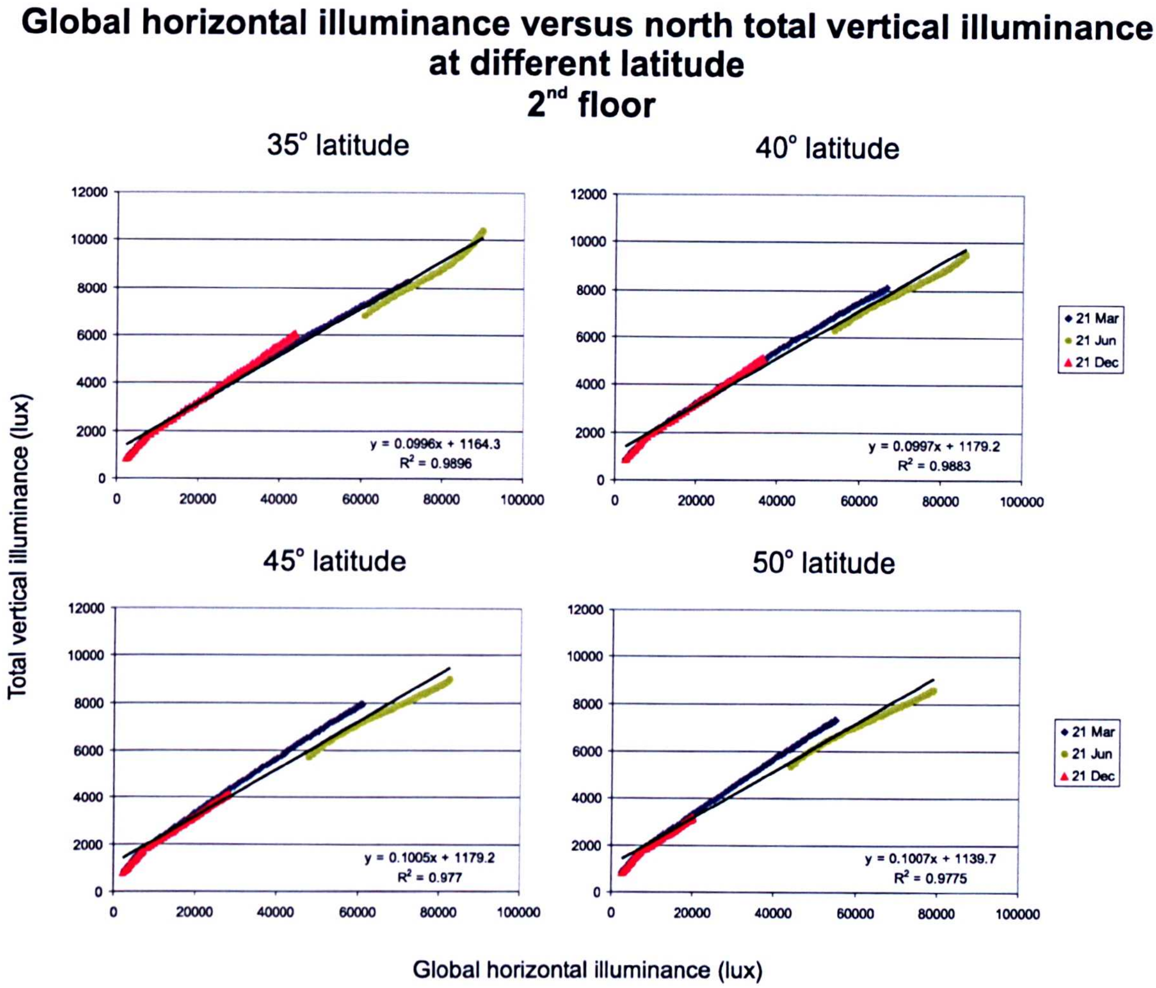



Figure 6.4: Global horizontal illuminance versus 2$^{nd}$ floor north total vertical illuminance on an 1:1 canyon with 0.2 reflectance in all surfaces for latitudes 35, 40, 45 and 50° in the northern hemisphere.

Fig. 6.4 represents the global horizontal illuminance plotted against the total vertical illuminance on the 2$^{nd}$ floor for different latitudes, varying from 35° till 50° with a 5° interval in the northern hemisphere.

An alteration of latitude does not affect the relationship between the global horizontal and the total vertical illuminance on a north facade in a 1:1 urban canyon when the sun is behind the building. All graphs produce similar coefficients, in terms of slope and intersection of the $y$ axis.

Table 6.1 on page 149 shows the slope and intersection coefficients for the equation previously defined (see eq. 4.1 on page 73) and a coefficient of determination on various floors for different latitudes in a 1:1 canyon with 0.2 reflectance on all surfaces. As before, there is no significant variation in the slope for different latitudes. Although the constant varies more on higher floors than on the mid floors for different latitudes, it is still fairly constant, therefore it does not alter the conclusion drawn for the second floor.

## 6.6 Model validation of analytical calculation

This section presents a simplified comparison of results from the calculation against those from the RADIANCE simulations. The sun and sky contributions are addressed separately and the arguments for the differences are presented. A suggestion for a reducing the error between the two methods is presented in appendix J.

### 6.6.1 Solar illuminance

Fig. 6.5 presents a comparison between results for the solar vertical illuminance obtained with the analytical calculation and those obtained using simulations with RADIANCE.

Results obtained with the calculation tend to overestimate the illuminance compared to those obtained with RADIANCE for high solar altitudes and underestimate it for lower solar angles. At altitude angles lower than 10° RADIANCE considers the solar brightness constant, whereas the formula progressively reduces it to zero, therefore the error increases substantially. For this reason, results for solar altitude angles lower than 10° should be ignored.

The worst case results occur at the winter solstice with a difference of around 30% before 9 am and after 3 pm. At noon, this difference reduces to 6%. On average the error is less than 7% for solar altitudes above 10°.

The differences in the results obtained with the calculation and with RADIANCE mainly occur when the ground is sunlit. This may be explained because of the different approaches taken by both methods. In the analytical calculation the sun patch on the ground is projected on the obstruction. Although under the same solid angle, the latter position will be further away from the building. The configuration factor for an element parallel to a surface will be higher than the configuration factor for an element perpendicular to the surface. On the other hand, RADIANCE stores information on the sampled rays reaching a surface in terms of the distance, direction and brightness of its contribution. Therefore, it is likely to be more accurate in calculating the contribution to the illuminance on the facade than the analytical calculation.

Fig. 6.6 presents the difference between the results from the analytical calculation and the RADIANCE simulation on the $5^{th}$ floor of a building in an urban canyon for the equinox and solstice days.

| Latitude | 35° | | | 40° | | | 45° | | | 50° | | | 55° | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| coefficients | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ | k | C | $R^2$ |
| Gnd | 0.08 | 847 | 0.96 | 0.07 | 1008 | 0.92 | 0.07 | 1042 | 0.90 | 0.07 | 955 | 0.93 | 0.07 | 831 | 0.97 |
| $1^{st}$ | 0.10 | 754 | 0.99 | 0.09 | 885 | 0.99 | 0.09 | 970 | 0.97 | 0.09 | 961 | 0.97 | 0.09 | 896 | 0.98 |
| $2^{nd}$ | 0.10 | 1164 | 0.99 | 0.10 | 1179 | 0.99 | 0.10 | 1180 | 0.98 | 0.10 | 1140 | 0.98 | 0.10 | 1063 | 0.98 |
| $3^{rd}$ | 0.10 | 1649 | 0.96 | 0.10 | 1605 | 0.97 | 0.10 | 1528 | 0.96 | 0.10 | 1436 | 0.97 | 0.10 | 1319 | 0.97 |
| $4^{th}$ | 0.10 | 2095 | 0.93 | 0.10 | 2035 | 0.94 | 0.10 | 1914 | 0.95 | 0.11 | 1780 | 0.96 | 0.11 | 1623 | 0.96 |
| $5^{th}$ | 0.10 | 2467 | 0.92 | 0.10 | 2416 | 0.93 | 0.10 | 2278 | 0.94 | 0.11 | 2123 | 0.95 | 0.11 | 1937 | 0.96 |

Table 6.1: Variation of the latitude for a 1:1 canyon with 0.2 reflectance for all surfaces.

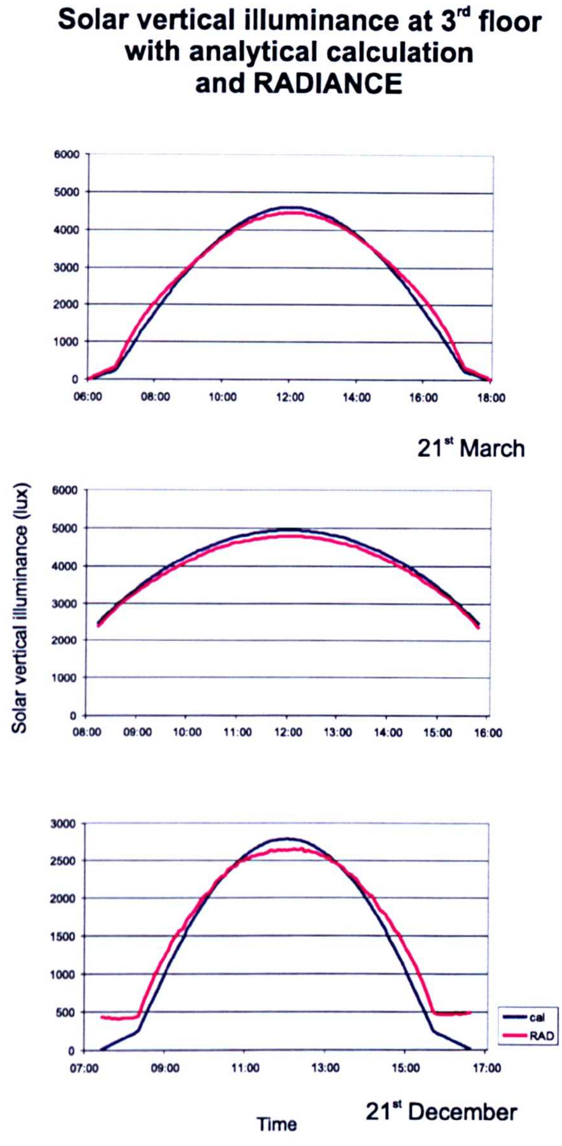



Figure 6.5: Solar vertical illuminance on a north facade in a 1:1 urban canyon calculated with the analytical calculation and with RADIANCE at the spring equinox, summer and winter solstice in Lisbon. All the surfaces have 0.2 reflectance. The solar illuminance on the facade includes interreflections within the canyon. The graph for 21st June excludes the times of the day when sunlight is incident on the facade.

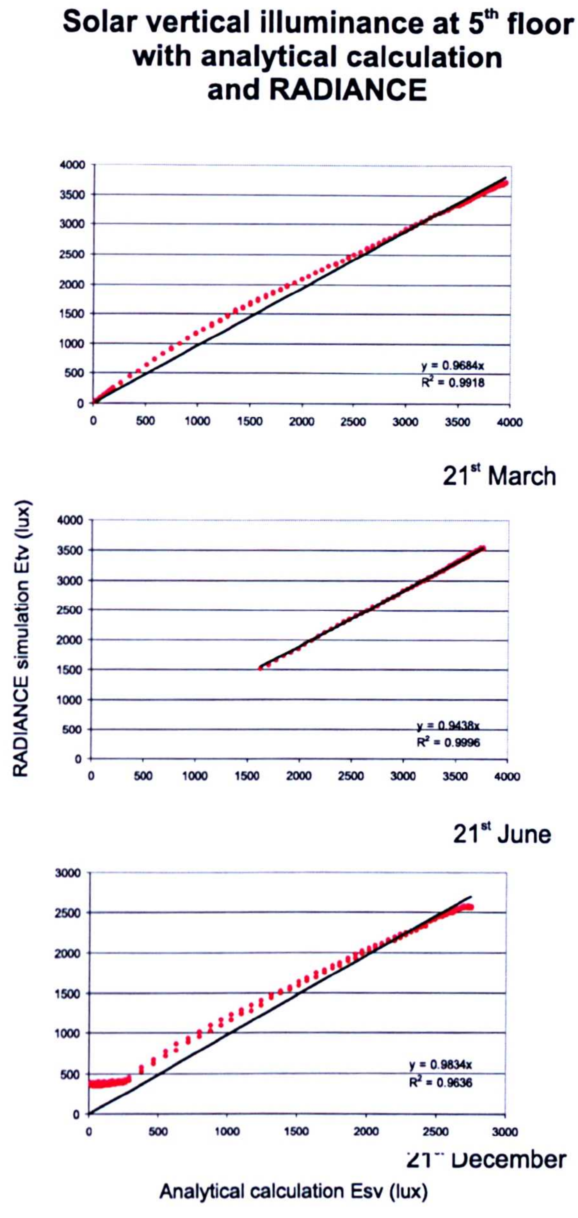



Figure 6.6: Comparison of results for the analytical calculation versus RADIANCE simulation on the solar vertical illuminance at $5^{th}$ floor on a north facade in a 1:1 urban canyon at the equinox and solstice days in Lisbon. The plot for $21^{st}$ June only refers to the time of the day when sunlight is not incident on the surface.

There is a strong relationship between results, with a coefficient of determination higher than 0.96 in the results for the three days presented. The slope of the linear trendline indicates that the results from the analytical calculation are higher than those produced with RADIANCE. The lowest slope is 0.94 and the highest 0.96. As they all approach unity they confirm a reduced error between the calculation and the simulation.

### 6.6.2 Diffuse illuminance

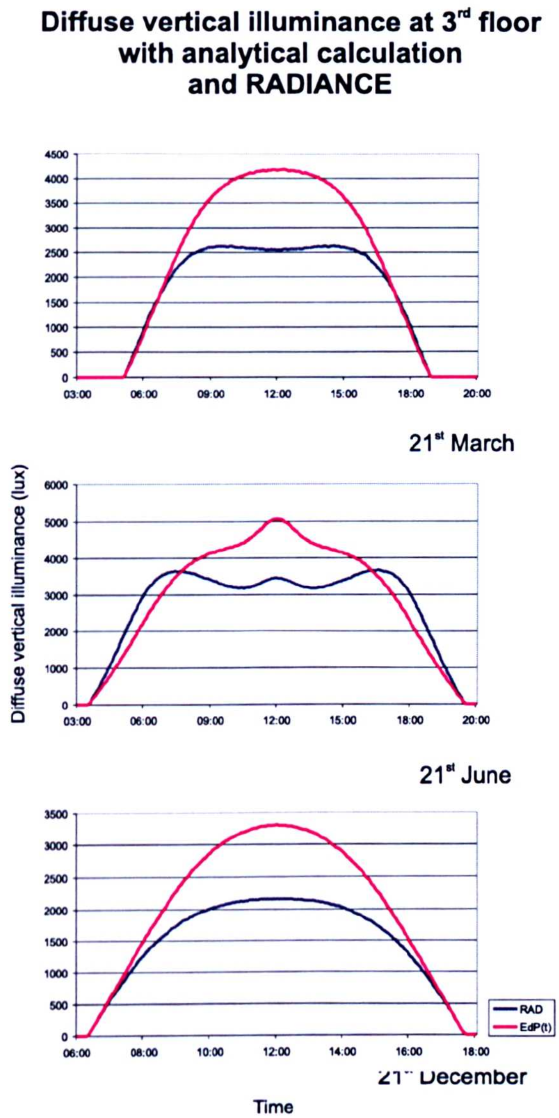



Figure 6.7: Diffuse vertical illuminance on the 3$^{rd}$ floor in a 1:1 canyon calculated with RADIANCE and the analytical calculation at the spring equinox, summer and winter solstice in Lisbon with a clear sky.

Fig. 6.7 presents a comparison of results for the diffuse sky contribution obtained with the analytical calculation and the RADIANCE simulation. The main reason for the difference of results between the two methods is a result of the assumption made in order to simplify the diffuse calculation, which considers the sky to have an uniform distribution. A clear sky distribution is quite complex and the brightness of any sky element is dependent on the position of the sun, which changes during the course of the day, therefore a simplification is compulsory for basic calculations. A building facing north mainly sees the less bright part of the sky (opposite to the sun position around a 90°), see fig. 6.8. An exception is made for the early and late hours of the day during the summer period, when the sun is in front of the building. As the calculation considers a uniform sky which produces a horizontal diffuse illuminance equal to the one produced by a clear sky, there are some sky elements that will be brighter than they would in a clear sky model. Therefore results from the calculation will overestimate the daylight levels compared to those from RADIANCE.

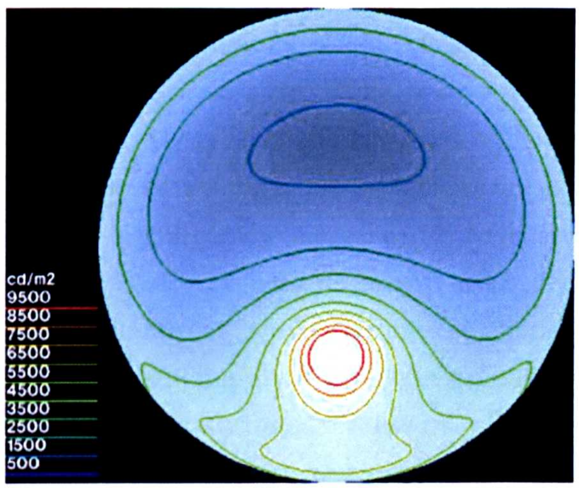



Figure 6.8: RADIANCE picture with luminance contour lines of a clear sky distribution without the source sun on $21^{st}$ March at 12:00 h solartime in Lisbon.

As previously seen in fig. 5.10 on page 113 the diffuse sky contributes around 40% to the illuminance reaching a north building in an urban canyon with a ratio of 1:1 for the periods without direct sunlight. Although the reflected light from the obstruction and ground can be considered as the main source of daylight, an effort should be made to predict the diffuse contribution more accurately.

An attempt to reduce the error derived from the simplification assumed is presented in appendix J. It takes into consideration the horizontal diffuse illuminance result of the half sky vault 'seen' by the facade, multiplied by a constant, instead of the whole sky.

## 6.7 Conclusions

Reflected sunlight is an important contribution to the illuminance of buildings when the sun is behind the building. In a 1:1 canyon reflected sunlight from vertical surfaces contributes significantly to the illuminance of the building in comparison to reflected sunlight from the ground. The contribution from the obstructions is around ten times higher than the contribution from the ground at the equinox in a canyon in Lisbon. For higher latitudes this difference may increase as the sun reaches lower altitude angles, therefore predominantly being incident on vertical surfaces. During the summer however, the ground contribution can be high, but for the remaining period of the year it is reduced or is even nonexistent as the lower winter sun angles may never reach the ground in a canyon. This conclusion is drawn for 0.2 reflectance on building surfaces and ground. Higher reflectance will significantly increase the illuminance of the building. However, the effects of reduced facade maintenance, dark colours, window reveals, setbacks and balconies casting shadows may significantly reduce the effective reflectance of the facades. A conservative figure of 0.2 reflectance may not be far distant from the reality.

Surface reflectance may significantly increase the reflected contribution. However increasing the reflectance of obstructions mainly affects the illuminance on the building during the winter and spring, while an increase of the ground reflectance affects the illuminance on the facade mainly during the summer period. Good daylight design may take advantage of this and an increase of reflectance of the obstruction or ground may vary accordingly to when during the year a higher illuminance is desired. If sunlight is desirable during the winter and spring, attention should be paid to increasing the reflectance of the obstruction. If sunlight is expected during the summer, then a higher reflectance of the ground should be adopted.

Although absolute values of illuminance are strongly dependent on sun altitude and therefore are variable for different times of day and latitudes, the linear relationship between the global and the total vertical illuminance on a north facade remains relatively constant at the equinox and solstice days. Moreover, the linear relationship does not alter with latitude. It was argued that this linear relationship can be representative of the year condition with an acceptable error. Moreover, results for different latitudes shows that this relationship does not change significantly with latitude, so it can be used as the basis of a calculation to apply for clear skies in urban canyons in Europe.

The analytical calculation has been shown to be a valid tool for quickly analysis parameters of interest for a daylight analysis in an urban canyon. Although a comparison with RADIANCE simulations produces similar results for solar illuminance, attention has been drawn to some of its limitations, particularly for the simplified sky distribution adopted. Nevertheless, considering that reflected sunlight is the main contribution (around 60%) to the illuminance of buildings when the sun is behind the building, even when the calculation overestimates the skylight, it is still within an acceptable accuracy.

# Chapter 7

# Internal daylight calculation

## 7.1 Introduction

Previous work has analysed daylight at a facade of a building facing an urban canyon. This chapter will consider daylight in a space behind a facade looking into an urban canyon.

The most common method of daylight analysis is the daylight factor approach, where the diffuse internal horizontal illuminance is directly proportional to the diffuse external horizontal illuminance.

Initially, the daylight factor calculation was based on a uniform sky distribution. Later, this isotropic sky distribution was substituted by the CIE overcast model, more closely modelling real cloudy sky conditions. More recently, the CIE has published a standard general sky, therefore more distributions are expected to be used in daylight calculations. However, by definition, sunlight is excluded from the daylight factor calculation, limiting the light sources to direct and diffuse ones from the sky. Besides the simplicity of the calculation it has been widely accepted on the basis of its independence of orientation. It will be argued that, whereas this characterisation is appropriate for heavily cloudy climates, it should not be used in sunny climates.

A simple calculation that takes into consideration the sunlight component and may apply for any day of the year is the basis of a new calculation presented next.

In a similar way to the daylight factor, a simplified method based on eq. 4.1 on page 73 that relates the global horizontal to the total vertical illuminance can be used to evaluate how well a space is daylit under a clear sky.

