Reflected Daylighting in Schools

An investigation into design principles of reflected daylighting in primary schools in the warm-dry climate of Iran

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This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where otherwise stated and referenced. It has not been and is not being, in part or wholly, submitted for any other degree, diploma or similar qualification. It does not exceed 80, 000 words in length, including references and bibliographies.

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ABSTRACT

This research investigates the different ways of using daylight in schools in the warm-dry climate of Iran for natural illumination while avoiding overheating and glare. It also reviews different approaches to daylighting design and recommends an integrative approach which takes the typological approach as a basis for designers and the phenomenological approach as an evaluative method to assess and promote the experiential aspects of daylighting.

This research identifies two main ways by which daylight is admitted in warm-dry climates. The first approach, *diffusion*, is basically admitting the harsh sunlight by filtering it through to the interior. There is either an exterior element such as foliage which acts as a filter for harsh sun rays or the specific design of the building envelope and window screens perform a similar function and filter the light. The second approach, *reflection* or using indirect daylight, is an appropriate daylighting strategy in this climate. The experimental and observational studies in this research address two issues. The first part is concerned with different general and specific factors influencing reflected lighting in schools. The second part addresses how this research can inform architects to design better daylit schools in such a climate.

Building orientation and configuration in the larger scale, as well as specific factors such as shading devices, daylighting systems, surface features, etc. can considerably affect reflected daylighting. This research suggests that room shape and its geometrical features, especially its height, has a significant effect on the reflected daylighting of a room. On the basis of findings from various case studies, it also recommends the use of lightshelves, clerestories, porticoes and courtyard configuration in order to improve the reflected daylighting performance in school design. Finally, a set of guidelines for daylighting design in schools in the warm-dry climate of Iran is proposed as the outcome of the research.

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CHAPTER 1: INTRODUCTION AND THE RESEARCH OUTLINE

1.1. Warm-dry climate daylighting issues and the Research question

Extreme climates have often presented a challenge to architects when building a shelter adaptable to the environment. Direct sunlight is the main cause of daytime overheating and can result in visual and thermal discomfort. It can also be observed in the traditional architecture of the warm/hot dry climate that keeping the direct sunlight off the windows and cooling the spaces are important in dealing with the problems of overheating. However, sunlight is clearly a great source of illumination and it is not sensible to block it out because of overheating issues. Therefore, the main research question arose as to how to use natural illumination effectively in the warm-dry climate of Iran and yet avoid overheating problems. This research investigates the different ways to use sunlight sensibly in such a climate in order to design high performance schools.

The varied climate of Iran, and more specifically daylighting features of the warm-dry climate of Iran, will be discussed in Chapter 2 with a reference to the vernacular architecture of the region. The lack of knowledge and awareness of effective ways of using sunlight within buildings in this climate of Iran has contributed extensively to high electricity bills, which are mainly due to using electric lights for illumination even while the sun is shining outside. Apart from economic reasons for using sunlight, there are other crucial reasons why classrooms and schools are better off naturally illuminated. Students' well being and their academic performance and other psychological factors are among other reasons to use natural sunlight; this will be addressed in detail in Chapter 3. The extensive literature in this field of study elucidates the importance of using natural illumination in classrooms and yet in most contemporary Iranian schools this matter is underestimated despite the abundance of sunlight.

Having chosen daylighting as the theme of research brought about the question as to which approach should be taken in daylighting design of schools, and more generally in other buildings. There is extensive research on different approaches to daylighting which will be discussed in detail in chapter 4. Different approaches such as quantitative vs. qualitative and typological vs. phenomenological will be evaluated. It will be argued each of these approaches is not sufficient on their own to provide a model for a well naturally lit and inspiring space, and that a combination of the approaches could bridge the gaps found in the individual ones. The conclusion of Chapter 4 will be attempted to be applied in Chapter 6 and 7 where case studies of traditional and contemporary exemplary schools will be investigated. Finally, on the basis of the empirical evidence and the findings of the previous chapters, Chapter 8 will suggest a set of design guidelines for daylighting design of schools in the warm-dry climate of Iran.

Having overviewed briefly the chapters of this thesis, it is important to address the difference between daylighting and sunlighting to clarify the terms and their implication. Daylight is the diffused, indirect or reflected light in the atmosphere, usually under overcast sky, whereas sunlight is direct sun rays emitted from the sun under clear or partially overcast skies. Sunlight is also considered as the direct component of daylight, the latter of which also includes diffused and reflected light. These terms might sometimes be used interchangeably, but in the warm-dry climate of Iran sunlight is the main available source of illumination. It is also important to mention that most of the literature review which will be discussed in chapter 3 and 4 address daylighting as they have been dealt with in the UK and European climate. Therefore, there is a gap in the literature on sunlighting which this research attempt to address.