In an urban canyon, the lower floors will tend to have a constant of relatively low value on eq. 4.1, due to a reduced view of the diffuse sky. If the constant is ignored, there is a direct proportionality between the horizontal and the vertical illuminance. Considering that this relationship does not change significantly during the year, a simplified method based on this relationship could be representative of a year condition, which would be appropriate for window design.

Just as the BRE or the Lynes's average daylight factor (see ref. 2.5.2) are based on the ratio of the window area to the surface area of the room (with corrections for glass transmittance and room reflectance), the 'average total daylight factor' can be applied in order to define window sizes under a clear sky distribution.

## 7.2 Room geometry

An internal daylight analysis was undertaken for a room with a window facing north in an urban canyon using the 45° rule.

The room (see fig 7.1) with dimensions w=2.8 m, d=4.2 m and h=2.7 m was located at the second floor level, see fig. 7.2. The window dimension (including frame) is 1.2 $m^2$, defined as 10% of the floor area to comply with the Portuguese regulation. However, for the purpose of daylight calculations a correction must be applied due to the oppacity of the frame. The effective window area (net area) becomes 1 $m^2$. The total area of the room surfaces is 61 $m^2$.

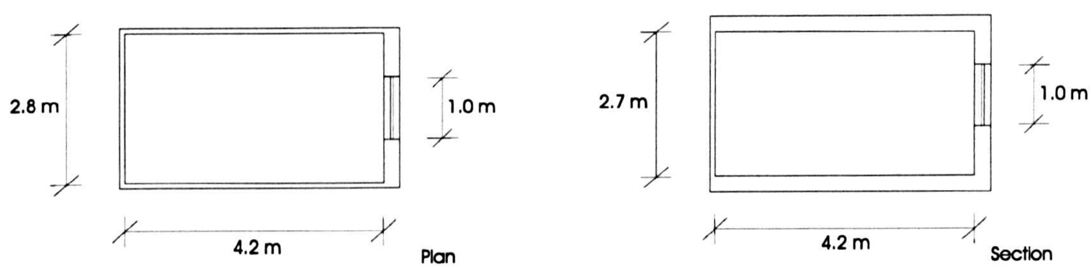



Figure 7.1: Room dimensions.

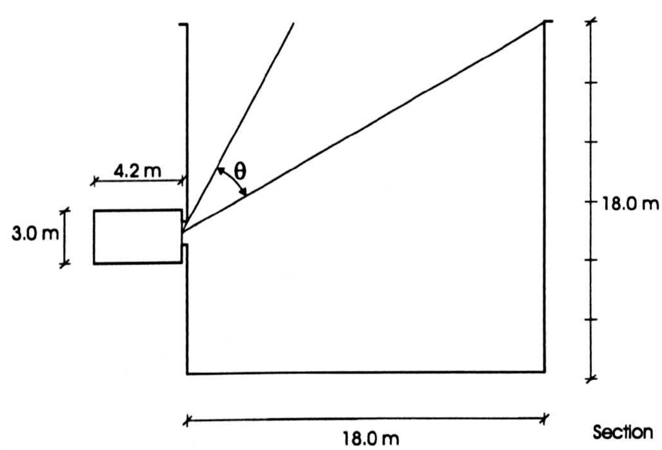



Figure 7.2: Vertical angle of visible sky.

The glass diffuse visible transmittances used for daylight calculations are 80% and 70%, for a single and double clear glass, respectively. With a maintenance factor of 0.8 applied the resulting transmittance becomes 64% for single and 56% for double glazing.

The reflectances of internal surfaces are as following:

- walls 50%
- ceiling 70%
- floor 30%
- single glazing 8%
- double glazing 14%

Given the room geometry previously defined, the weighed average reflectance is 0.49.

Both ground and opaque surfaces on the obstruction have a reflectance of 0.2. Daylight calculations with RADIANCE take into consideration the reflectance of the window panes on the obstruction depending on the angle of incidence between the surface normal and the sun. However, using simplified calculations, the reflectance of the vertical surfaces may be an area-weighed mean between the opaque area and the glazing area.

## 7.3 Daylight factor

Daylight analysis in the UK has been traditionally associated with the CIE overcast sky for the following reasons:

- If the natural lighting is sufficient on an overcast day it is likely to be more than adequate during a clear day;
- The overcast sky luminance is independent of the azimuth therefore the effect of orientation is not considered in the calculation;
- The indoor illuminance is directly proportional to the simultaneous outdoor horizontal unobstructed illuminance independent of the overcast sky brightness. (Mardaljevic, 1999)

A calculation that considers a static sky distribution does not take into consideration the variations in quantity and quality of light that is typically associated with the natural conditions. However, the simplicity of the calculation gives advantages in spite of the loss of accuracy and realism.

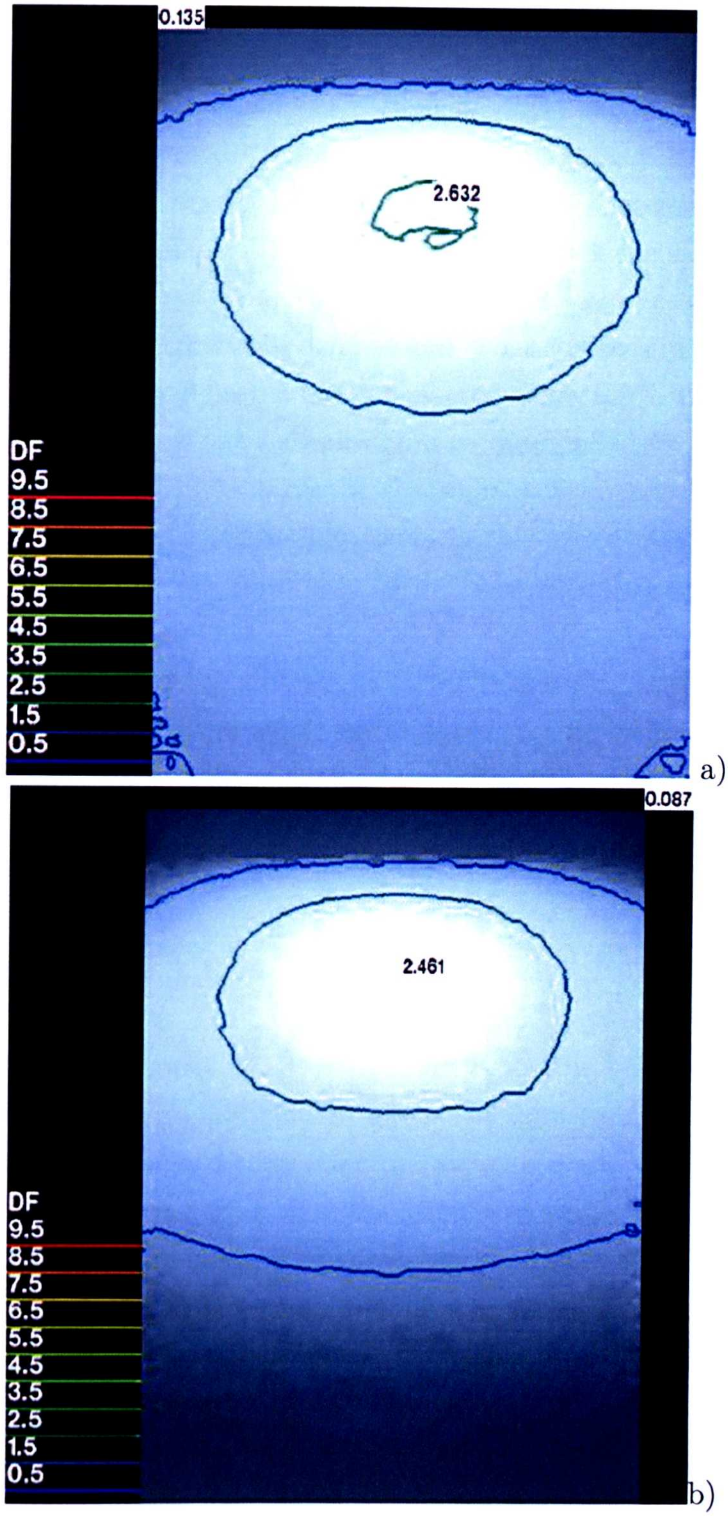



Figure 7.3: Daylight factor (%) on the working plane (0.85 m) on a 2$^{nd}$ floor room without a facing obstruction (a) and with one with an obstruction angle of 45° (b). Maximum and minimum values are presented.

Fig. 7.3 presents the daylight factor distribution on the working plane (at a height of 0.85 m) in a room with an unobstructed view and facing an obstruction with the horizontal skyline parallel to the building within a 45° angle. Single glazing transmittance was used.

Neither geometry appears to have a high daylight factor. The window area defined appears to be too small to obtain acceptable light levels. An unobstructed view of the sky allows light deeper into the space. Light is therefore distributed more uniformly on the working plane. The obstruction will block the sky view in the back of the room, defining a no sky-line, beyond which the light received is exclusively reflected from external obstructions, ground and other surfaces in the room. A room with a facing obstruction will have a daylight factor below 0.5% in almost half of the working area, which is below the 1% minimum recommended for residential spaces. (Hopkinson and Kay, 1969)[1] As a result, the room will be poorly daylit and tend to look gloomy. An increase of the light level in this space may be obtained with a bigger window area to allow more light in or more reflective surfaces, to increase the interreflected component.

Table 7.1 presents the average daylight factor in a room located at the gnd, 1st, 2nd , 3rd, 4th , and 5th floor for a single and double glazing unit according to Lynes and BRE's formulae as eq. 2.9 and 2.10 on page 21 as[2]

$$\overline{D} = \frac{\tau A_w \theta}{2A\left(1-\rho_{av}\right)} \tag{7.1}$$

$$\overline{D} = \frac{M \tau A_w \theta}{A\left(1-\rho_{av}^2\right)} \tag{7.2}$$

as eq. 2.9 and 2.10 on page 21, See appendix K for the basis of the calculation.

The geometry of the room and window size is the same as in the previous daylight factor analysis. The average daylight factor (average of the values) of 0.8% from RADIANCE, in fig. 7.3 b) is higher than the calculated value with the BRE equation (0.63%). The BRE equation is considered against the Lynes as the former embodies a correction factor to adapt the average illuminance over all surfaces to the horizontal reference plane. (Cuttle, 1991) This is consistent with eqs. 2.9 and 2.10 not taking into consideration the interreflections in the canyon. Also, the obstruction and ground are assumed to have one tenth of the mean sky luminance and a reflectance of 0.2, whereas the simulation calculates a higher luminance on the obstruction.

[1]Kitchens a minimum 2% $D$ over half of the floor area with a minimum of 4.65 m$^2$.

Living rooms a minimum of 1% $D$ over at least 6.97 m$^2$ penetrating no less than three quarters the depth the room.

Bedrooms a minimum 0.5% $D$ over at least 5.57 m$^2$ penetrating no less than three quarters the depth the room.

[2]Lynes's formulae calculates the average daylight factor over all internal surfaces and not specifically on the working plane as the BRE formula does, at 0.85 m height. In theory, the illuminance

Table 7.1: Average Daylight factors.

single glazing / double glazing

| $\bar{D}$ | BRE | Lynes | $\bar{D}$ | BRE | Lynes |
|---|---|---|---|---|---|
| Gnd | 0.46 | 0.34 | Gnd | 0.40 | 0.30 |
| 1st | 0.54 | 0.40 | 1st | 0.47 | 0.35 |
| 2nd | 0.63 | 0.47 | 2nd | 0.55 | 0.41 |
| 3rd | 0.73 | 0.55 | 3rd | 0.64 | 0.48 |
| 4th | 0.85 | 0.63 | 4th | 0.74 | 0.55 |
| 5th | 0.97 | 0.73 | 5th | 0.85 | 0.64 |

As mentioned before, the window is too small to provide acceptable average daylight factors. Not even the top window, which subtends a sky component (38%) close to that of an unobstructed vertical window (39%) receives enough skylight.

Table 7.2: Window area required to achieve a 2% average daylight factor. Different floor levels will have different obstruction angles. The area of the window wall is 7.6 $m^2$.

single glazing / double glazing

| $A_w$ | BRE | Lynes | $A_w$ | BRE | Lynes |
|---|---|---|---|---|---|
| Gnd | 4.37 | 5.86 | Gnd | 4.99 | 6.68 |
| 1st | 3.74 | 5.01 | 1st | 4.27 | 5.71 |
| 2nd | 3.20 | 4.28 | 2nd | 3.65 | 4.88 |
| 3rd | 2.74 | 3.67 | 3rd | 3.12 | 4.18 |
| 4th | 2.36 | 3.16 | 4th | 2.69 | 3.61 |
| 5th | 2.05 | 2.75 | 5th | 2.34 | 3.14 |

Both eqs. 2.9 and 2.10 can be rearranged so as to enable the calculation of the area of the window required to achieve a given average daylight factor. Table 7.2 presents the window area required to achieve a 2% average daylight factor in the room at different heights in an urban canyon.

It is difficult to meet the required 2% average daylight factor in an urban canyon with a 45° obstruction angle on the floor level especially on lower floors. There is a structural limitation on the area of the wall occupied by the window. Also, very large windows increase the thermal gains and losses of the building envelope, possibly causing discomfort to occupants and/or a high building energy consumption.

The U.K. rule of thumb for achieving a 2% average daylight factor on the working plane with an obstruction not higher than a 25° angle above the horizon defines the window as being 4% of the total room area. (DETR, 1998) For this geometry

on the working plane is higher than the mean illuminance on the room surfaces.

the window area would be 2.5 $m^2$, corresponding to 21% of the floor area. A 25° obstruction angle occurs in the mid point of the facade (between the $2^{nd}$ and $3^{rd}$ floor) of this 1:1 canyon geometry, therefore floors above could have smaller window areas. Comparing with results presented on table 7.2 for the BRE formula, this rule overestimates slightly the daylight appearance of the rooms in the canyon. Given the BRE formula, this area would meet the required daylight factor only on the top floors of the canyon with a single glazing window. However, results are sufficiently close so that this rule of thumb can be accepted in the initial phases of a design.

As a rule of thumb, the average daylight factor may be used to characterise the perception of how well a space is lit according to:

- Below 2% the room will appear dull under daylight. Supplementary artificial light will be needed during daylight hours;
- Between 2 and 5% the room will appear increasingly daylit. Electrical task lighting may be needed for visual accuracy;
- Above 5% the room will be strongly daylit. Electrical lighting is rarely needed. However, the excessive dimension of the windows are likely to cause thermal problems.

The average daylight factor will be strongly affected by the reflectance of the interior surfaces. Good reflecting properties will improve the quantity of internal light as well as its distribution, therefore enhancing the quality of the space.

While a reference illuminance level might be maintained easily with artificial lighting, this is much more difficult with daylight due to its variable nature. However, it is accepted that people tend to prefer daylight to artificial light. (IES Daylighting Committee, 1979) Moreover, people will accept lower light levels and variability in a daylit room more willingly than they would in an artificially lit environment.

During the day, even if a visual task is performed under task lighting, it is important to have a naturally lit ambient as our circadian rhythm expects a daylit period during the daily routine.

## 7.4 Total daylight factor

The 'Total Daylight Factor', $TD$, at a point is the ratio of the total internal illuminance, i.e. direct and indirect for both sky and sun, to the external unobstructed global illuminance.

Fig. 7.4 represents the total daylight factor on a reference plane in a room facing an obstruction. The TD is always below 0.5 but uniformly distributed over the working plane. The average total daylight factor (average of values) is 0.16% which

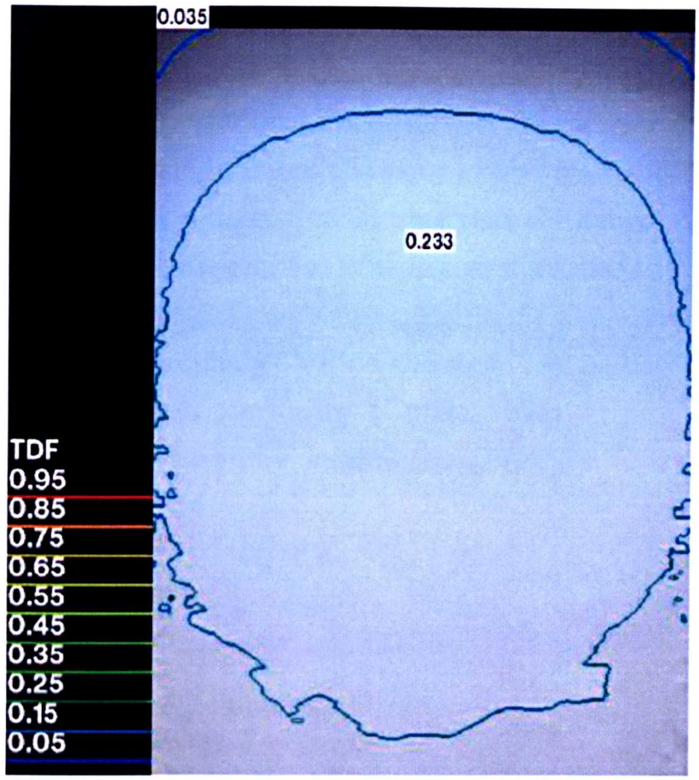



Figure 7.4: Total daylight factor on the working plane (0.85 m) on a 2$^{nd}$ floor room facing north in a 1:1 urban canyon in Lisbon in the spring equinox at noon.

is within a 4% error to the value of 0.17% calculated with the simplified method, to be defined next, for the same geometry.

On the one hand a facing obstruction may reduce the illuminance from the sky. On the other hand it may reflect sunlight deep into in the room, resulting in a higher uniformity ratio.

It has been shown (Tregenza, 1980; Tregenza, 1999; Mardaljevic, 1999) that "the ratio of internal to external illuminance varies greatly under real skies". However, in an urban canyon when direct sunlight is excluded, there is a relationship between the external (vertical) and the global illuminance, as presented in the previous chapters. To a certain extent an urban canyon will tend to behave similarly to a photometric integrator, where the illuminance after interreflections is uniform and independent of the angle of incidence.

The principle of the integrating sphere is based on work developed by Sumpner in 1892 with a light source inside a sphere whose inner coating is a perfectly diffusing paint. Walsh (Walsh, 1958; Walsh, 1961) presents this principle clearly. The luminance of any part of the inner surface, due to light reflected from the rest of the sphere is the same and it is proportional to the total flux emitted by the source.

The analogy has its limitations in the assumption that the light reflected in the canyon is evenly distributed over all the surfaces. In reality, not only are the reflectance and isotropy of various surfaces different, but an urban canyon is rarely free of departures from the ideal geometry. Furthermore, the conversion of a spheric geometry to a parallelepiped one introduces further inaccuracy as the illuminance on a surface due to reflected light is not the same everywhere and it is not angularly independent as it is within a sphere. Considering that the canyon is not an enclosed geometry, missing surfaces (side and top) further compromise the uniformity of the space.

Similarly, the average illuminance within the room can be based on the principle of the interreflection explained previously. (Cuttle, 1991)

Let the flux entering the room be $\Phi_0$ as

$$\Phi_0 = E_{tv} \cdot A_w \cdot \tau \tag{7.3}$$

where

| | |
|---|---|
| $E_{tv}$ | is the total vertical illuminance; |
| $A_w$ | is the net glazed area of window; |
| $\tau$ | is the diffuse light transmittance of the glazing. |

If $A$ is the total area of interior surfaces, ceiling, floor and walls including windows, the average illuminance on the surfaces, $\overline{E_0}$, due to the flux entering the room is

$$\overline{E_0} = \frac{\Phi_0}{A} = \frac{E_{tv} \cdot A_w \cdot \tau}{A} \tag{7.4}$$

The average illuminance due to the first reflected flux, $\overline{E_1}$ is

$$\overline{E_1} = \frac{\Phi_1}{A} = \frac{\Phi_0 \cdot \rho_{av}}{A} = \frac{E_{tv} \cdot A_w \cdot \tau \cdot \rho_{av}}{A} \tag{7.5}$$

where

| | |
|---|---|
| $\rho_{av}$ | is the area-weighed average reflectance of interior surfaces. |

The average illuminance due to secondary reflection will be the product of the first reflected flux times the reflectance of the surfaces. And so

$$\begin{aligned} \overline{E_2} &= \frac{\Phi_1 \cdot \rho_{av}}{A} \\ &= \frac{E_{tv} \cdot A_w \cdot \tau \cdot \rho_{av} \cdot \rho_{av}}{A} \end{aligned} \tag{7.6}$$

The total average illuminance, $\overline{E_{in}}$, within the room due to multiple reflections is

$$
\begin{aligned}
\overline{E_{in}} &= \frac{\Phi_0}{A} + \frac{\Phi_0 \cdot \rho_{av}}{A} + \frac{\Phi_0 \cdot \rho_{av} \cdot \rho_{av}}{A} + \dots \\
&= \frac{\Phi_0(1 + \rho_{av} + \rho_{av}^2 + \dots)}{A} \\
&= \frac{\Phi_0}{A \cdot (1 - \rho_{av})} \\
&= \frac{E_{tv} \cdot A_w \cdot \tau}{A \cdot (1 - \rho_{av})}
\end{aligned}
\tag{7.7}
$$

Then

$$\frac{\overline{E_{in}}}{E_{tv}} = \frac{A_w \cdot \tau}{A \cdot (1 - \rho_{av})} \tag{7.8}$$

This ratio $\frac{\overline{E_{in}}}{E_{tv}}$ defines a geometrical relation between the window area and the room area.

The average total daylight factor is $\overline{TD} = \frac{\overline{E_{in}}}{E_{gh}}$ and can be expressed according to eq. 7.7 as

$$\overline{TD} = \frac{E_{tv} \cdot A_w \cdot \tau}{E_{gh} \cdot A \cdot (1 - \rho_{av})} \tag{7.9}$$

Previous research has presented a simplified relationship between the vertical and global horizontal illuminance when the building does not receive direct sunlight and is enclosed in an urban canyon. It is defined as eq. 4.1 on page 73 as

$$E_{tv} = k \cdot E_{gh} + C \tag{7.10}$$

where $k$ and $C$ are constants.

Also, it has been proved that this relationship does not change significantly during the year. It may therefore be applied to an equation and thus be representative of a year condition.

Results showed that constant $C$ is mainly the direct contribution from the diffuse sky. Then, if the constant $C$ is excluded, there is a direct proportionality between the horizontal and vertical illuminance, similar to a daylight factor but for clear skies. In those cases the slope $k = \frac{E_{tv}}{E_{gh}}$ can be applied to eq. 7.9 to obtain the average total daylight factor.

Then the average total daylight factor in eq. 7.9 can be expressed as a percentage by

$$\overline{TD} = \frac{k \cdot A_w \cdot \tau}{A \cdot (1 - \rho_{av})} \tag{7.11}$$

Table 7.3 and fig. 7.5 presents the average total daylight factor for rooms on different floors using eq. 7.11 and the $k$ coefficient presented in table 5.7 on page 124 derived with the global best fit approach. The average total daylight factor tends

Table 7.3: Average total daylight factor for different room heights in different canyon ratios (narrow, equal and wide) with different surface reflectances in the canyon (0.2, 0.3, 0.5 and 0.7) for single glass transmittance. Room dimensions and characteristics remain the same as before. The direct contribution from the sun (early and late hours in summer) is excluded from the calculation. Results were obtained with Eq. 7.11 and the $k$ coefficient was derived from the global best fit approach and is presented in table 5.7 on page 124.

| Canyon ratio | 1:0.5 | | | |
|---|---|---|---|---|
| rho | 0.2 | 0.3 | 0.5 | 0.7 |
| Gnd | 0.11 | 0.17 | 0.33 | 0.59 |
| 1$^{st}$ | 0.14 | 0.21 | 0.40 | 0.68 |
| 2$^{nd}$ | 0.14 | 0.21 | 0.39 | 0.66 |
| 3$^{rd}$ | 0.13 | 0.20 | 0.36 | 0.59 |
| 4$^{th}$ | 0.13 | 0.18 | 0.31 | 0.51 |
| 5$^{th}$ | 0.12 | 0.16 | 0.26 | 0.40 |

| Canyon ratio | 1:1 | | | |
|---|---|---|---|---|
| rho | 0.2 | 0.3 | 0.5 | 0.7 |
| Gnd | 0.13 | 0.17 | 0.35 | 0.57 |
| 1$^{st}$ | 0.17 | 0.25 | 0.44 | 0.70 |
| 2$^{nd}$ | 0.17 | 0.25 | 0.44 | 0.69 |
| 3$^{rd}$ | 0.16 | 0.23 | 0.40 | 0.62 |
| 4$^{th}$ | 0.15 | 0.21 | 0.36 | 0.55 |
| 5$^{th}$ | 0.14 | 0.19 | 0.31 | 0.47 |

| Canyon ratio | 1:1.5 | | | |
|---|---|---|---|---|
| rho | 0.2 | 0.3 | 0.5 | 0.7 |
| Gnd | 0.12 | 0.17 | 0.30 | 0.47 |
| 1$^{st}$ | 0.17 | 0.24 | 0.41 | 0.62 |
| 2$^{nd}$ | 0.18 | 0.25 | 0.42 | 0.63 |
| 3$^{rd}$ | 0.17 | 0.24 | 0.40 | 0.60 |
| 4$^{th}$ | 0.16 | 0.23 | 0.37 | 0.55 |
| 5$^{th}$ | 0.16 | 0.21 | 0.34 | 0.50 |

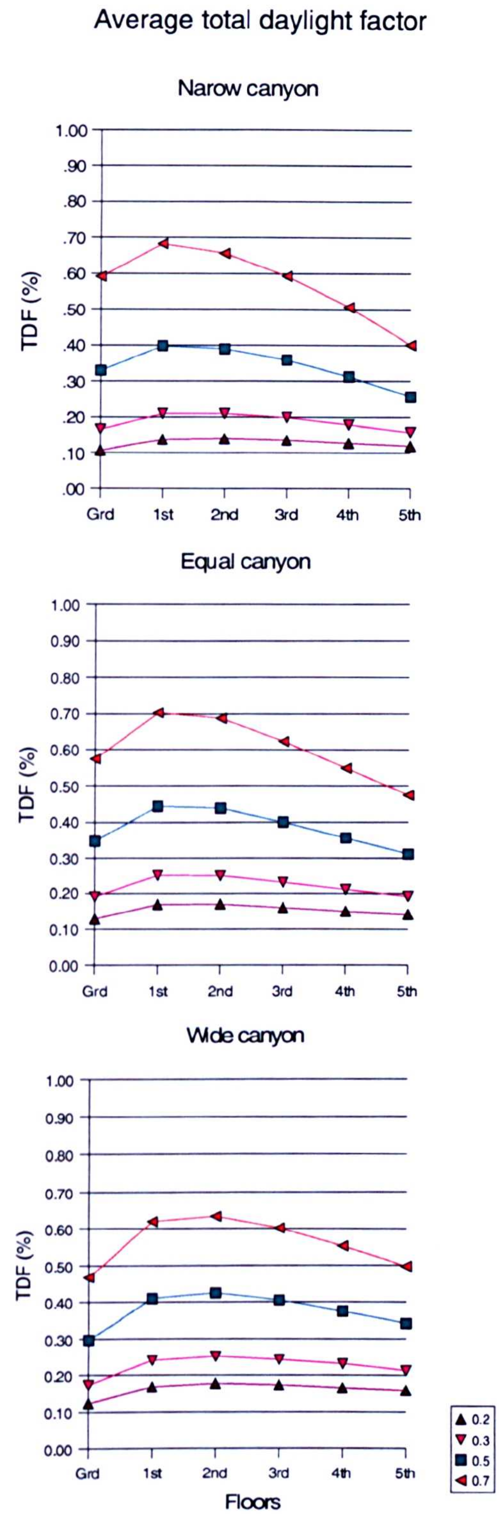



Figure 7.5: Average total daylight factors

to be higher in a room at the mid height of the canyon. This may be a result of the flux transfer between the obstruction and the facade being highest for this point. Nevertheless, the average total daylight factor does not change significantly on the other floors for these canyon geometries. In fact, a single value may give a fair approximation for an initial estimation of daylight appearance on all floors of a building in an urban canyon. Appendix L presents the average total daylight factor using coefficient $s$ defined in table 5.5 derived with the solar best fit approach. The reflectance of the surfaces will strongly affect the illuminance in the room. The higher the reflectance of the external surfaces of the canyon the higher the total daylight factor. Higher reflectance in the obstruction will be more effective on lower floors in narrow canyons, as those floors will mainly rely on reflected light from external surfaces.

A maximum average total daylight factor occurs in a 1:1 canyon (equal height and width) and decreases slightly for wider and more narrow canyons, for lower reflectances. Conversely, the average total daylight factor decreases slightly for narrow canyons and more for wider canyons with high reflectances on the obstructions.

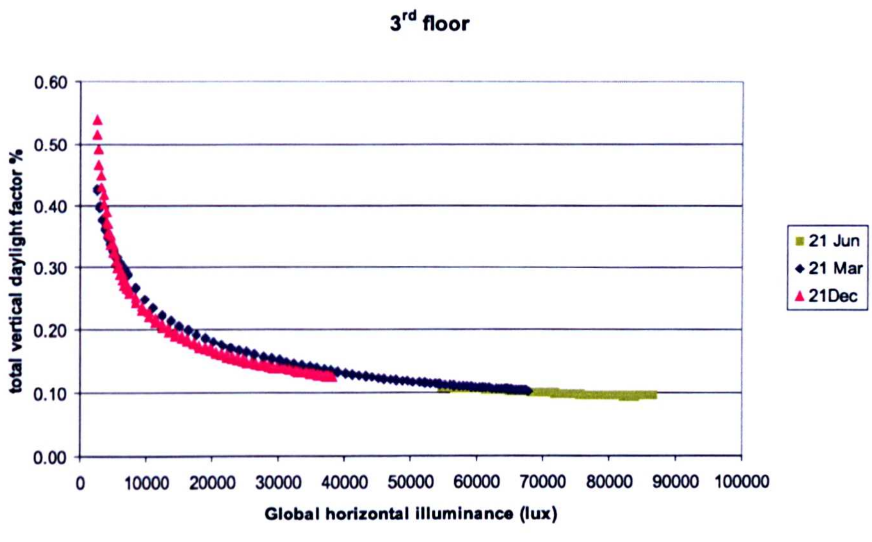



Figure 7.6: Global horizontal illuminance versus total vertical daylight factor at 3rd floor window in a 1:1 canyon in Lisbon in the equinox and solstice days.

The constant $C$ weighs significantly in the illuminance on the facade when global illuminance is low. However, on a clear day the illuminance obtained on the horizontal plane can be high, therefore $C$ may be ignored. Fig. 7.6 shows that the constant $C$ contributes significantly to the overall illuminance on the facade when the global horizontal illuminance is below 10 000 lx. On a clear day these values will correspond to a solar altitude below 10°, therefore can be ignored without significant influence on the overall illuminance.

A similar calculation that considers the direct contribution from the sky can be applied on higher floors or wider canyons, where the constant $C$ may not be negligible. See appendix M for the calculation.

Nevertheless, just as the average daylight factor gives an initial estimate of how well a room is daylit in overcast conditions, the average total daylight factor may be the basis of a similar analysis in locations where sunny skies are predominant.

Recommended levels for the average daylight factor were presented in the previous and 2.7 sections. These criteria are based on the assumption that when people prefer to have a naturally lit environment, the sky is sufficiently bright to admit to the interior sufficient illumination to perform visual tasks. If the sky is dark the space will be perceived as dull and electric light would be used more often. (Hopkinson, 1969) Similarly on a brighter day people may have a sense of spaciousness and well being in the space or may be disturbed by glare.

A clear sky (including the sun contribution) will be much brighter than an overcast sky. The recommended percentage of average daylight factors for an overcast sky may be reduced for a clear sky in this case. However, our sense of brightness depends on the contrast to the background. If the outdoors is brighter, we will expect much higher illuminance levels indoors than we would on an dull day.

Higher light level may benefit visual adaptation when moving in and out of the building. Furthermore, discomfort glare may be avoided by reducing the brightness or colour contrast between the source of light and the surroundings. It was found that the higher the level of illumination the smaller is the tolerable ratio between the brightness of the source and the surroundings. However, a certain degree of interest and sparkle should be considered in visual surroundings to avoid dullness and promote visual stimulation. (BRS, 1954)

Nevertheless the analysis of the brightness should depend on the visual task to be performed. Recent research has shown that, although the levels in the working plane were considered acceptable, as the walls were dark, the occupants complained about dullness and lack of light. The survey undertaken therefore focused on measurements of average luminance in the 40° band about the horizontal line at eye level. An average luminance in the band of 30 cd/m$^2$ was found to delimit the perception of the space from being dull to generally bright and no significant change was obtained beyond 100 cd/m$^2$. (Wilson, ; Loe et al., 1994) Although this survey was done for artificial light a similar approach may be used for natural light.

The definition of recommended average total daylight factors goes beyond the time framework of this thesis. It requires further studies, possibly involving surveys in different spaces under sunny sky conditions. Nevertheless, an initial estimation of average total daylight factor as a quarter of the recommended values of the average daylight factor may be put forward. This estimation is based on the following assumptions:

- London's location and the U.K. daylight recommendations define the criteria for overcast conditions. Lisbon is the location for the case study under clear sky conditions for the development of the average total daylight factor criteria for sunny climates;

- The diffuse horizontal illuminance from a CIE overcast sky is significantly lower than the global horizontal illuminance from a CIE clear sky (with turbidity 2.75), in Lisbon. On average the former is around one quarter of the latter for the equinox and solstice days when the sun altitude is above 10°. If 10 000 lx is considered a realistic horizontal illuminance from an overcast sky (the average for the simulated days is around 10 600 lx) then one can express the illuminance from a clear sky as 40 000 lx (though the average for the simulated data is around 47 000 lx);

- The global horizontal illuminance of 10 000 lx is exceeded for 60% of the time from sun rise to sunset in London. The global horizontal illuminance of 28 000 lx is exceeded for the same percentage of the time in Lisbon. See fig 8.5 on page 180. This illuminance value is smaller than that previously obtained from the simulation. The justification is that it includes both clear and overcast distributions, though the latter may not be that frequent. Also it accounts for early and late hours when the sun is just over the horizon instead of above 10° as adopted in the simulation results. Therefore the initial value of 40 000 lx may be adjusted as a reference for southern European sunny skies;

- If the illuminance of a realistic clear sky is around four times as great as that from an overcast sky, a recommended 2% average daylight factor may be reduced to a quarter of that figure for the average total daylight factor. This analogy assumes the dimension of the window remain constant;

- By definition the average total daylight factor is the ratio between the average internal illuminance and the external horizontal illuminance. It can be written as:

$$\overline{TD} \cdot E_{gh} = \frac{\overline{L} \cdot \pi}{\rho_w} \tag{7.12}$$

where

$E_{gh}$ is the global horizontal illuminance. An illuminance of 40 000 lx was previously assumed as realistic under a clear sky;

$\overline{L}$ is the average luminance of the walls. It was suggested that 30 cd/m$^2$ is a minimum average luminance on the walls to ensure a bright appearance;

$\rho_w$ is the average reflectance of the walls. It is assumed that the reflectance of the walls are around the average reflectance of the room surfaces, with a value of 0.5.

Then the average total daylight factor daylight factor could be used to estimate whether the space has a daylit appearance. This calculation results in a value around 0.5%. This minimum reference average daylight factor is an initial estimation towards the definition of a classification of a sunny daylit space.

Alternatively, the calculation allows for the sizing of the window for a certain average total daylight factor. Given the ratio of the total vertical illuminance over the global horizontal illuminance not changing significantly for different floor heights, a single value may be adopted for all the heights. Parameters for window design in a sunny urban canyon are assumed to be taken at the lower floors where the diffuse contribution from the sky is reduced. Table 7.7 gives the window size needed for a room (dimensioned as before) for a 0.3%, 0.5, 0.7 and 1% average total daylight factors to be met.

The order of magnitude of the average total daylight factor is decimal. Window areas obtained for $\overline{TD}$ above 1.1% will have for this geometry a structural limitation to fit the wall area.

In theory, results from the average total daylight factor may be compared with those from Lynes's average daylight factor, as both are based on an average internal illuminance over all surfaces, without a correction factor to adapt it for the working plane (BRE method). See table 7.8 for window areas (for the same room) defined for 1%, 2 and 3% average daylight factor.

While results are relatively stable for the sunny calculation and a single area is suggested, for the overcast based method the window areas vary substantially for different floor heights. Nevertheless, in terms of the subjective appreciation of a daylit space a 2% $\overline{D}$ was suggested previously to correspond to 0.5% $\overline{TD}$. Then, window areas can be smaller when designing for clear skies than for overcast conditions.

Table 7.7: Window areas for 0.3, 0.5 and 0.7 $\overline{TD}$ [%]

| $\overline{TD}$ [%] | 0.1 | 0.3 | 0.5 | 0.7 | 1 |
|---|---|---|---|---|---|
| 1st floor (single glazing) | 0.65 | 1.96 | 3.27 | 4.58 | 6.54 |

Table 7.8: Window areas for 1, 2 and 3 $\overline{D}$ [%]

| $\overline{D}$ [%] | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| | BRE | Lynes | BRE | Lynes | BRE | Lynes |
| 1st floor (single glazing) | 1.87 | 2.51 | 3.74 | 5.01 | 5.61 | 7.52 |
| 2nd floor | 1.60 | 2.14 | 3.2 | 4.28 | 4.79 | 6.43 |

## 7.5 Conclusions

A case study of a simple room at the mid height of an urban canyon showed that a window area based on 10% of the floor area produces a poorly daylit space. Under an overcast sky the minimum window area needed to achieve an 2% average daylight factor is around 3 times one tenth of the floor area. Alternatively higher reflectance of surfaces will significantly increase the internally reflected component therefore enhancing the overall brightness. Under a clear sky the window dimension may still be reduced to provide acceptable light levels. However, reflected light from obstructions and ground redirect the light deep into the room, promoting a uniform distribution.

There are several factors that affect the illuminance of a space in an urban canyon under clear skies. The reflectance of the obstruction clearly is the one that contributes most to a daylit appearance. The canyon ratio also affects the illuminance. A 1:1 ratio promotes the maximum illuminance on mid floors. It is followed by the wider and last the narrow canyon considering low reflectance on the surfaces. Mid floors in the canyon are those that take most advantage of reflected sunlight. However, the variation between floors is reduced and a single value may be used in initial phases of the project.

Daylighting 'rules of thumb' defining window areas based on percentage of the floor area or the total area of surfaces in the room, should allow for the glass transmittance to be considered. A significant reduction in daylight levels may occur with a simple substitution of single to double glazing. An increase of window area may therefore be desirable in this case.

Although simplified rules may prove to be important in the initial phases of the project, significant differences between the project and the assumptions considered in the rules should be further analysed. The use of the equation from which the rule was derived may sometimes be sufficient to allow alterations to incorrectly defined parameters.

The definition of a simplified calculation for daylight analysis under clear sky distributions is important in order to avoid the use of calculations designed for overcast conditions and their consequent inadequacy. Although the new calculation is similar to that for the average daylight factor, therefore taking advantage of its simplicity, it considers the sun component reflected from surfaces in a canyon allowing another major light contribution to be taken into consideration. The average total daylight factor may provide a similar characterisation of how well a space is lit as well as allows for the sizing of windows.

An initial estimation of average total daylight factor as a quarter of the recommended values of the average daylight factor have been put forward. In should be stressed that estimations proposed to characterise a daylit space are based on quantitative data obtained in this study with RADIANCE simulations. The definition of visual comfort indices similar to those assumed for the average daylight factor should mainly be based on experimental surveys in real situations.

Like the average daylight factor, the average total daylight factor is proportional to the window size and can thus be an useful method for estimating window sizes in early stages of design. This is helped by the fact that the use of the average total daylight factor does not require the window shape or position to be known in advance. As expressed above the selection of an indices needing to be cemented with other studies, will affect the definition of window area.

# Chapter 8

# Planning guidelines for Europe

## 8.1 Introduction

A pleasant indoor environment with low energy consumption is the major aim of good building design and planning. Establishing criteria for daylight design may prove to be critical in the initial phases of the project, when incorrect decisions quite often compromise the final design. The aim is to obtain a comfortable visual environment where light levels are sufficiently high to allow the use of the space. However, defining what constitutes a good and pleasant environment can be complex and subjective. Furthermore, analysing the conditions and defining tools to obtain answers that comply with the prerequisites and aims make the process even harder.

Daylight calculations are usually based on an overcast sky but in locations where sunny skies are predominant such calculations underestimate daylight levels and might lead to inappropriate urban planning and window design. If daylight factors are an accepted calculation for cloudy skies, a simple calculation to apply for clear skies has been presented. Its major improvement comes from considering sunlight reflected in urban canyons, a significant contribution to the illuminance reaching the facade.

Although solutions to the problem of promoting daylight into buildings may be similar for both overcast and clear skies, some factors may be more relevant under one or another sky condition. The main decision to be made is to select an appropriate approach based on the dominant sky condition for the location.

It is the role of planners and architects to provide urban spaces with potential for daylight. Guidelines for building development should emphasise daylight whenever possible.

The use of calculations that are adapted to the site may benefit the end users of the spaces assuming a better design is achieved, as well as promoting a more efficient and cost effective building design.

The adoption of simple calculations may prove to be sufficient to prevent initial decisions that compromise the spaces in terms of daylight. If they are easy to apply, they may become more widely adopted and comprehended by architects. Average daylight factors have been used to give a simple indication of how daylit a space appear to be under overcast sky conditions. The average total daylight factor may allow the development of a similar calculation to apply for clear skies in an urban canyon when sunlight is behind the building. More detailed daylight analyses expected to be made in later stages should be carried out by experts in the area.

Nowadays, the availability of personal computers and a variety of software has reduced the use of manual methods in favour of computerised data. Daylight analysis previously made on a drawing board is being substituted by computer calculations and renderings. The new tools are superior in terms of visual presentation but their accuracy can leave a lot to be desired. The wide-spread idea that any simulation can provide reliable results, without an understanding of the physics involved just by ticking selections on the screen, is a dangerous approach to building design. Calculations that were previously defined and performed by experts in the field are being done now without the necessary knowledge of the subject. Sometimes it is better to use simplified methods and rules of thumb rather than sophisticated machine calculations. The complexity of such calculations or the wrong impression of simplicity given by default parameters may increase the error due to user input.

The recent development of the glazing industry has been enormous and probably will continue further than for any other type of building material. It is now possible to select glazing materials that are switchable to solar radiation, selective in their transmissivity for a particular part of the spectrum, refractive to light and so one. However, it is still common practice to select standard clear float glass, where emphasis is put on the reduction of conductivity to minimise the heat exchange between the building and the outside environment. In climates where high levels of solar radiation in the summer can cause excessive solar gains, it has become common to use glazing with low transmittance, mainly tinted or film coated. Unfortunately, a reduced solar factor is typically associated with a reduced light transmittance. Spaces that could be naturally lit are now using electrical light because insufficient light is getting through the windows. As a consequence, there is an increase of energy consumption for lighting if not for cooling due to the increased internal gains. Furthermore, a non daylit space may reduce human acceptance and work productivity.

## 8.2 Daylight availability

Daylight simulations usually use one of the four widely accepted sky distributions, namely clear, intermediate, overcast or uniform. However, they may be a limited representation for some locations. CIE has recently published a new standard general sky (S 011/E:2003), that lists 16 luminance distributions in recognition of a wider range of conditions from a heavily overcast to a cloudless sky. (CIE, 2002)

Ideally, daylight analysis should make use of data obtained for the location provided it is representative of the climate and not just an occasional occurrence. Unfortunately, illuminance data have not been frequently recorded by weather stations, assuming the existence of those in the first place.

TRY[1] weather files, based on statistical analysis over a period of years, may be representative for a particular location. However, they are hourly values and are based on readings of the full solar spectrum, rather than visible light. If models of luminous efficacy may be applied to obtain data in the visible spectrum from the solar radiation records, their usefulness will depend on the accuracy of the model chosen. However, the biggest set-back on the reliability to the data may be the frequency of the measurements taken. While the temperature of a location is unlikely to suffer significant variations over short periods, daylight can vary abruptly from one minute to the other on cloudy days. Long intervals between readings are therefore far from ideal.

A few recent research projects have been concerned with the collection daylight data that can be used for daylight analysis. Among them it is worth mentioning the Satel-light project that provides on-line solar and daylight data averaged over a period of 5 years, for any location in Europe. Some examples of data recorded between 1996 and 2000 in Europe are presented in the graphs figs. 8.4, till 8.7. Although it is still data processed from solar radiation, it provides a good reference if no frequent readings of illuminance data are available.

New techniques for collecting and storing data, increased facility to access and process it, as well as research funding as an incentive for the creation of a daylight atlas, may eventually provide us with valuable information in terms of daylight data which is recorded directly rather than derived from other measurements.

The luminance and luminance distribution of the sky as a source and availability of light are the main factors in daylight analysis. Daylight design strategies should therefore be closely related to the weather conditions at the location.

Fig. 8.1 presents the luminance distribution for the section of the sky that contains the sun location (without the sun source) for various sky types generated with RADIANCE. Both clear and intermediate skies have higher luminance than the overcast sky in the circumsolar area around the sun position. However, in the areas of the sky opposite in azimuth to the sun position, the overcast sky is much brighter than the clear or the intermediate sky. In the area close to the horizon (15° ring), the clear sky distribution is brighter than the overcast distribution. Unfortunately,

[1]Typical reference year

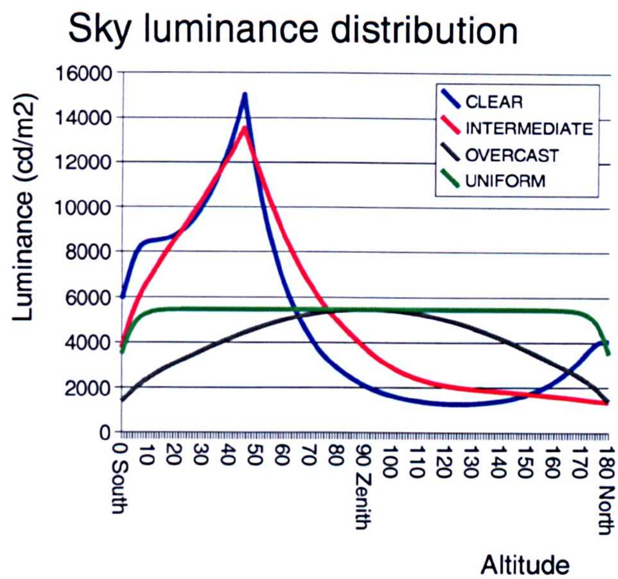



Figure 8.1: Sky distribution without the sun source for sun altitude 45° and azimuth 180°. Results were obtained with RADIANCE for the CIE sky distributions.

in urban areas, this bright area is usually of limited advantage to the illuminance of the buildings as that part of the sky is usually obstructed by the surrounding buildings. In a real overcast sky the orientation is of limited importance as the sun is covered by the clouds. Under sunny sky conditions building design should address that factor as one that can strongly affect the illuminance reaching the building.

Nevertheless, the strategy or approach to be used will strongly depend on the probability or frequency of occurrence of a particular sky condition. See fig. 8.2.

Data on sunshine duration, see fig. 8.3, may also give a fair indication about the sunlight availability for a location.

On an year average Lisbon will have 64% sunny days, with a minimum of 47% in December and maximum of 82% in August. Overcast skies will only occur on 9% of the days on a year. London will have a yearly average of 31% clear skies and 27% of overcast skies, see fig. 8.4. Clearly, the sky distribution to be used in the daylight calculation should be different for these two locations.

Natural light changes in both spacial and spectral distributions with time, location and atmospheric conditions. This affects the amount of light that reaches a given point not only in terms of quality but also quantity.

Other important statistics for daylight design are the analysis of the percentage of hours for which a certain daylight value will be exceeded, see fig. 8.5. If a window is dimensioned for a 2% daylight factor, a level of 500 lx indoors (corresponding to 25 000 lx outdoors) will be obtained for 65% of the daylight hours for the average year with a minimum of 45% during December in Lisbon. The same conditions will be obtained for around 38% of the daylight hours for the average year in London.

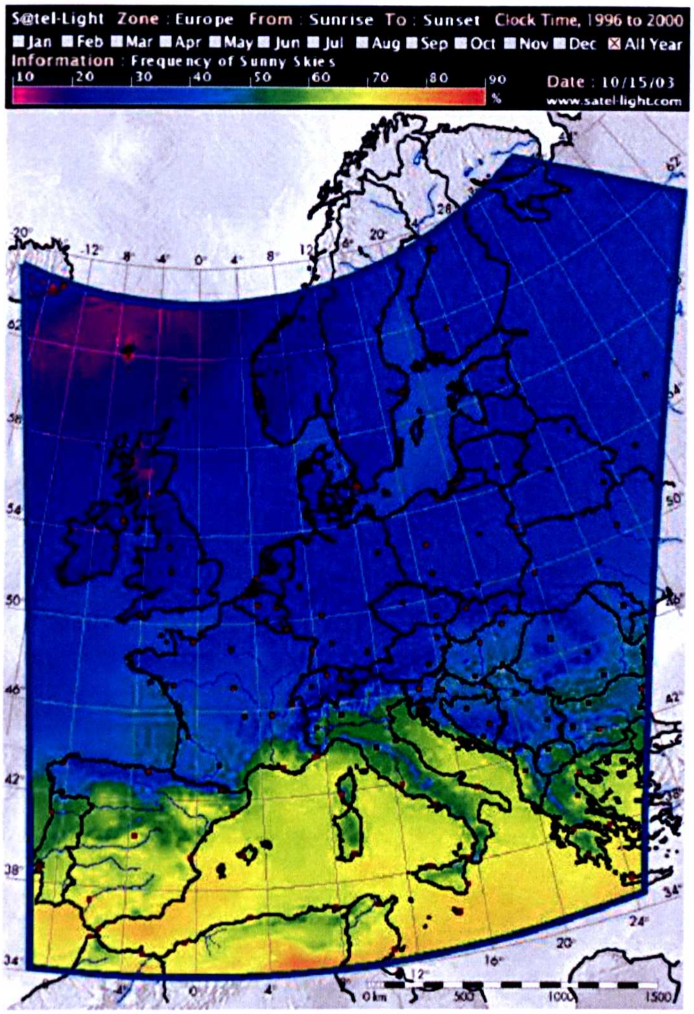



Figure 8.2: Frequency of sunny skies in Europe, yearly average.

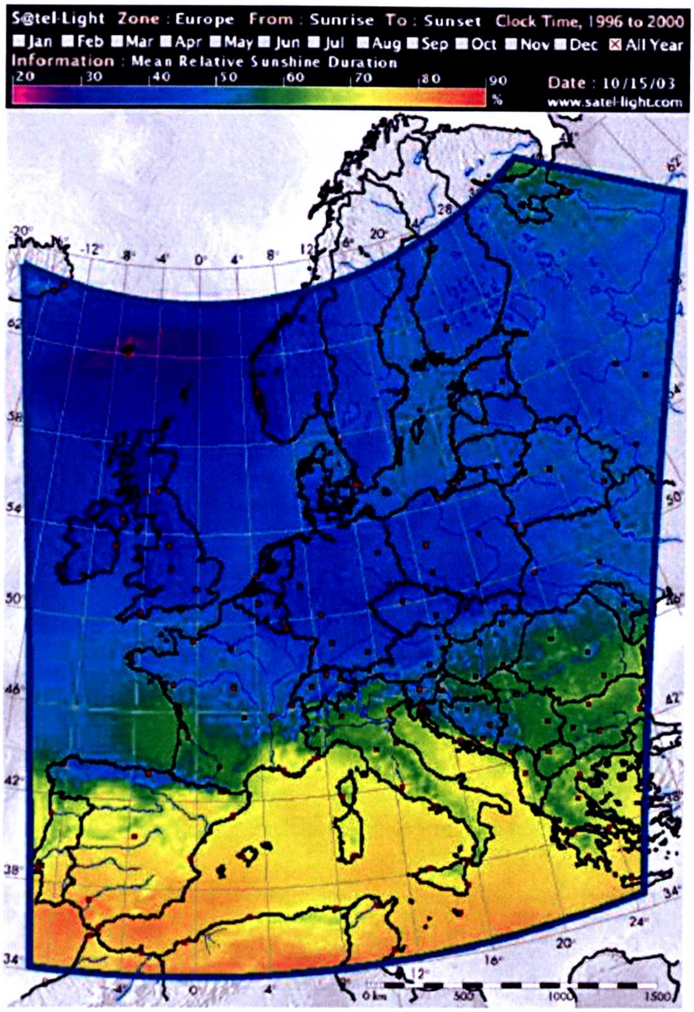



Figure 8.3: Mean relative sunshine duration in Europe, yearly average.

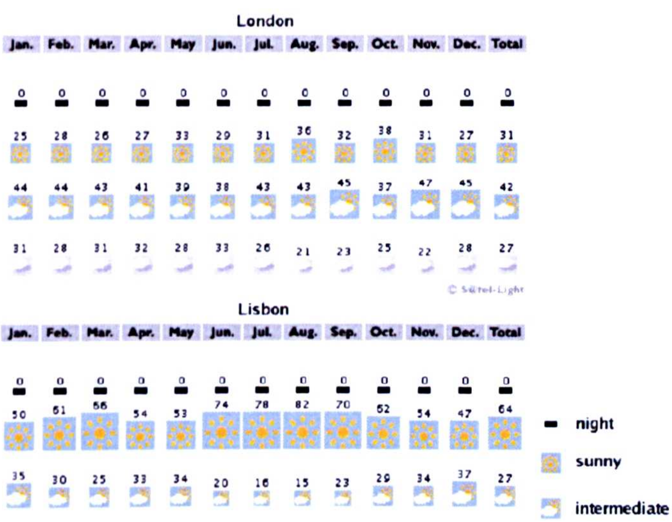



Figure 8.4: Percentage of sky type in London and Lisbon.

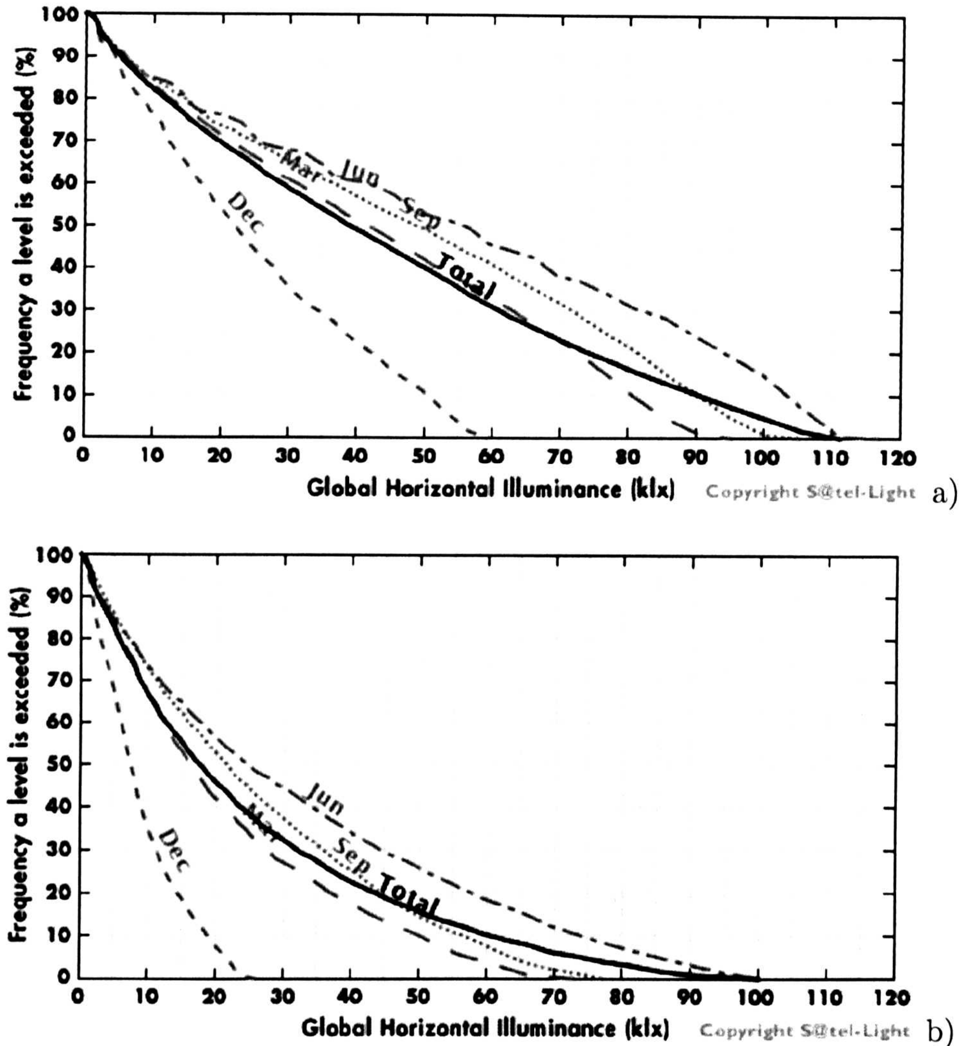



Figure 8.5: Cumulative frequency of half an hour (from sunrise to sunset) values of the global horizontal illuminance in Lisbon a) and London b).

In December the outside illuminance is not sufficient to obtain 500 lx indoors for a 2% daylight factor. If that level of illuminance is required the window must be enlarged. If the window is designed for 4% daylight factor the 500 lx will be meet for 25% of the daylight hours in December and a 60% during the year average in London. See fig. 8.5.

## 8.3 Daylight strategy

Daylight provision in buildings provide a sense of spaciousness and amenity, preferred by occupants. It should be the aim of the architect to design spaces where daylight is thoroughly assessed and the criteria met unless other conditions reduce or prevent their achievement.

There are some steps to follow for daylight design analysis:

1. Definition of criteria according to space, function and period of occupancy if known;
2. Establishment of weather conditions prevailing for the location and selection of sky condition for daylight calculation;
3. Analysis of external conditions for light access such as urban canyon ratios, obstructions and trees;
4. Analysis of building design in terms of orientation and form;
5. Window design in terms of size, shading systems or daylight enhancement systems;
6. Evaluation of overall design to achieve the requirements.

Different spaces require different visual ambient conditions. During the first stage of daylight analysis, decisions should be made in regards to the visual requirements for a defined situation. The strategy must take into consideration different parameters that influence building design. The occupants, as the users of a space, should have a significant input into the definition of its characteristics. Occupancy, being daily, seasonly or yearly can even influence the decision as to whether the design should allow for daylight or not.

The intended function also influences daylight design, not only in terms of quantitative values but also in terms of the quality of light expected. Sometimes a combination with artificial light can prove to be more energy efficient and visually more pleasant than a situation where both are provided individually. For this case, daylight design should be reduced to providing general ambient light. A daylit space differs from an artificially lit one in that, if daylight comes from a side window, it will have a different directionality than the light emitted from a lamp in the ceiling. Also, daylight varies with the time of the day or climate and electrical light tends to be constant. Both have different spectra and colour rendering properties.

Within the task of defining the criteria it is necessary to make a decision to adopt the type of sky distribution predominant for the location. A previous section 8.2 has presented the arguments for the selection of the sky model to be used.

In urban planning, provision of daylight access should be made for existing buildings as well as future developments, in order to avoid the necessity of expensive solutions to allowing daylight into buildings at a later stage of design. The geometry of the street can play a significant role in daylight design. On an overcast day the illuminance in the building will be higher for wider canyons. Then, the main contribution to the illuminance in the building is from the sky therefore higher sky components on wider canyons results in higher illuminance on the building. Given the case study from the last chapter, on a clear day a north facing building in an urban canyon of equal ratio (height/width) will have a higher illuminance than it would on a narrow (half the size) or a wide (one and a half times the size) canyon. That canyon geometry (1:1) appears to be the better of the three to promote reflected sunlight into the building, increasing its illuminance.

When designing for clear skies care must be taken to take the most advantage of the sun's positions in the sky either aiming at direct or reflected sunlight. External surfaces will then play a significant role in the way they may interfere with sunlight access to the building. Just as the reflectance of the internal surfaces are important in order to enhance the illuminance indoors, the external surfaces of the canyon can play a significant role in the illuminance that reaches the window. An urban canyon geometry may also enhance the interreflections of light within the cavity therefore increasing the illuminance in the buildings.

Surrounding obstructions may potentially have a bigger effect on the daylight access of a building under a clear sky than they would under an overcast sky. In a sunny climate, an obstruction can block direct sunlight or at least obstruct the bright sky around the horizon. With an overcast sky, the part of the sky obstructed in the sky dome is the least bright. Nevertheless, care should be taken to avoid prolonged obstruction to direct sunlight as it reduces significantly the illuminance in the building. A building whose access to daylight is obstructed may only receive sunlight after a minimum of two interreflections in the surrounding surfaces.

On the other hand, obstructions can also reflect light from other parts of the sky. For some orientations or times of the day where the sun is behind the building, obstructions are an extremely important means of directing sunlight into the building which would otherwise be unavailable to the building. As seen in previous chapters, sunlight reflected from obstructions and ground can contribute to around 60% of the illuminance on the mid floor of a building in an urban canyon in Lisbon. Light reflected from obstructions contributes around 50% of the illuminance on the facade in the winter and spring. The ground contribution is only around 10%. However, in the summer period, the contribution from the obstruction is reduced to around 25%, whereas that from the ground increases to 35%. In either case, higher reflectance of the surfaces may increase the building illuminance. Depending on the season, the times when the higher illuminance is desired may influence the decision to increase the reflectance of the ground or obstruction.

Furthermore, light reflected from obstructions and ground will reach deeper areas in a side lit room and other surfaces than the horizontal plane, contributing to a better uniformity of the light inside the room.

However, given European latitudes where the solar altitude may be low, on a clear day the contribution of reflected light from the ground may be reduced. Exceptions may occur on summer days when the sun's altitude is high, or when the solar azimuth is around the same direction as the canyon axis in which situation the ground may be fully sunlit.

On an overcast day, the illuminance on the ground plane may be higher than on the facade as the ground plane 'sees' the brightest part of the sky around the zenith. This may benefit lower floors in the building as they are closer to the emitting surface.

The sun's apparent movement in the sky with different altitudes and azimuths during the day and for different days in the year affects significantly the illuminance that reaches vertical surfaces on different orientations. See fig. 8.6 for the sunpath in the first six months of the year in Lisbon. It will affect particularly buildings along urban canyons.

When designing for clear skies, a major decision to be made is in regards to the orientation of the building. The decision should be made in order to take most advantage of the variability of sunlight availability on different orientations and at different times of day. If direct sunlight is desired a room should face within 90° of due south and the height of the obstructions should be analysed. (Littlefair, 1992a) However, the other side of the street will face north and will mainly be dependent on reflected sunlight from obstructions and ground. Buildings facing east or west may benefit from direct sunlight for half the daylight period if the obstructions do not block the lower sun altitudes in the morning and late afternoon.

A building that faces north may only receive direct sunlight early and late in the day during the summer months. In the remaining period it will have to rely on sunlight reflected from obstructions and ground. On the other hand, when the sun is in front of the building its solar altitude may be low and it may therefore

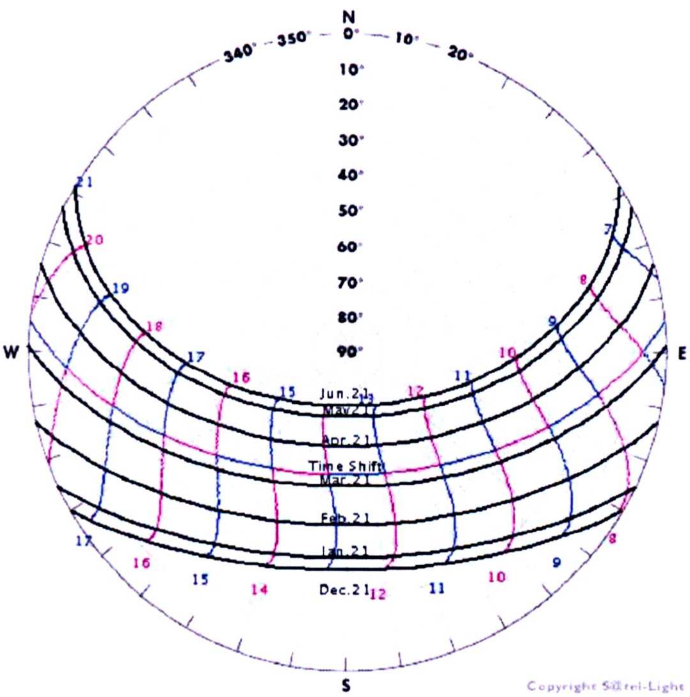



Figure 8.6: Sunpath horizontal equidistant projection 1st semester, clock time for Lisbon.

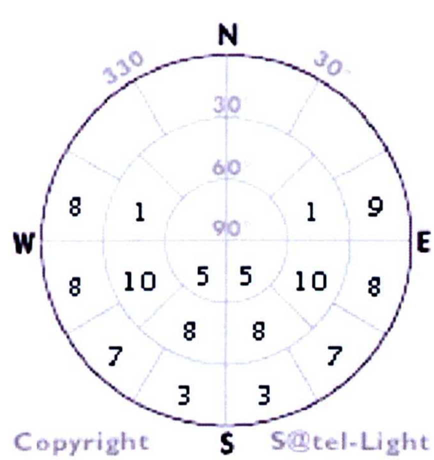



Figure 8.7: Sun position statistics in a 24 zones sky division for the year average in Lisbon.

be obstructed by the facing buildings. A building facing east may have sunlight during the morning whereas one facing west may benefit from sunlight during the afternoon.

It has been common practice in daylight analysis to use the daylight factor calculation independent of the prevailing sky conditions at the location. One justification for this has been that a simple calculation is acceptable for the purpose of the initial phases of building design. However, the justification that if the light level is acceptable under an overcast sky it is likely to be so under a clear sky, can be erroneous. In fact, under a clear sky distribution, if a window is oriented north, the illuminance on the wall due to the visible clear sky may be smaller than that due to the half hemisphere of an overcast sky. If the window is designed for overcast conditions it may be undersized, therefore electrical light may be used more often than is desirable from the point of view of energy conservation. An exception may be for the early and late hours of days in the the summer months when direct sunlight may occur. Similarly, east and west orientations may face the less bright part of the sky during half of the day, therefore the windows should not be sized for overcast conditions except when these are predominant for the location.

It has been argued that the visible part of a clear sky when the sun is behind the building may be of lower luminance. For a clear sky, the lowest sky patch is located at around 90° to the solar disk along its meridian. If the sun is low in altitude and there is little reflected light, a building facing this part of the sky may receive less light than from a standard overcast distribution where the peak sky luminance is at zenith, from where the facade of an urban canyon receives most of its light. Whilst in humid climates the clear and overcast skies may be of high brightness, in hot and dry climates, the clear sky is often of very low luminance (except for the circumsolar disk). Clear skies of very low brightness may be a result of a pure (reduced levels of aerosols, cloud droplets and ice crystals) and dry atmosphere with less molecules to scatter light. The combined effect of reduced Mie scattering and predominantly Rayleigh scattering at low wavelength results in a dark blue, less bright sky. Although these skies mainly occur in tropical climates, southern European locations may experience similar conditions. The horizontal diffuse illuminance from a CIE clear sky (with turbidity 2.7) is lower than the illuminance from a CIE overcast sky at noon on the equinox and solstice days in Lisbon. The diffuse horizontal illuminance is around 10 300, 12 500 and 8 200 lx for the clear distribution and 14 600, 18 100 and 8 900 lx for the overcast sky at the equinox, summer and winter solstice days respectively. The clear sky was found to produce consistently lower diffuse horizontal illuminance than an overcast sky did, except when the sun altitude is below 22°. Thus, when the building faces the sky opposite to the sun position, overcast skies may not be the worst condition.

The window design and size will strongly affect the illuminance inside a space. Previously it was mentioned that window size ought to be analysed with appropriate calculations for the specific location. Therefore this research has defined a simplified calculation that can be used to analyse window areas in an urban canyon to take advantage of reflected sunlight. It is suggested that windows in urban canyons facing north, east and west should be dimensioned for reflected sunlight when clear skies are predominant. The average daylight factor is the method adopted for dimensioning windows under overcast skies.

When sunlight is incident on the window, its intensity is strong and likely to provide sufficient daylight even with reduced window areas. However, it may also provoke glare due to strong contrast with the surrounding surfaces. Care should be taken to avoid sharp contrasts or consider the provision of efficient shading devices. Splayed reveals may contribute to a smother adaptation between different surface brightnesses. Shading systems are important for preventing glare, as well as, a thermal strategy or for the protection of privacy. However, a careful selection of the shading system should be made, particularly as it may significant reduce the illuminance of the space.

Daylight enhancement systems may be used to improve the light in the space, either quantitatively by increasing the light levels, or qualitatively by providing a more uniform distribution. They may be particularly useful for reducing the strong contrast between a sun patch and the darker areas in the space. Similarly, reflected light may increase either the depth of penetration or the illuminance inside a space.

If sunlight penetration is expected in a room the ratio of window head height to width as well as the ceiling height should be optimised.

The definition of a well daylit space is subjective and may strongly depend on the activity, mood, social background, age or even expectations of the occupants. The previously mentioned daylight analyses may not be a guarantee that those objectives are met. Nevertheless, the analyses give guidance and a methodology to apply for daylight design. Moreover, they are useful for detecting situations that are likely to affect daylight provision to the space.

## 8.4 Daylight design guidelines

Although the majority of Europe lies mainly within a latitude between 35 and 55° the sky distribution may vary significantly between these two extremes. Daylight criteria normally applied for an overcast sky should not be used in locations where clear skies are predominant, as explained in previous sections.

### 8.4.1 Overcast skies

Design guidelines for use under overcast skies are well documented in standards and recommendations on daylight design. See chapter 2. In the initial phases of building design they involve concerns with the effect of surrounding buildings on the window size and positioning. The CIE overcast sky is usually the main source of light, followed by skylight reflected by obstructions. Although sunlight is excluded from the calculations, its importance is suggested in the preferred orientation of the building within 90° of due south in order to achieve a certain number of probable sunlight hours during the year and a minimum over the winter season.

Good daylight design for predominantly overcast skies may be achieved if the following rules are met:

- Building design conditioned by the angular height of surrounding obstructions or a minimum vertical sky component in order to provide good access to light from the sky. Table 2.1 on page 38 presents values for different latitudes. A 25° obstruction angle in the middle of the window is defined as a maximum spacing angle for receiving sufficient skylight in the U.K.;
- With a room with side-lit windows the room depth should not exceed twice the room width. This is based on eq. 2.13 on page 49 for a typical window head height of 2 m and average reflectance of 0.5;
- No significant part of the working plane should lie beyond the no-sky line. Defined in section 2.18 on page 50[2];
- A room will tend to have a daylit appearance if the area of the glazing is 4% of the total room area. This rule is based on achieving an average daylight factor of 2% based on eq. 2.10 on page 22. Alternatively, the window area may be calculated based on eq. 2.12 on page 22;
- Surfaces that are closer to the window, within twice the window head height above the working plane, should receive sufficient daylight for task lighting for most of the daylight period. This figure is based on achieving a minimum 2% daylight factor on the working plane.

It should be noted that under overcast conditions, the sky contribution has the most weight in the illuminance reaching a point, therefore larger solid angles of visible sky will improve daylight access, particularly to lower floors of a building in an urban canyon. From the average daylight factor calculation the window size is inversely proportional to this angular visible sky, therefore narrow canyons may

[2] 50% of the working plane should receive a 0.2% sky factor to prevent legal remedy by 'Rights of Light'.

compromise daylight access by imposing impractical window sizes, particularly if these are likely to cause overheating and higher heat losses during winter. Daylight design for overcast skies can be compromised if planning guidelines do not guarantee minimum sky components dependent on the latitude of the location. The increase of surface reflectance on external obstructions will not compensate significantly for a reduction of the sky component. However, the reflectance of the internal surfaces of the room may play a significant role in increasing the illuminance indoors and will contribute to a better uniformity of the light.

### 8.4.2 Clear skies

The literature review (see section 2.6 on page 25) shows a significant deficiency in existing design guidelines and simple calculations that can be applied for clear skies. This research is therefore aimed at defining a simplified daylight calculation for buildings in an urban canyon under predominantly clear skies and at generalising planning guidelines. The average total daylight factor applies for rooms in urban canyons when sunlight is not incident on the facade. This calculation was developed using the hypothesis that daylight design should not be based on extreme conditions. If the predominant sky is clear, daylight calculations should not be based on overcast distributions. Similarly, under clear skies, windows should not be sized for direct sunlight as they will be undersized when the sun is behind the building and the light levels are much lower. Furthermore, when sunlight is incident, people may close the blinds to avoid glare due to excessive contrast between the bright window and the surrounding surfaces.

Guidelines for sunny climates in Europe are based on results obtained in previous chapters. The findings of this study should strictly apply to similar conditions, particularly with reference to canyon geometry. They are summarised as:

- there is a linear relationship between the global horizontal illuminance and the vertical illuminance when sunlight is not incident on the facade (see figs. 5.13 on page 117);
- this relationship is relatively stable throughout the year (see fig. 5.17 on page 127);
- the reflectance of the surfaces of the canyon, in particular that of the obstruction have the most effect on the illuminance of the buildings, for European latitudes (see fig. 6.3 on page 146);
- The orientation of the buildings does not affect the linear relationship when the sun is behind the building in an urban canyon (see fig. 5.22 on page 134);

- A variation of the latitude does not affect the linear relationship for the urban canyon (see fig. 6.4 on page 147);

- The slope of the linear relationship is similar for different canyon aspect ratios, but the constant of the equation tends to increase with floor height and for wider canyons due to larger angles of visible sky. (see table 5.7 and fig. 5.16 on page 125);

- The slope of the relationship is relatively constant at all floors for lower obstruction's reflectance, but varies with higher reflectance (see fig. 5.16 on page 125);

- The average total daylight factor calculation is a simple calculation similar to the average daylight factor but taking into consideration reflected sunlight in an urban canyon (see section 7.4 for the calculation);

- The average total daylight factor is proportional to the window size, therefore may be an useful method for estimating window sizes in early stages of design. Particularly as it does not require the definition of the window shape or position to be known in advance.

These conclusions apply for orientations and at times when sunlight is not incident on the facade.

In the northern hemisphere, buildings facing north will depend on reflected sunlight for most of the time. Buildings with east and west orientations will experience a similar effect during half of the day. It has been argued that windows in these orientations should be designed for reflected light, to avoid their being undersized. The south orientation is privileged in terms of number of hours during the day with direct sunlight.

In practice daylight design should only be based on direct sunlight for buildings oriented south, all other orientations should be analysed for reflected light. A canyon with an east-west axis should then be dimensioned to guarantee a certain number of hours of direct sunlight on the south facade, as well as to promote reflected sunlight into buildings opposite.

The reflectance of the surfaces may contribute enormously to the illuminance on the facade, and should therefore be given much thought. However, the reflectance may be reduced, considering that window reveals, setbacks and balconies will cast shadows. (Mardaljevic, 2004) Poor building maintenance and large areas of glazing with a reduced reflectance may also contribute to a low overall reflectance. A conservative value of 0.2 is often close to the reality and is appropriate for daylight design in urban canyon calculations.

A variation of the urban canyon aspect ratio does not affect significantly the illuminance under sunny climates. Relatively constant slope coefficients among the three ratios analysed (1:05, 1:1 and 1:1.5) show a reduced variation of the illuminance in the building.

The global horizontal illuminance can be extremely high under clear skies. The diffuse illuminance is relatively constant and has a lower contribution to the overall illuminance, except during early and late hours when the sun is below 10°. Then, a great variance of the constant for the equations on low and high floors or narrow and wide canyons is minimised under clear skies. Nevertheless, the canyon aspect ratio should prevent overshadowing of the obstructions. If the distance to the obstruction is too large, its effect on the illuminance of the building is reduced.

Results have shown that the relationship is relatively stable for north, east and northeast orientations. This may suggest that the conclusions drawn for the east-west axis canyon (north and south facing buildings) would apply for other orientations. Thus, canyon ratios dimensioned for reflected sunlight may be independent of orientation.

The illuminance on the facade depends on the site's latitude. However, the relationship between the global and the vertical illuminance remains relatively unchanged. A calculation based on this relationship may be applied for the different latitudes.

A linear relationship that is relatively stable throughout the year forms the basis for the calculation to apply in rooms in an urban canyon in sunny climates, see section 7.4.

Good daylight design in urban canyons for predominantly sunny skies may then be achieved if the following guidelines are met:

- The dimensions of the urban canyon are defined by the angular height of the obstruction according to table N.1 in appendix N to provide a minimum period of four hours of incident radiation on the south facade (depending exclusively on the latitude of the place and not on weather conditions)[3];

- A canyon width of between half the height and one and a half times the height allows reflected sunlight to be effective for the illumination of the building;

- The orientation of the building should be within 90° of due south if direct sunlight is expected. However, care should be taken to avoid overheating and glare. Shading devices should be used;

- Buildings oriented north should take the most advantage from reflected sunlight to compensate for the reduced period during the year when they benefit

[3]A recommendation of at least 4 hrs in the middle of the window has been included in DIN 5034 Part 1 of the German standard on daylight provision. (Littlefair, 2001)

from direct sunlight;

- Windows in east or west facades should be sized for reflected sunlight and not incident sunlight, to prevent their being undersized during half of the day;

- With the obstruction and ground having a reflectance of 0.2, sufficient amounts of reflected sunlight will contribute to the illuminance of a building in an urban canyon. This reflectance has been analysed for different orientations, canyon ratios (1:0.5, 1.1 and 1:1.5) and latitude (between 35° and 55°). Higher reflectances may significantly increase the illuminance levels, however they might not be realistic in real canyons. Nevertheless, a higher ground reflectance mainly contributes to an increase of the illuminance in the summer, whereas higher reflectance in the obstruction mainly increases the illuminance during winter and spring;

- An initial estimation of window dimensions for buildings which are oriented north, east or west orientations may be obtained with the average total daylight factor in eq. 7.11 on page 165 in order to take reflected sunlight into consideration (see appendix O);

- If a daylit appearance is expected, an initial estimation of 0.5% $\overline{TD}$ may be desirable. See section 7.4.

It has been shown that building design for reflected light is independent of the building's orientation. The importance of the reflectance of the surfaces has been emphasised, whilst it was established that the canyon aspect ratio and latitude of the site have a smaller effect. Nevertheless, urban planning for clear skies should guarantee a minimum space between buildings to allow sunlight incidence on buildings. If sunlight is blocked by obstructions, the illuminance on the facade will be significantly reduced, as sunlight only reaches the building after a minimum of two interreflections in the canyon. Not only does this compromise the light levels on the building, but it will also impair reflected sunlight into buildings opposite.

### 8.4.3 Combination of skies

It was expressed previously that defining the predominant sky condition for a location is very important. Its distribution can significantly affect urban planning and window design. It was mentioned that methods for evaluating the visual environment may vary from one sky condition (overcast or clear) to another. Whilst an average daylight factor may be used for daylight analysis under a predominantly overcast sky, the average total daylight factor approach is presented as a simplified method for use in sunny climates. However, there may be locations where the frequency of the skies distributions make the selection of the method to apply less obvious than the examples presented. The use of shading devices that effectively reduce the window area or its transmittance when the illuminance is high may prove effective in adapting the areas to both conditions. However, the users of the space must be educated and proactive in applying those changes. The use of an intelligent system with sensors that monitor the weather and apply the changes may prove to be more effective.

The two sky distributions can alternatively be weighed and a location that does not fit in any of these two classifications can make use of both calculations weighing over the frequency of occurrence of one sky and the other.

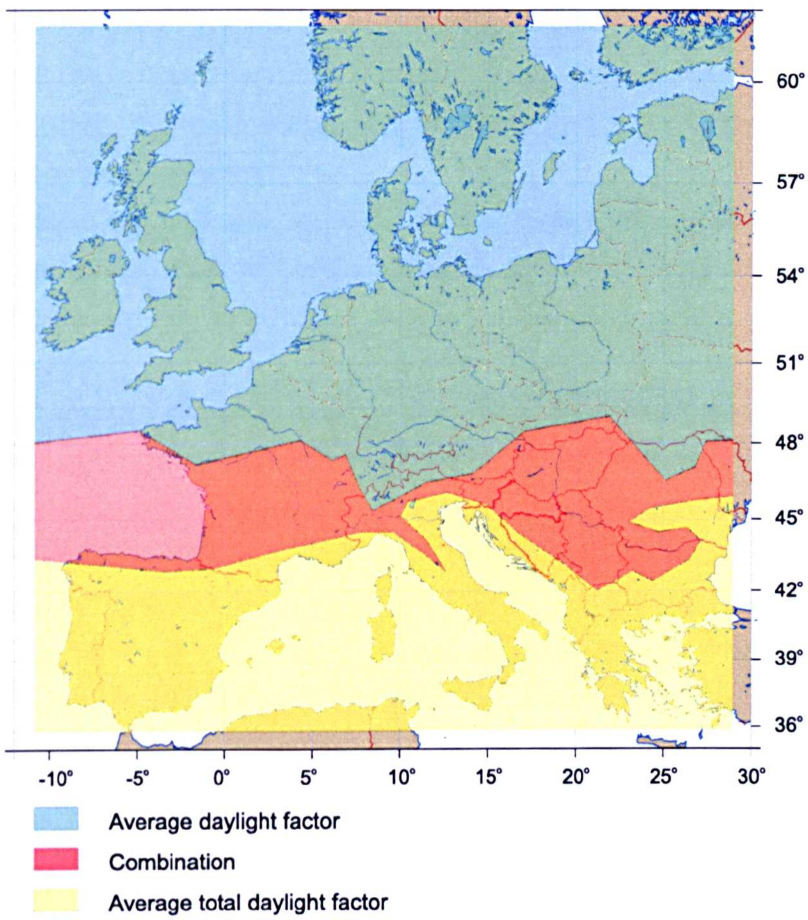



Figure 8.8: Criteria zones for daylight design in Europe.

Fig. 8.8 presents the definition of three daylight design zones in Europe where the average total daylight factor and the average daylight factor may apply and the transitional area where a combination of both calculations may be weighed by the frequency of the sky distribution. The delimitation is based around the year frequency of clear skies below 40%, between 40 and 50% and above 50% obtained with satel-light data.

## 8.5 Conflicts with other criteria

Whilst the energy consumption for lighting is not a main concern in residential buildings in comparison with office buildings, it should not result in less attention to designing for daylight. In fact, with life expectancy increasing people tend to spend more time at home. The current trend towards distance working also makes the home environment more used during daylight hours.

Although the same level of light might be required for performing a visual task in a residential building and in an office, the amount of hours necessary are usually much reduced in the former. People at home are also more likely to accept more variability in light levels due to changes in weather than in the office, where a steady level of light is sometimes preferred. Particular attention should be made to daylight in spaces where the energy consumed for lighting is a large part of the total building energy consumption. Window design should primarily focus on daylight benefit and secondarily on heat gain/loss control.

With building design aiming primarily to meet daylight criteria, care should be taken to avoid overheating as well as to prevent heat losses during the heating period. Window design for daylight may result in larger window areas than if priority is given to thermal aspects.

Designing buildings for passive solar systems will in some cases be different to designing for daylight. In thermal design, if solar radiation access is welcome during the winter period it should be avoided during the summer. On the other hand light access is needed during the whole year. The materials in the interior might be different when prioritising for one objective or the other. Optimised for their thermal performance they will probably be more absorptive in order to store the energy for later use. If chosen for daylighting they should be more reflective to distribute the light into the space more uniformly.

## 8.6 Conclusions

The achievement of a good daylight environment may prove to be difficult if the criteria adapted for the case are not analysed. Particularly, daylight design should be closely related to the weather conditions at the location. The sky distribution for the daylight analysis should have a statistical representation for the place and not be a random value that may not be representative of the climate of the place.

The decision as to whether to design for overcast or clear skies influences the strategy to be followed. Although some criteria may apply under both sky conditions, some factors may be more important under one sky distribution than the other.

The definition of a simplified calculation for clear skies should reduce the use of daylight factor calculations independent of prevailing sky conditions.

Urban planning based on daylight calculations for overcast skies may recommend less dense areas, reduced construction heights or bigger window areas in rooms. With the cost of urban terrain these measures should be applied exclusively where similar sky conditions are the rule rather than the exception.

Daylight design for overcast conditions will result in larger window areas in order to meet recommended average daylight factors. Large windows may increase the thermal gains and losses by the building envelope, possibly causing discomfort to occupants and/or a high building energy consumption.

When designing for clear skies, the first decision to be made is whether design for direct or reflected sunlight is desired. In practice, only buildings oriented south will receive sufficient quantities of direct sunlight for an extended period. North facing buildings will depend on reflected sunlight most of the time. Windows in the east and west orientations should not be sized for direct sunlight, as they will be undersized when the sun is behind the building for half of the day.

Urban planning for clear skies should guarantee a minimum distance between buildings to allow sunlight to reach the facade. If sunlight is blocked by obstructions, the illuminance on the facade will reduce drastically, as sunlight will only be available after a minimum of two interreflections in the canyon. Moreover, a poorly sunlit facade will impair reflected sunlight into buildings opposite.

When designing for reflected sunlight, the orientation of the building (north, east, west) does not affect the relationship between the global horizontal illuminance and the total vertical illuminance, when the sun is behind the building. That relationship remains stable for different latitudes, therefore a single calculation may apply for sunny climates in Europe.

The factor most affecting the illuminance of buildings is the reflectance of the surfaces of the canyon. An increase of the obstruction reflection mainly affects the illuminance of the building in the winter and spring. An increase of the ground reflectance take affect during the summer period. However, the reduced sun's altitude for higher latitudes in Europe may compromise this effect, with the obstruction-reflected component becoming more important.

There is a growing concern for energy efficient measures to do with reduction in energy consumption, derived from fossil fuel reserves, as well as the reduction of carbon dioxide emissions to prevent catastrophic global warming. Daylight is not only more energy efficient with a better colour rendering than artificial light, but it is also free and does not pollute the atmosphere. Furthermore, nations that rely on import of fossil fuels, with heavy consequences on their economic deficit, should look at the other energy sources available to them. The potential for solar energy use is enormous and daylight can play a significant role if effective measures are analysed and put into practice in the initial phases of projects or in urban planning.

In urban areas where clear skies are predominant, a calculation that considers reflected sunlight not only may prove to be more adapted to the real conditions, thereby improving the comfort of the inhabitants but it may also reduce the energy consumption of buildings. The building sector accounts for 40% of the European final energy consumption from which 11% is used in lighting and appliances in the domestic sector and 14% for lighting in the commercial sector. Effective measures to reduce these values and meet the greenhouse gas emissions reduction required under the Kyoto protocol should be implemented. Daylight efficient design may play an important role in achieving these objectives.

# Chapter 9

## Conclusions

This final chapter aims at presenting the final conclusions of this research. A summary of the outcomes from this research and suggestions for future work is presented next.

## 9.1 Aims and results

The first aim of this thesis was to analyse the contribution of reflected sunlight to the illuminance on the facade of buildings in an urban canyon. The analysis of physical measurements taken, presented in chapter 4, confirmed the contribution of reflected sunlight in an urban canyon in Lisbon. Chapter 5 shows that the reflected component is around 60% of the illuminance on the facade in a 1:1 urban canyon in Lisbon under sunny and around 18% under overcast skies. This conclusion is derived from results with a reflectance of the surfaces (ground and vertical planes) of 0.2. A higher reflectance (above 0.5) of the vertical surfaces, will roughly double the contribution of reflected light under a clear sky and increase it to around 22% at the mid-point of the facade under an overcast sky. However, typical building reflectance (where glazing weighs with a reduced diffuse reflectance of around 14% to the average of the surface), urban pollution, poor building maintenance, windows reveals and setbacks casting shadows make a conservative value of 0.2 more realistic.

Nevertheless, the variation of the reflectance of the surfaces is the factor that affects the most reflected sunlight access to the building in an urban canyon and should therefore be given much thought. The orientation of the building (north, east and west), and the latitude of the location and the canyon aspect ratio (between 1:05 and 1:1.5) have a lesser effect.

The average total daylight factor fulfils the second aim of this research, a simplified calculation to apply for urban canyons under sunny climates. The calculation developed is analogous to the average daylight factor concept but takes into consideration sunlight reflected from obstructions and ground. It is based on the principle of the integrating sphere and the ratio derived from computer simulations, between the total vertical illuminance on the facade of an urban canyon and global horizontal illuminance.

Like the average daylight factor, the average total daylight factor is proportional to the window size, it can thus be a useful method for estimating window sizes in early stages of design. This is helped by the fact that the use of the average total daylight factor does not require the window shape or position to be known in advance.

A simple method for daylight analysis and window design under clear sky conditions is the most important contribution to knowledge that emerged from this work. Although the definition of visual comfort indices and window dimensioning goes beyond the time frame of this thesis, the simple tool lays the foundations for further research in this field.

Measurements taken in Lisbon showed a linear relationship between the global horizontal illuminance and the total vertical illuminance when the facade is not receiving direct sunlight. Further analysis with computer simulations and an analytical calculation presented in chapters 5 and 6 confirmed an approximately linear relationship. Deviations from this trendline affecting the lower floors of the building occur mainly in the summer period when most of the street is sunlit. However, they do not weigh significantly in the overall relationship. Furthermore, results showed that this relationship does not change very much during the year, therefore a general equation can be representative for the whole year with a reduced error. As it is relatively constant on different floor heights (slightly higher in mid floors), a single value may be used when high accuracy is not required, i.e. in a calculation to apply in the initial phases of the project.

Although the illuminance on the facade will vary with site latitude, the linear relationship with the global horizontal illuminance remains relatively constant for the latitudes analysed (between 35° and 55°) and can therefore be used as the basis of a calculation to apply for clear skies when sunlight is not incident on the facade in urban canyons in Europe.

While results obtained from the three methods present significant variations, they all show a linear relationship between the global horizontal and total vertical illuminance when there is no sunlight incident on the facade. Reasons for differences between physical measurements and those obtained by the other two means may be due to irregularities of the facade in terms of window reveals, setbacks or balconies, which contrast to the perfectly flat surfaces defined in the model for the simulation or analytical calculation, reducing the effective reflectance of the obstruction. Any protruding element on the facade will cast a shadow with a sharp contrast when sunlight is incident. If interreflections in the canyon are reduced, those umbras will have a very low luminance. Not only will the average reflectance of the facade be significantly reduced, it may create zones of potential glare due to a harsh contrast between strongly sunlit areas and the shadows. Under an overcast sky the shadow will be much softer. Since sunlight is very directional and much stronger than light from the rest of the sky, the shadows are much softer under an overcast sky than they are under a sunny one, reducing the contrast between the lit and the unlit areas on the facade.

Planning guidelines are the final objective of this research. The research aims at defining simple guidelines that may encourage planners and architects to adopt efficient measures for the provision of daylight to buildings under clear skies.

The analysis of results derived from the three different approaches shows that the illuminance of buildings in an urban canyon is affected by a number of factors. A simplified calculation was developed, which may be used as an indicator of how well-lit a space is and allowing for the sizing of windows under predominantly sunny climates, as well as guidelines for good daylight practice. This formed the basis for the definition of guidelines for daylighting and urban planning in Europe.

Two different approaches to daylight design were presented in section 8.4. The first one applies for predominantly overcast skies and is mostly based on the old and tested daylight factor approach, while a new one, centred around the total daylight factor introduced and defined in this thesis, is more suited for clear sky conditions. The two approaches relate to northern and southern European climates, respectively. Since the main criterion for choosing one or the other route is the sunshine probability, a third region was identified where a more detailed analysis of the local climate is desirable in order to select whether the total daylight factor should be favoured over the daylight factor approach, or whether indeed both apply to the same extent.

It is thus now possible to derive daylighting and planning guidelines that may be applied to any European climate and location, without having to assume the existence of overcast skies for most of the year.

## 9.2 Results and previous theory

The literature review showed that there are several tools or calculations available for daylight design. On the one hand it revealed the wide acceptance of the daylight factor approach for daylight calculations. Although this calculation may have some limitations in terms of accuracy, its simplicity has proved to be the main incentive to its use. On the other hand, it revealed the need for a simplified tool taking into consideration the sun component for use in the initial phases of the design. This formed the basis for the development of the total daylight factor, which, in contrast to the daylight factor, also accounts for reflected light contributed by the obstruction and ground. While the daylight factor calculation may be used for overcast conditions, a similar calculation based on the total daylight factor has been put forward for clear skies.

Daylight calculations mainly provide ways for calculating daylight in terms of illuminance levels. The average daylight factor, as a way to characterise the perception of how well a space is lit, appears to be more appropriate to daylight analysis. The average total daylight factor was based on the same approach, promoting the development of such a characterisation for sunny climates.

It was found in this research that the relationship between the global horizontal illuminance and the total vertical illuminance on a facade within an urban canyon does not change significantly during the year or with latitude. Although it was difficult to validate this hypothesis due to the nonexistence of previous data on urban canyons, an analogy between a canyon and a photometric integrator may go some way to proving the results obtained.

This study is innovative in terms of the collection of real measurements in an urban canyon, aiming at obtaining results for sunny climates. Previous research in atria buildings may present similarities. However, the results were mainly focused on daylight under overcast skies, and therefore are of limited interest to this study. While reflected sunlight is recognised as a contribution to daylight, little research has been carried out on its potential, particularly in urban areas. When a facade is sunlit, the building opposite may benefit from reflected sunlight. Measurements of vertical illuminance on the outside of the facade confirmed the importance of this contribution to the illuminance of buildings.

It was found that the current literature still lacks guidance on daylight design for sunny climates. Chapter 8 attempted to overcome this deficiency by presenting guidelines to be applied for overcast and clear skies.

## 9.3 Results and practice

There is a long tradition of daylight research, particularly in the United Kingdom. However, daylight provision in building design is quite often intuitive or secondary. One main reason for the reduced practice of daylight design may be the nonexistence of daylight regulations. Anything that is not compulsory and may seem difficult to apply tends to be ignored by building designers. Additional reasons may be conflicts with other regulations or an insufficient knowledge of the basic principles of daylight and the benefits of a well-daylit space to the inhabitants.

As daylight recommendations quite often conflict with other building requisites, a careful decision needs to be made accordingly to the needs of people and expectations for the space. Daylight aims at improving the quality of life and well-being of the occupants of a building. A daylit space is preferred by occupants, as it is perceived as more spacious and relaxing. Whenever possible, buildings should be designed for daylight.

A new directive from the European Union on the energy performance of buildings expresses the growing concern for energy consumption in buildings which accounts for 40% of the total energy consumption in the European Community and significantly increases its carbon dioxide emissions. (anon., 2003) Daylight, as a free, inexhaustible and non pollutant energy, may play an important role in meeting those objectives. The implications of a design that is deficient in terms of daylighting can be enormous. It may affect the occupants health, well being and productivity. It may increase the building's running costs, contribute to the depletion of fuel reserves and contribute to a move away from meeting the Kyoto protocol commitments to reduce the greenhouse gases emission to 8% below 1990 levels by 2008-12.

The main advantages of simple daylight calculations and rules of thumb are their applicability in the initial phases of design and their ease of use, making them tools even for planners and architects with little or no knowledge in this field. Nevertheless, their limitations should be acknowledged and they should not be taken as a substitute for detailed studies when those are required. It is hoped that the division of Europe into three distinct zones of different daylight criteria will prove useful and will lead to a widespread use of the new European planning guidelines, see fig. 8.8 on page 192.

The obstruction angle of urban canyons should not be above what is recommended accordingly to the predominant sky conditions and latitude of the site (see tables 2.1 on page 38 and N.1).

Under an overcast sky, the main contribution to the illuminance of the building in an urban canyon is the direct light from the sky. Wider canyons will increase the vertical sky component (larger solid angle of visible sky), particularly on lower floors. Diffuse light reflected from obstructions and ground is not significant to the illuminance of the building, unless highly reflective materials are applied. Urban planning design should primarily aim at guaranteeing low obstruction angles.

With a clear sky, the sun position and the orientation of the building may strongly affect the sunlight availability to a building in an urban canyon. Sunlight reflected by obstructions and ground may significantly increase the illuminance in the building. On the one hand, obstructions may block sunlight access to the building. On the other hand, however, reflected sunlight from obstructions and ground can play an important role in the illumination of buildings particularly for orientations and times of the day when sunlight is not incident on the facade. Furthermore, they can redirect the light deep into a side-lit space and to surfaces other than the horizontal plane, promoting a better uniformity of the natural light inside the space.

The first decision to be made is whether design aiming for direct or reflected sunlight. In practice, daylight design should only be based on direct sunlight for buildings oriented south, as this orientation is privileged in terms of number of hours during the day with direct sunlight. All other orientations should be analysed for reflected light. North facing buildings will depend on reflected sunlight most of the time. Buildings with east and west orientations will experience a similar effect during half of the day. Therefore, windows in these orientations should not be sized for direct sunlight, as they will be undersized when the sun is behind the building, for half of the day. Furthermore, when sunlight is incident, people may close the blinds to prevent glare caused by an excessive contrast between the bright window and the surrounding surfaces, and to avoid overheating of the space.

Urban planning for clear skies should guarantee a minimum distance between buildings to allow sunlight to reach the facade and promote reflected sunlight into opposite buildings. A width of urban canyons between half the height and one and a half times its height allows sunlight reflected to be effective to the building without too much reduction of skylight on lower floors and overshadowing from obstructions. If sunlight is blocked by obstructions, the illuminance on the facade will reduce drastically, as sunlight will only be available after a minimum of two inter-reflections in the canyon, and will impair reflected sunlight into buildings opposite.

Results have shown that the relationship between the global horizontal illuminance and the total vertical illuminance, when the sun is behind the building is relatively stable for north, east and northeast orientations. Then, urban planning for reflected sunlight may be independent of the building's orientation. That relationship also remains unchanged for different latitudes, therefore a single calculation based on this relationship may be applied for any sunny climate in Europe.

The factor most affecting the illuminance of buildings is the reflectance of the surfaces of the canyon. An increase of the obstruction reflectance mainly affects the illuminance of the building in winter and spring. An increase of the ground reflectance takes affect during the summer period. However, the low sun altitude for higher latitudes in Europe may compromise this effect, with the obstruction-reflected component becoming more important. Results for different orientations, canyon ratios (1:0.5, 1:1 and 1:1.5) and latitude (between 35° and 55° $N$) shows that the surfaces of the canyon having a reflectance of 0.2 will allow sufficient amount of reflected sunlight to contribute to the illuminance of a building in an urban canyon.

Window dimensioning should make use of either the average daylight factor calculation or the average total daylight factor calculation for overcast or clear skies, respectively. A daylit appearance may be achieved with a 2% average daylight factor for overcast conditions or a 0.5% average total daylight factor for clear sky conditions (see appendix O).

## 9.4 Suggestions for future research

Although computer simulations, scale models and analytical calculations may prove to be an important sources of data, real measurements are the most valid resource. A wider range of measurements taken over a full year and under different external conditions would allow the derivation and comparison of coefficients obtained in this research with those obtained using theoretical methods.

Weather data in the visible range of the spectrum are important for daylight design. As vertical windows may primarily face half of the sky dome, the systematic collection of illuminance values at least for the four cardinal points should be carried out. A common simplification in analytical calculations is the assumption that the diffuse contribution from any sky is the same as that from a uniform sky. Given the horizontal illuminance of a clear sky, this assumption may overestimate the illuminance on vertical surfaces facing the less bright area of the sky opposite to the sun. An attempt was made to reduce this inaccuracy by defining correction factors. Further research necessary in this area is indicated.

The average total daylight factor is based on the relationship between the global horizontal and the total vertical illuminance in an urban canyon. It was shown that this relationship does not change significantly throughout the year. This hypothesis is based on data obtained with a CIE clear sky model on different days of the year, but with a constant turbidity factor. Further analysis under real conditions is needed. Results for different orientations (north, east and northwest) have presented similar relationships in a case study in Lisbon. An analysis for latitudes between 35° and 55° (5° interval) for a north orientation do not show significant differences. This may give scope for the adoption of a single factor, simplifying the calculation even more. Further studies confirming these assumptions under real sky conditions may refine and validate its use.

The average total daylight factor approach presented in this thesis mainly defines a simplified calculation to be applied for daylight analysis. Initial estimations proposed to characterise a daylit space are based on quantitative data obtained in this study with RADIANCE simulations. The definition of visual comfort indices similar to those assumed for the average daylight factor should be based on experimental surveys in real situations.

The average total daylight factor is proportional to the window size and may be used as a method for estimating window sizes. As expressed above a choice for recommended indices should be cemented with further studies. Previous results showing low variability of coefficients for different floor heights and the strong influence of the reflectance of the surfaces may suggest window design based on parameters obtained for lower floors of buildings in an urban canyon, where the contribution from the sky may be reduced. Factors such as orientation, latitude or canyon ratio do not affect the overall calculation much, whereas the reflectance of the surfaces will play the most important role.

However, attention should be paid to the fact that non-flat surfaces will increase the chances of sunlight casting shadows with the consequence of reducing the effective reflectance of the surface. It would be interesting to collect data on the overall reflectance of sunlit facades in urban canyons.

The definition of the three daylight design zones in Europe was based on the yearly frequency of clear skies below 40%, between 40 and 50% and above 50% obtained with Satel-light data. The study of a daylight atlas may suggest a different classification.

Guidelines proposed in this study are aimed at promoting good practice in daylight design, thereby improving the visual quality of interior spaces. Any suggestions as to further implications with the thermal behaviour of a building, its energy consumption and the comfort of the occupants have been educated guesses based on previous practice in this field. A combined study that analyses the thermal and daylight aspects may confirm and refine the suggestions made.

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# Appendix A

## Coefficients for the calculation of daylight factor Eq. 2.7 (Lynes, 1968)

Table A.1: Coefficient for $a$

| Floor reflection factor | 0.3 | | | 0.1 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ceiling reflection factor | 0.7 | | | 0.7 | | | 0.5 | | | 0.3 | |
| Wall reflection factor | 0.5 | 0.3 | 0.1 | 0.5 | 0.3 | 0.1 | 0.5 | 0.3 | 0.1 | 0.3 | 0.1 |
| Room index | Values of $a$ | | | | | | | | | | |
| 1.0 | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| 1.25 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 1.5 | 1.2 | 1.1 | 1.1 | 1.2 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 |
| 2.0 | 1.2 | 1.2 | 1.1 | 1.2 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 |
| 2.5 | 1.3 | 1.2 | 1.2 | 1.3 | 1.1 | 1.1 | 1.2 | 1.1 | 1.0 | 1.0 | 1.0 |
| 3.0 | 1.5 | 1.4 | 1.3 | 1.4 | 1.2 | 1.1 | 1.3 | 1.2 | 1.1 | 1.1 | 1.0 |
| 4.0 | 1.7 | 1.6 | 1.4 | 1.5 | 1.3 | 1.2 | 1.4 | 1.3 | 1.2 | 1.1 | 1.0 |
| 5.0 | 2.0 | 1.8 | 1.6 | 1.7 | 1.4 | 1.3 | 1.5 | 1.4 | 1.3 | 1.1 | 1.0 |

Table A.2: Coefficient for $v$

| Floor reflection factor | 0.3 | | | 0.1 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ceiling reflection factor | 0.7 | | | 0.7 | | | 0.5 | | | 0.3 | |
| Wall reflection factor | 0.5 | 0.3 | 0.1 | 0.5 | 0.3 | 0.1 | 0.5 | 0.3 | 0.1 | 0.3 | 0.1 |
| Room index | Values of $v$ | | | | | | | | | | |
| 1.0 | 4.0 | 2.9 | 2.1 | 3.5 | 2.2 | 1.6 | 3.1 | 2.0 | 1.3 | 1.7 | 1.0 |
| 1.25 | 3.9 | 2.6 | 2.0 | 3.1 | 2.0 | 1.6 | 2.7 | 1.8 | 1.3 | 1.6 | 0.9 |
| 1.5 | 3.8 | 2.3 | 1.8 | 2.7 | 1.8 | 1.4 | 2.5 | 1.6 | 1.1 | 1.3 | 0.8 |
| 2.0 | 3.5 | 2.2 | 1.7 | 2.5 | 1.7 | 1.4 | 2.1 | 1.4 | 1.0 | 1.1 | 0.8 |
| 2.5 | 3.2 | 2.0 | 1.6 | 2.3 | 1.6 | 1.3 | 1.8 | 1.3 | 0.9 | 1.0 | 0.6 |
| 3.0 | 2.7 | 1.7 | 1.3 | 2.1 | 1.4 | 1.1 | 1.6 | 1.1 | 0.9 | 1.0 | 0.6 |
| 4.0 | 2.5 | 1.6 | 1.1 | 1.8 | 1.3 | 1.0 | 1.3 | 1.0 | 0.8 | 0.9 | 0.5 |
| 5.0 | 2.1 | 1.3 | 1.0 | 1.6 | 1.1 | 0.9 | 1.0 | 0.9 | 0.6 | 0.8 | 0.4 |

Room index is given by the equation

$$\frac{rd \cdot rw}{rw \cdot (rd + rw)} \tag{A.1}$$

where

$rd$ is the room depth;

$rw$ is the room width;

$rh$ is the room height above working plane.

Table A.3: Coefficient for $e$

| Angle of obstruction from centre of window (degrees above horizontal) | $e$ |
|---|---|
| 0 (i.e. unobstructed) | 1.9 |
| 10 | 0.9 |
| 20 | 0.8 |
| 30 | 0.65 |
| 40 | 0.5 |
| 50 | 0.35 |
| 60 | 0.25 |
| 70 | 0.18 |
| 80 | 0.13 |

# Appendix B

## Daylight attenuation in top-lit atria (Tregenza, 1997)

The illuminance on the horizontal plane, $E_{hh\,total}$ at a height $h$ from top and the vertical illuminance at the same level is $E_{vh\,total}$

$$E_{hh\,total} = E_{h0}[(2\alpha - R_1)\exp(-\alpha k WI)]/[2\alpha(1 - R_1 R_2)] \tag{B.1}$$

$$E_{vh\,total} = E_{hh\,total} k(1 + R_1)/4 \tag{B.2}$$

where

$E_{h0}$ mean horizontal illuminance at the top of the well;

$E_{v0}$ mean vertical illuminance at the top of the well;

$\alpha$ fraction of light incident on walls that is not reflected downwards $\alpha = (1 - \rho_{vd})/(2 - \rho_{vs})$;

$\rho_{vd}$ mean diffuse reflectance of walls;

$\rho_{vs}$ mean specular reflectance of walls;

$k$ attenuation parameter $k = (4E_{v0}/E_{h0})(1 - WI/8)$;

$WI$ well index of the space above the illuminated plane $WI = h(l+w)/2kw$;

$l$ length of rectilinear form;

$w$ width of rectilinear form;

h height of rectilinear form;

$R_1$ is the cavity reflectance of the space above the illuminated plane;

$R_2$ is the cavity reflectance of the space below the illuminated plane.

# Appendix C

# Modification of the split-flux formulae for mean daylight factor and internal reflected component with large external obstructions (Tregenza, 1989)

The mean daylight factor, $DF_{mean}$, is

$$DF_{mean} = tW\left(\frac{C}{A_{fw}} + \frac{C\rho_{fw} + D\rho_{cw}\rho_g}{A\,(1-\rho)}\right) \tag{C.1}$$

The mean internal reflected component, $IRC_{mean}$, is

$$IRC_{mean} = t\left(\frac{W}{A}\frac{C\rho_{fw} + D\rho_{cw}\rho_g}{1-\rho}\right) \tag{C.2}$$

Where

$t$ — overall transmittance of the window system taking into account diffuse glass transmittance, dirt, glazing bars, curtains and other obstructions;

$W$ — window area;

$A$ — total internal area: floors, walls, ceilings windows;

$A_{fw}$ — area of floor and wall surfaces below the centre-height of the windows, excluding the window wall surfaces;

$\rho_{fw}$ — mean reflectance of the floor and wall surfaces below the centre-height of the windows, excluding the window wall surfaces;

$\rho_{cw}$ — mean reflectance of the ceiling and wall surfaces above the centre-height of the windows, excluding the window wall surfaces;

$\rho$ — mean internal reflectance: floor, walls, ceiling, windows;

$\rho_g$ mean ground reflectance (the area of effective ground extends from building some 3 to 3.5 times the height of the ceiling above ground).

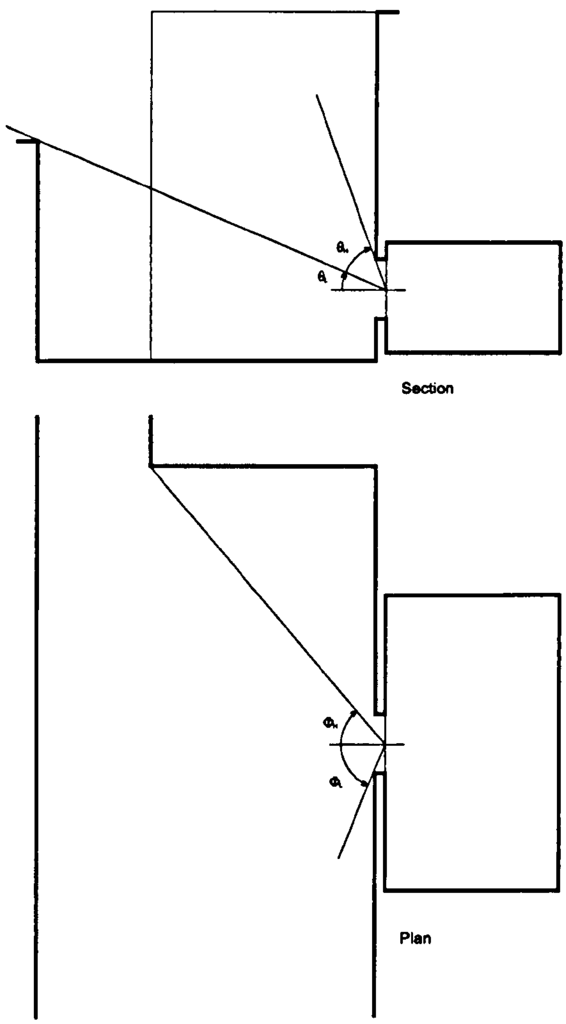



Figure C.1: The angle of visible sky is defined by the angles $\theta_L$ and $\theta_H$in altitude, $\phi_L$ and $\phi_R$ in azimuth. Angles are measured in radians.

The coefficient $C$, is given by

$$C = \frac{9}{7\pi} f \left(1 + \frac{\rho_b}{\pi(1-\rho_o)} g\right) \tag{C.3}$$

Where

$$f = \left(\frac{1}{3}(\sin\phi_L + \sin\phi_R) \cdot \left(\frac{\theta_H - \theta_L}{2} + \frac{\sin 2\theta_H - \sin 2\theta_L}{4} - \frac{2\cos^3\theta_H - 2\cos^3\theta_L}{3}\right)\right) \tag{C.4}$$

$$g = \left(\frac{\pi}{2} - (\sin\phi_L + \sin\phi_R) \cdot \left(\frac{\theta_H - \theta_L}{2} + \frac{\sin 2\theta_H - \sin 2\theta_L}{4}\right)\right) \tag{C.5}$$

$$\rho_o = \frac{\rho_b + \rho_g}{4} \tag{C.6}$$

See fig. C.1 for definition of angles.

The coefficient $D$, may be found assuming:

$E_g/E_h$ the illuminance on the ground outside is a fraction of the unobstructed illuminance;

$L_g$ is the luminance of the ground and lower parts of all obstructions form a half-infinite diffusing plane defined as $L_g = \rho_g E_g/\pi$ .

Then the relative illuminance from reflected light into the window plane is

$$E_{wg} = \frac{\rho_g E_g}{2E_h} \tag{C.7}$$

With ground reflectance around 0.2 it was not considered worthwhile to calculate the fraction corresponding to the ground illuminance, assuming a value 0.5. The $D$ coefficient is $D = 25$.

# Appendix D

## Mean daylight in Rooms Facing Sunlit Streets (Tregenza, 1995)

The fraction, $p_{sg}$, of the street that is sunlit is defined as

$$p_{sg} = 1 - \frac{h \cos \mid \alpha_b - \alpha_s \mid}{w \tan \gamma_s} \tag{D.1}$$

where

| | |
|---|---|
| $h$ | height of obstruction; |
| $\alpha_b$ | is the azimuth of the line perpendicular to the facade; |
| $\alpha_s$ | is solar azimuth; |
| $\gamma_s$ | is solar altitude; |
| $w$ | is the width of the canyon. |

The mean ground illuminance, $E_g$, is

$$E_g = E'_g = E_{dh} + p_{sg} E_{sn} \sin \gamma_s \tag{D.2}$$

where

| | |
|---|---|
| $E_{dh}$ | is the diffuse horizontal illuminance; |
| $E_{sn}$ | is the solar normal illuminance. |

The fraction, $p_{sf}$, of the facade that is sunlit is defined as

$$p_{sf} = \frac{w \tan \gamma_s}{h \cos(\alpha_b - \alpha_s)} \tag{D.3}$$

The total direct illuminance on the window pane is

$$E_{ws} = E_{dh}\frac{1-\sin\omega}{2} + E_{sn}\cos\theta \tag{D.4}$$

when the window is sunlit
and

$$E_{ws} = E_{dh}\frac{1-\sin\omega}{2} \tag{D.5}$$

otherwise.
Where

$\omega$ is the angle of obstruction at centre of window.

The illuminance on the window including inter-reflections within the canyon is

$$E_{wo} = \frac{(E_{ws}+E_{wg})(0.5\rho_w\sin\omega)^2 + (E'_{ws}+E'_{wg})(0.5\rho_w\sin\omega)}{1-(0.5\rho_w\sin\omega)^2} \tag{D.6}$$

where

$\rho_w$ is the reflectance of the window facade.

The direct illuminance on the internal surfaced is
$E_{ci} = \frac{A_W}{A_c}[E_{ws}t_{sc} + E_{wo}t_{oc} + E_{wg}t_{gc}]$
$E_{vi} = \frac{A_W}{A_v}[E_{ws}t_{sv} + E_{wo}t_{ov} + E_{wg}t_{gv}]$
$E_{pi} = \frac{A_W}{A_p}[E_{ws}t_{sp} + E_{wo}t_{op} + E_{wg}t_{gp}]$
where

$A_w$ is the glazed area of window;

$A_c$ is the area of ceiling;

$A_v$ is area of walls above working plane (excluding window pane);

$A_p$ is the area of the working plane.

The mean illuminance over all room surfaces from inter-reflected is approximately

$$E_r = \frac{E_{ci}A_c\rho_c + E_{vi}A_v\rho_v + E_{pi}A_p\rho_p}{A(1-\rho)} \tag{D.7}$$

where

$\rho_c$ is the reflectance of the ceiling;

$\rho_v$ is the reflectance of the walls (excluding window wall);

$\rho_p$ is the reflectance of the working plane.

The final illuminance of the room are

$$E_c = E_{ci} + E_r \tag{D.8}$$

$$E_{vw} = E_r \tag{D.9}$$

$$E_v = E_{vi} + E_r \tag{D.10}$$

$$E_p = E_{pi} + E_r \tag{D.11}$$

where

$E_c$ final illuminance on ceiling;

$E_{vw}$ final illuminance on window wall;

$E_v$ final illuminance on other walls;

$E_p$ final illuminance on the working plane;

# Appendix E

## Geometrical relations

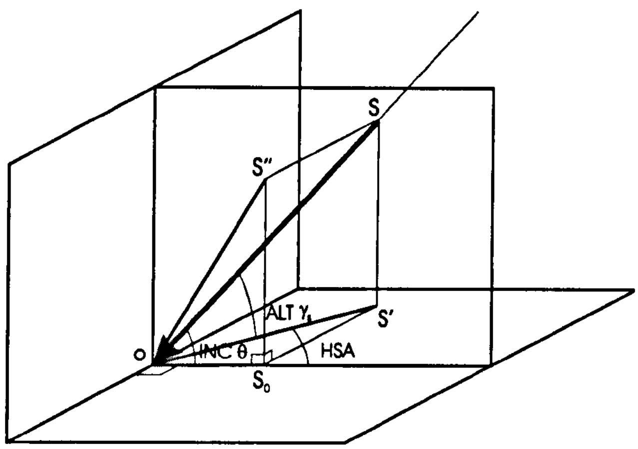



Figure E.1: Vector geometry

Given the point $O$ in the vertical surface and a point $S$ in the direction line of the sun ray unity distant from $O$, see fig. E.1, the following geometrical relations apply:

$OS \cdot \cos \gamma_S = OS'$

$OS' \cdot \cos HSA = OS_0$

$OS \cdot \cos \gamma_S \cdot \cos HSA = OS_0 = OS \cdot \cos \theta$

$OS \cdot \sin \gamma_S = SS' = S''S_0 = OS_0 \cdot \tan VSA$

$OS \cdot \frac{\sin \gamma_S}{\tan VSA} = OS_0 = OS \cdot \cos \theta$

$\cos \theta = \cos \gamma_S \cdot \cos HSA = \sin \gamma_S \cdot \frac{1}{\tan VSA}$

where

$S'$ is the projection from point $S$ in the horizontal plane;

$S''$ is the projection from point $S$ in the vertical plane;

$S_0$ is the projection of the vertical projection, $S''$, in the horizontal plane containing $S'$ .

# Appendix F

## Configuration factor for element parallel to rectangle (Tregenza and Sharples, 1993)

The configuration factor between a point $P$ in the facade and a finite obstruction $\delta$ is

$$\begin{aligned} CF_{\delta-P} &= \left(\frac{A \cdot \arctan B + C \cdot \arctan D}{360}\right) \cdot 2 \\ &= \left(\frac{\left(\frac{a}{\sqrt{c^2+a^2}}\right) \cdot \arctan\left(\frac{b}{\sqrt{c^2+a^2}}\right) + \left(\frac{b}{\sqrt{c^2+b^2}}\right) \cdot \arctan\left(\frac{a}{\sqrt{c^2+b^2}}\right)}{360}\right) \cdot 2 \end{aligned} \tag{F.1}$$

where

$A = \frac{a}{c \cdot \sqrt{1+\frac{a^2}{c^2}}} = \frac{a}{\sqrt{c^2+a^2}}$

$B = \frac{b}{c\sqrt{1+\frac{a^2}{c^2}}} = \frac{b}{\sqrt{c^2+a^2}}$

$C = \frac{b}{c\sqrt{1+\frac{b^2}{c^2}}} = \frac{b}{\sqrt{c^2+b^2}}$

$D = \frac{a}{c\sqrt{1+\frac{b^2}{c^2}}} = \frac{a}{\sqrt{c^2+b^2}}$ see figure F.1,

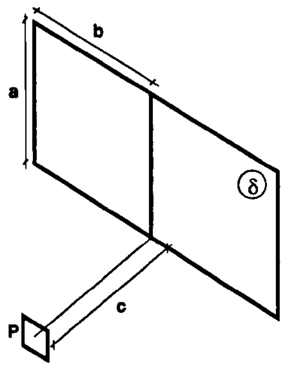



Figure F.1: Geometry between a point and a surface for the finite configuration factor.

with angles expressed in degrees.

# Appendix G

# Illuminance from first reflection in urban canyon with surfaces of equal reflectance

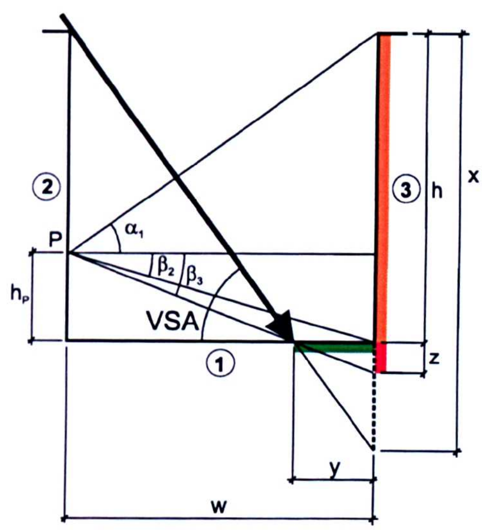



Figure G.1: Section of an urban canyon showing the angles between a point P and the sun patch on the ground plane extended to the obstruction.

If the reflectance $\rho_1$ of surface $S_1$ is the same as the reflectance $\rho_3$ of surface $S_3$, the configuration factor, $CF_{3e-P}$ between the sun patch extended in the obstruction and the point $P$ is

$CF_{3e-P} = \frac{\sin\alpha_1 + \sin\beta_3}{2}$

where

$\alpha_1 = \arctan\left(\frac{h-h_P}{w}\right)$;

$\beta_3 = \arctan\left(\frac{h_P \cdot \tan VSA}{h}\right)$.

The illuminance $E_P\,(1)$ is

$$
\begin{aligned}
E_P\,(1) &= E_3 \cdot \rho \cdot CF_{3e-P} + E_1 \cdot \rho \cdot CF_{3e-P} \\
&= \rho \cdot CF_{3e-P} \cdot (E_3 + E_1) = \rho \cdot CF_{3e-P} \cdot E_{sn}\,(\cos\theta + \sin\gamma_s) \qquad \text{(G.1)}
\end{aligned}
$$

# Appendix H

## Orientation factors

Table H.1: Orientation factors (CIBSE, 1999)

| Orientation | Factor |
|---|---|
| North | 0.97 |
| East | 1.15 |
| South | 1.55 |
| West | 1.21 |
| Horizontal | 1.00 |

Orientation factors in table H.1 allows for different amounts of skylight from a CIE overcast sky (isotropic in azimuth) to be considered on different orientations.

# Appendix I

## Formulaes

Solar Brightness, $Sb$, in Watt/steredian/m$^2$ is

$Sb = \frac{1500000000}{208} \cdot 1.147 - \frac{0.147}{\sin\gamma_s}$

if $\sin\gamma_s > 0.16$ ;

otherwise

$Sb = \frac{1500000000}{208} \cdot 1.147 - \frac{0.147}{0.16}$

where

$\gamma_s$ is the solar altitude,

208 is the sun efficacy, in lumen/Watt

Solar normal illuminance, $E_{sn}$, in lux is

$E_{sn} = Sb \cdot 179 \cdot 0.00006$

where

179 is RADIANCE luminous efficacy, in lumen/Watt;

0.00006 is the sun solid angle in steredian.[1]

Solar horizontal illuminance, $E_{sh}$, in lux is (Tregenza, 1995)

$E_{sh} = E_{sn} \cdot \sin\gamma_s$ .

Diffuse horizontal illuminance, $E_{dh}$, is

$E_{dh} = 800 + 15500 \cdot \sqrt{\sin\gamma_s}$

if $\sin\gamma_s > 0$ ;

otherwise

$E_{dh} = 0$ .

[1]Formulas subtracted from the source code of the Radiance software.

# Appendix J

## Sky partition

Initial assumptions adopted to simplify the analytical calculation will somewhat limit the accuracy of the results. This appendix presents an attempt made to reduce the error in the sky distribution as shown in section 6.6.2 on page 152. It considers the horizontal diffuse illuminance as a result of half of the hemisphere that can be seen by the building, instead of the whole sky vault. As this results in a lower horizontal illuminance level, it is necessary to use a multiplier to compensate for the missing half hemisphere. Fig. J.1 presents these results. The diffuse illuminance that reaches the 3$^{rd}$ floor of a north facade was obtained from the horizontal illuminance from half a hemisphere multiplied by a constant, assuming an uniform sky distribution. For this particular example the multiplying factors used were 2.2 in 21$^{st}$ March, 1.8 in June and 2.4 in December. These factors depend on the aperture of the canyon, the reflectance of the surfaces and the height in the facade. If individual factors will reduce significantly the error between the results obtained with the two methods, even an average of the three factors multiplied by the half of the sky contribution will provide a better approximation than using the whole sky.

Table J.1: Constants by which to multiply the horizontal diffuse illuminance result of half north hemisphere.

| North - 3$^{rd}$ floor | 21$^{st}$ March | 21$^{st}$ June | 21$^{st}$ December |
|---|---|---|---|
| 34deg rule OBS $\rho = 0.2$ GND$\rho = 0.2$ | 2.3 | 1.9 | 2.5 |
| 45deg rule OBS $\rho = 0.2$ GND$\rho = 0.2$ | 2.2 | 1.8 | 2.4 |
| 64deg rule OBS $\rho = 0.2$ GND$\rho = 0.2$ | 1.7 | 1.7 | 2 |

Table J.1 presents the multiplying factors for a wider and a narrow canyon with 0.2 reflectance on the surfaces.

### Data availability

Although a higher accuracy can be obtained by using the diffuse horizontal illuminance from half a sky hemisphere multiplied by a constant, daylight databases rarely

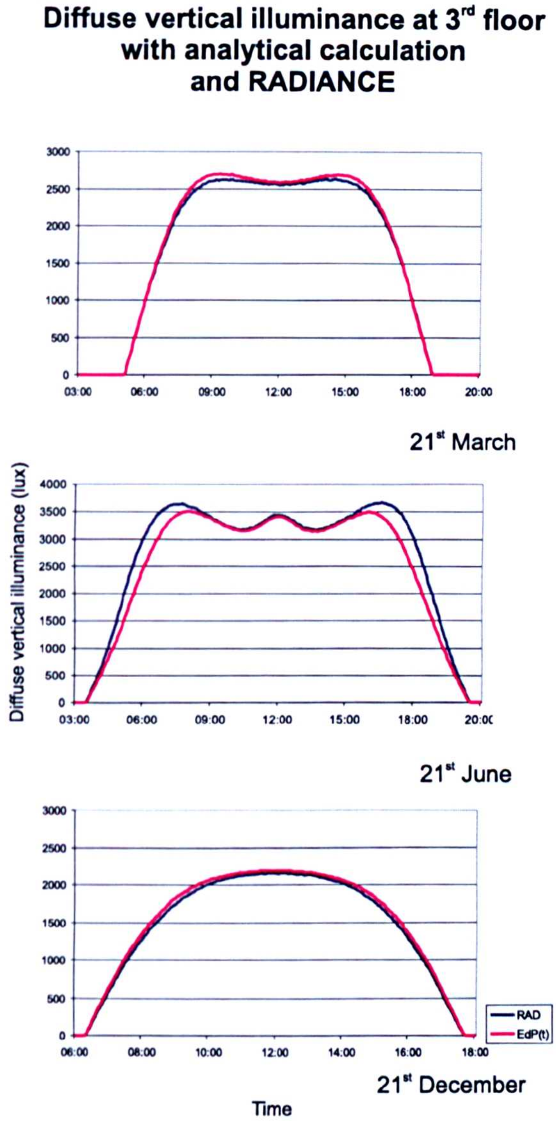



Figure J.1: Diffuse vertical illuminance on the 3rd floor of a north facing building in an urban canyon. The calculation was made with RADIANCE simulations and an analytical calculation were the diffuse horizontal illuminance was taken to be half of the sky hemisphere times a constant.

consider that information.

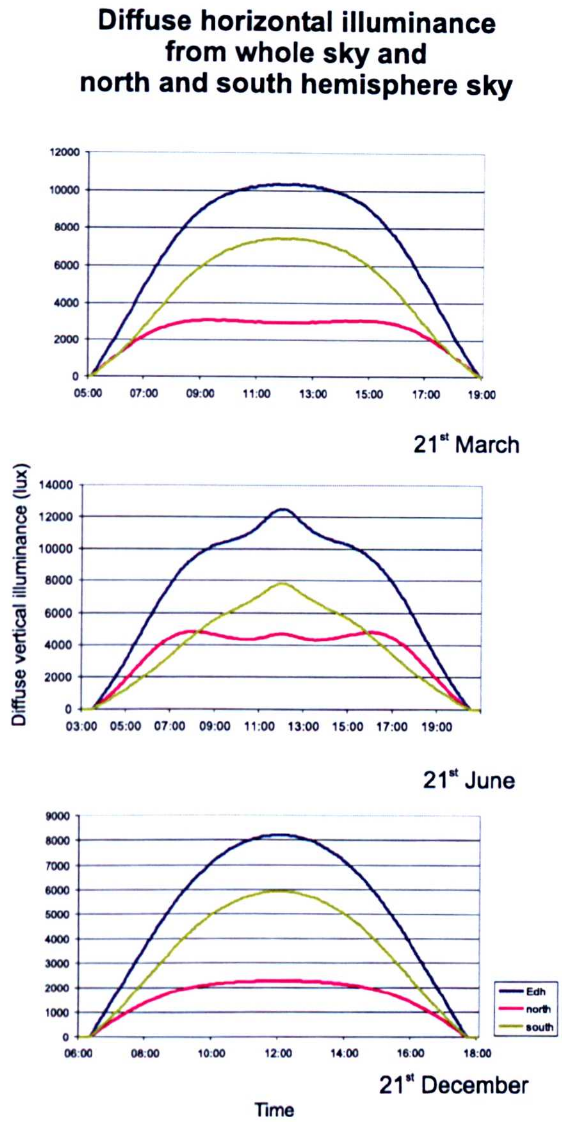



Figure J.2: Diffuse horizontal illuminance from the whole sky hemisphere and from the north and south sky hemisphere for the equinox and summer and winter solstice. The calculation was made with RADIANCE for a clear sky distribution without the sun contribution in Lisbon. The atmospheric turbidity was considered moderate, as 2.75.

Fig. J.2 presents the diffuse horizontal illuminance from the whole sky hemisphere and from the half north and half south sky hemispheres. The sum of the diffuse illuminances from the half north and half sky hemispheres equals the diffuse horizontal illuminance, Edh.

An attempt to obtain that data for the north half hemisphere was made by using the diffuse horizontal illuminance multiplied by an equation related to the sine of the solar altitude angle.

Fig J.3 presents the equations derived from the relation between the diffuse horizontal illuminance from the whole sky hemisphere divided by the half north hemisphere and the $\sin \gamma_s$.

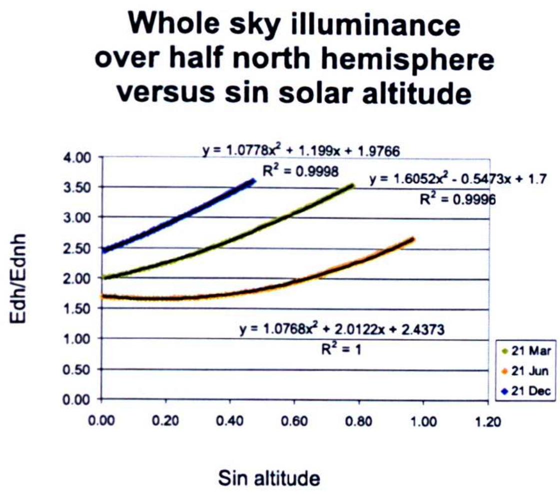



Figure J.3: Diffuse horizontal illuminance, $E_{dh}$, from the whole sky hemisphere divided by the half north hemisphere, $E_{dnh}$, over the sine of solar altitude, $\gamma_s$.

The coefficients of determination for the estimated equations approach the unity for the days considered. Therefore these equations can be used as a parameter to alter the illuminance resulting from the whole sky hemisphere to the one resulting from the half north hemisphere.

Fig. J.4 presents the error between the half of the hemisphere and the whole sky divided by an equation when the variable is the sine of the solar altitude angle.

Although both results show an almost perfect fit they have to be taken as a single example that may be applied for this latitude and sky partition. However, they express a possible development for future research to increase the accuracy of the analytical calculation.

Fig. J.5 presents a comparison between the results from RADIANCE and those obtained with the analytical calculation, considering the diffuse horizontal illuminance taken from the whole sky times an equation and multiplied by a constant to approach a distribution closer to the one 'seen' on the north oriented facade.

If single day results can be similar, they are not representative for the whole set, as different equations and coefficients apply. Further studies will be required to obtain a representative equation for the year.

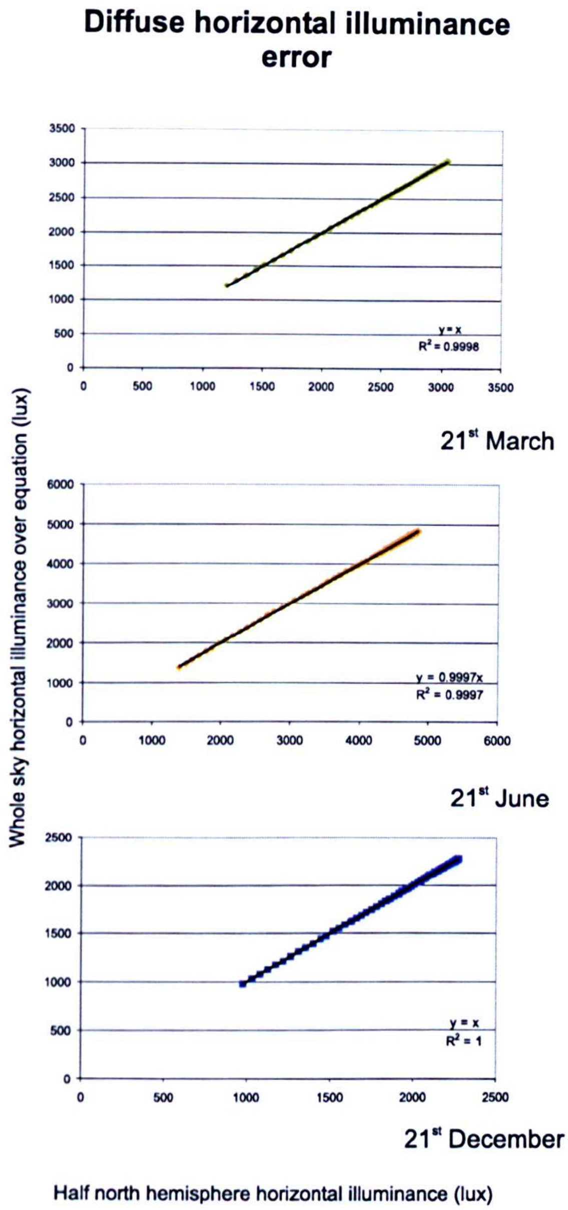



Figure J.4: Error between the calculation of the diffuse horizontal illuminance obtained with the whole sky hemisphere divided by an equation expressed in relation to the $\sin \gamma_s$ and from the half north hemisphere.

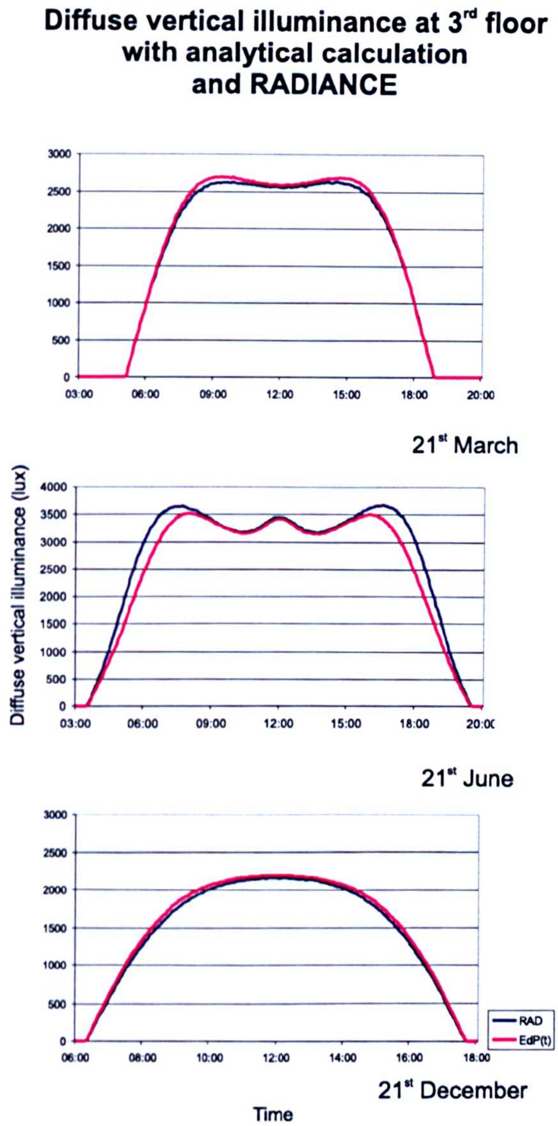



Figure J.5: Comparison between the diffuse vertical illuminance on the 3rd floor obtained with a RADIANCE simulation and the analytical calculation. The latter calculation used a diffuse horizontal illuminance from the half north hemisphere obtained from the whole sky times an equation and multiplied by a constant, depending on the day.

# Appendix K

## Average daylight factor (Lynes, 1979)[1]

The mean daylight factor averaged over the interior surfaces of a room is proportional to the light flux entering the window.

Considering the daylight factor on outside face of the window, $D_v$, expressed as a percentage by

$$D_v = \frac{E_{dv} \cdot 100\%}{E_{dh}} \tag{K.1}$$

then

$$E_{dv} = \frac{D_v \cdot E_{dh}}{100\%} \tag{K.2}$$

Where

$E_{dv}$ is the diffuse vertical illuminance, in lux;

$E_{dh}$ is the unobstructed diffuse horizontal illuminance, in lux.

If the ground and obstructions have about one tenth of the mean sky luminance, $D_v$ is given approximately by:

$$D_v = \frac{\theta}{2} \tag{K.3}$$

where

$\theta$ is the vertical angle of visible sky measured at a section perpendicular to the facade at the centre of the interior plane of window opening, in degrees.

Then

$$E_{dv} = \frac{\theta \cdot E_{dh}}{200} \tag{K.4}$$

[1]Symbols altered.

Let the flux entering the room be:

$$\Phi_0 = E_{dv} \cdot A_w \cdot \tau = \frac{\theta \cdot E_{dh} \cdot A_w \cdot \tau}{200} \tag{K.5}$$

where

$\tau$ is the diffuse light transmittance of the glazing, including the effects of dirt, expressed as a decimal;

$A_w$ is the net glazed area in $m^2$ (not including frames glazing bars or other obstructions).

The average daylight factor indoors, $\overline{D}$, averaged over all room surfaces as

$$\overline{D} = \frac{\overline{E_{in}} \cdot 100}{E_{dh}} \Leftrightarrow \overline{E_{in}} = \frac{\overline{D} \cdot E_{dh}}{100} \tag{K.6}$$

where

$\overline{E_{in}}$ is the average illuminance indoors, in lux.

The flux incident, $\Phi_{in}$, on indoor surfaces, in lumen, is

$$\Phi_{in} = \frac{\overline{D} \cdot E_{dh} \cdot A}{100} \tag{K.7}$$

where

$A$ is the total area of interior surfaces, ceiling, floor and walls including windows $m^2$;

The flux absorbed, $\Phi_{abs}$, by indoor surfaces, in lumen, is

$$\Phi_{abs} = \frac{\overline{D} \cdot E_{dh} \cdot A \cdot \alpha_{av}}{100} = \frac{\overline{D} \cdot E_{dh} \cdot A \cdot (1 - \rho_{av})}{100} \tag{K.8}$$

If scattering and luminescence can be neglected, $\alpha_{av} + \rho_{av} = 1$.

where

$\alpha_{av}$ is the area weighted mean absorption factor of indoors surfaces;

$\rho_{av}$ is the area weighed mean reflectance.

The conservation laws requires the flux entering the room to equal the flux absorbed. Then

$$\frac{\theta \cdot E_{dh} \cdot A_w \cdot \tau}{200} = \frac{\overline{D} \cdot E_{dh} \cdot A \cdot (1 - \rho_{av})}{100} \tag{K.9}$$

$\Leftrightarrow$

$$\overline{D} = \frac{\theta \cdot A_w \cdot \tau}{2 \cdot A \cdot (1 - \rho_{av})} \tag{K.10}$$

# Appendix L

## Average total daylight factor

This apprendix presents the average total daylight factor calculated with eq. 7.11 on page 165 rewriten as

$$\overline{TD} = \frac{s \cdot A_w \cdot \tau}{A \cdot (1 - \rho_{av})} \tag{L.1}$$

where

| | |
|---|---|
| $s$ | is the slope of the regression line that best fits the relationship between the solar horizontal illuminance and the solar reflected vertical illuminance. See details of the calculation of the coefficient on page 120; |
| $A_w$ | is the net glazed area of window; |
| $A$ | is the total area of interior surfaces, ceiling, floor and walls including windows; |
| $\tau$ | is the diffuse light transmittance of the glazing; |
| $\rho_{av}$ | is the area-weighed average reflectance of interior surfaces. |

Table L.1: Average total daylight factor for different room heights in different canyon ratios (narrow, equal and wide) with different surface reflectances in the canyon (0.2, 0.5 and 0.7) for single glass transmittance. Room dimensions and characteristics are defined in section 7.2. The direct contribution from the sun (early and late hours in summer) is excluded from the calculation. Results were obtained with Eq. 7.11 and the $s$ coefficient is the ratio of the solar vertical illuminance against the solar horizontal illuminance, values are presented in table 5.5 on page 122.

| Canyon ratio | 1:0.5 | | |
|---|---|---|---|
| rho | 0.2 | 0.5 | 0.7 |
| Gnd | 0.07 | 0.16 | 0.24 |
| $1^{st}$ | 0.09 | 0.20 | 0.31 |
| $2^{nd}$ | 0.10 | 0.23 | 0.35 |
| $3^{rd}$ | 0.10 | 0.25 | 0.38 |
| $4^{th}$ | 0.10 | 0.25 | 0.37 |
| $5^{th}$ | 0.08 | 0.21 | 0.31 |

| Canyon ratio | 1:1 | | |
|---|---|---|---|
| rho | 0.2 | 0.5 | 0.7 |
| Gnd | 0.09 | 0.18 | 0.26 |
| $1^{st}$ | 0.12 | 0.21 | 0.31 |
| $2^{nd}$ | 0.12 | 0.22 | 0.32 |
| $3^{rd}$ | 0.11 | 0.21 | 0.31 |
| $4^{th}$ | 0.11 | 0.19 | 0.29 |
| $5^{th}$ | 0.09 | 0.17 | 0.26 |

| Canyon ratio | 1:1.5 | | |
|---|---|---|---|
| rho | 0.2 | 0.5 | 0.7 |
| Gnd | 0.08 | 0.15 | 0.20 |
| $1^{st}$ | 0.11 | 0.19 | 0.24 |
| $2^{nd}$ | 0.12 | 0.19 | 0.25 |
| $3^{rd}$ | 0.11 | 0.19 | 0.24 |
| $4^{th}$ | 0.11 | 0.18 | 0.23 |
| $5^{th}$ | 0.09 | 0.16 | 0.21 |

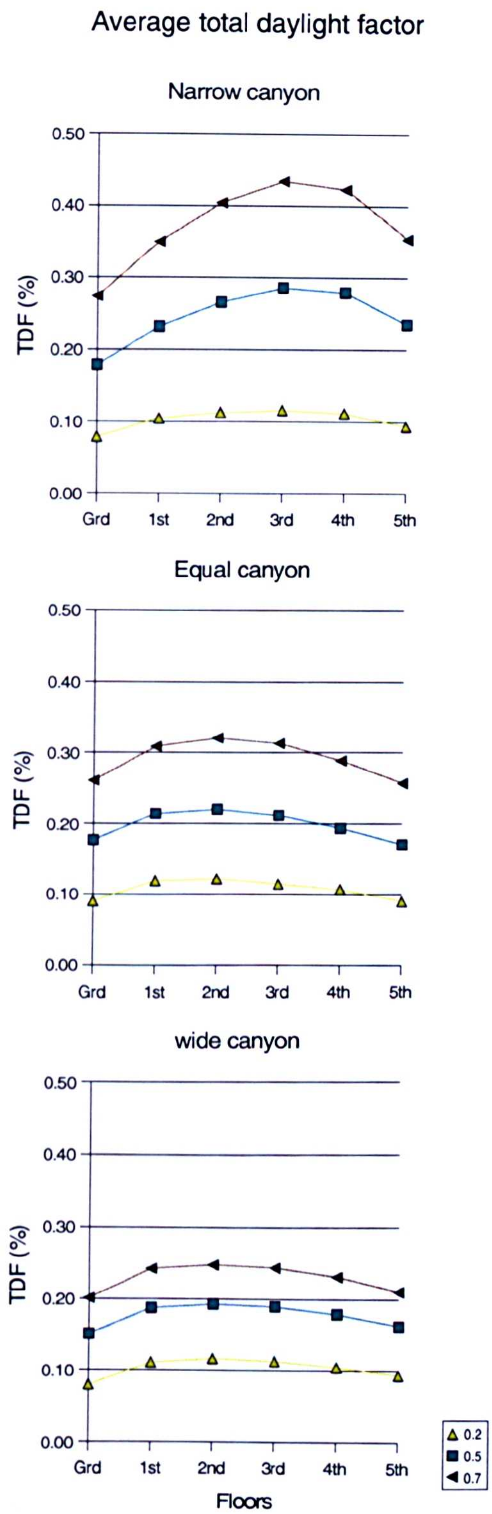



Figure L.1: Average total daylight factors for different canyon ratios, surface reflectances at different floor heights in an urban canyon.

# Appendix M

## Diffuse contribution to the total average daylight factor

Given the 'reference daylight factor' on a surface of a space as the ratio of the average illuminance inside the space to a reference outside horizontal illuminance, if the constant $C$ is assumed as the diffuse sky contribution outside the window and the outside reference is taken as the diffuse illuminance exceeding 70% of the year average, then the average illuminance inside the space due to $C$ is

$$\overline{E_c} = \frac{C \cdot A_w \cdot \tau}{A \cdot (1 - \rho_{av})} \qquad \text{(M.1)}$$

Where

$\overline{E_c}$ is the average illuminance inside a space due to $C$, constant defined in the eq. 4.1 on page 73;

The remaining variables are expressed as before

and the average daylight factor from constant $C$ is

$$\overline{D}_c = \frac{C \cdot A_w \cdot \tau}{E_{dh70} \cdot (1 - \rho_{av})} \qquad \text{(M.2)}$$

where

$E_{dh70}$ is the diffuse horizontal illuminance of values exceeding 70% of the year average.[1]

The diffuse horizontal illuminance value exceeded for 70% of the day is around 11 000 lx in Lisbon and 8 000 lx in London. This data was obtained from the satellight database considering cumulative half an hour values of the diffuse horizontal illuminance from sunrise to sunset for a period between 1996 and 2000 inclusive.

[1]This percentage was selected based on the work developed by Littlefair et al. on recommended obstruction angles for the U.K. and later for other European Latitudes. Littlefair recommends vertical sky component or equivalent obstruction angle for different latitude based on certain diffuse illuminance is exceeded for 70% of the day. (Littlefair, 1998; Littlefair, 2001)

As light follows the principle of additivity, this result can be added to that previous calculated without the contribution from $C$ to give the average total daylight factor.

The final average total daylight factor is

$$\overline{TD_f} = \frac{k \cdot A_w \cdot \tau}{A \cdot (1 - \rho_{av})} + \frac{C \cdot A_w \cdot \tau}{E_{dh70} \cdot (1 - \rho_{av})} \tag{M.3}$$

# Appendix N

## Obstruction angle for sunny climates

The definition of obstruction angles in urban canyons for sunny skies is based on solar incidence on the south facade for a minimum period of four hours on the equinox day. The period selected has been included in DIN 5034 Part 1 of the German standard on daylight provision. (Littlefair, 2001) The procedure consists of guaranteeing in terms of solar geometry the incidence of sunlight on the point at 10:00 am on the equinox day.

Sunlight is incident on a point $P$ of the facade when

$\cos\theta > 0$

and

$x \geq a$

with

$x = w \cdot \tan VSA$

$a = w \cdot \tan\alpha_1$

where

$\theta$ is the angle of incidence of the sun beam on the vertical surface. See chapter 3 for its calculation;

$VSA$ is the vertical shadow angle, defined as the angle measured on a perpendicular plane to the vertical surface between the horizontal plane and a plane tilted from the horizontal axis that includes the sun;

$\alpha_1$ is the obstruction angle at the point $P$, as $\alpha_1 = \arctan\left(\frac{h-hp}{w}\right)$

$h$ is the height of the canyon;

$hp$ is the height of point $P$ in the building facade;

$w$ is the width of the canyon.

Table N.1: Spacing angles for sunlight incidence in the facade at 10:00 am solar time on the equinox day. A minimum of 4 hours of sunlight is expected in the south facade and 2 hours on the east.

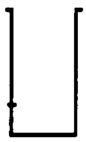
| Latitude (degrees) | south | east |
|---|---|---|
| 35 | 54 | 55 |
| 40 | 49 | 53 |
| 45 | 44 | 51 |
| 50 | 40 | 48 |
| 55 | 35 | 44 |
| 60 | 30 | 40 |

Table N.1 show the maximum obstruction angles to provide sunlight incidence on the facade for a minimum period of four hours on the south facade on the equinox day according to latitude. No climate analysis have been taken into consideration.

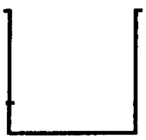
When the building is facing east a minimum of 2 hours of sunlight should be desirable. This assumes that at least another two hours of reflected sunlight may be expected.

# Appendix O

## Window areas for a 0.5% $\overline{TD}$ for different canyon ratios and different average reflectance at the obstruction



| | $\rho_{av}$ | | |
|---|---|---|---|
| | 0.2 | 0.3 | 0.5 |
| window area [m$^2$] | 3.9 | 2.7 | 1.4 |



| | $\rho_{av}$ | | |
|---|---|---|---|
| | 0.2 | 0.3 | 0.5 |
| window area [m$^2$] | 3.4 | 2.3 | 1.3 |

| | $\rho_{av}$ | | |
|---|---|---|---|
| | 0.2 | 0.3 | 0.5 |
| window area [m$^2$] | 3.4 | 2.3 | 1.4 |

Room area is taken as before, the average reflectance of internal surfaces is 0.5 and the glass transmittance is 0.56.