This brings us back to the challenging research issue of using sunlight effectively in the warm-dry climate of Iran; keeping direct sunlight off the windows to avoid overheating and yet using it indirectly for illumination. More specifically the issue is how to use sunlight effectively in primary schools in warm-dry climate of Iran to illuminate the classrooms naturally and yet avoid overheating. This will lead to the idea of reflected lighting, which will be discussed in Chapter 5. Finally, the research issue can be divided into two main parts. The first part of research question is concerned with different exterior and interior factors influencing reflected lighting in classrooms. The second part of research question addresses how this research can inform architects and designers to design better schools in such a climate, in order to address the above issues.

1.2. Practical Solutions and a hypothesis

There are two main ways by which sunlight is admitted in warm-dry climates: *Diffusion* and *Reflection.* The first approach, diffusion, is basically admitting the harsh sunlight by filtering it through to the interior rooms. Firstly, by looking at the vernacular architecture of such climate in Iran, it can be seen that the foliage plays an important role in filtering the harsh sunlight. Weather conditions and cloudy skies can also play a significant role in diffusing sunlight, but as such weather conditions are unlikely to occur through most of year, the diffusing cloud element will not be taken into consideration.

Secondly, on the basis of vernacular observation, geometric screens (blinds) which are usually made of complex latticed screens (wooden or ceramic) are seen as another way to infiltrate harsh sunlight into the rooms and make it less glaring. They will be further discussed in the case studies in Chapter 6. This method is also used innovatively in some modern buildings of such climates. Thirdly, with the advances in glass technology in modern building examples, optical division screens are also alternatives to diffuse harsh sunlight in such climates which will be dealt with in Chapter 5. In summary, in the first diffusion approach there is either an exterior element acting as a filter for harsh sun rays or the building envelope and windows perform a similar function and filter the light through into the room.

The second approach, reflection or using indirect sunlight, seems to have been a suitable daylighting strategy in this climate in the past. This approach has been developed in the vernacular architecture of this climate as the result of experience and good sense of local architects in the handling of practical problems (Rudofsky 1964). The first rule of thumb of the reflection approach is to keep bright reflecting surfaces awayfrom the indoor viewers, because seeing a bight surface from the window causes glare and visual discomfort. Secondly, courtyards are good examples of this approach by which harsh sunlight is reflected off the courtyard floor into the rooms surrounding it, and hence reflects off the ceiling down to the spaces in the room. The material, colour and texture of courtyard flooring have a considerable effect on the efficiency of this method. Courtyards are widespread in the vernacular architecture of such climate, while they have only occasionally been used in modern examples.

It is suggested that an appropriate solution for the challenging research question is reflected lighting, which in return is influenced by a number of factors. There are general exterior physical factors such as building orientation and configuration in the larger scale, as well as specific interior physical factors which affect reflected lighting considerably. This research suggests that room shape and its geometrical features especially its height, has a significant effect on the reflected daylighting in the room. This can well be seen in traditional buildings and the vernacular, while it is not taken sufficiently into account in modern buildings, due partly to higher construction costs as well as the lack of awareness on the designers' part. It is a hypothesis of the research that these general and specific factors have significant influence on reflected lighting as a suitable solution for warm-dry climate daylighting. This hypothesis will be tested through experiments and simulations in chapter 5 and 6.

The findings and results of the experiments in chapter 5 & 6 address the first part of research question. Studies into daylighting approaches in chapter 4 as well as exemplary schools studies in chapter 7 address the second part of research question. The findings of the main body of the research in chapter 5, 6 & 7 will contribute to the guidelines for daylighting design in schools in chapter 8.

1.3. Research Methodology

This research involves two main approaches for its methodology: theoretical and experimental. The theoretical approach is summarized in the typological vs. phenomenological argument which will be thoroughly discussed in Chapter 4. In addition, an observational and yet analytical study will be carried out in Chapter 7 on a number of exemplary schools which will contribute to the final design guidelines.

However, the main body of the research is to address the reflected daylighting issue in the warm-dry climate of Iran. This will be investigated through physical model experiments as well as computer simulations. The collaborative for high performance schools (CHPS 2006, p.205) suggests there are three general categories of tools and methods for evaluating daylighting and fenestration: physical models, lighting computer simulation programmes, and whole-building energy simulations programmes. This research has only employed the first two of these available tools for its methodology, because the third one considers all aspects of the fenestration's impact on building energy use, which is beyond this research scope.

1.3.1. Physical model experimentation

> *"A plan proceeds from within to without. A building is like a soap bubble. This bubble is perfect and harmonious if the breath has been evenly distributed and regulated from the inside. The exterior is the result of the interior." (LeCorbusier 1923, 1989p.181)*

Interior space is the focus of daylighting analysis since light as architectural form is mainly concerned with space within or *"space that can be lived in a dynamic way"* (Zevi 1991). Interior space allows architects to control the effects of light since the source is manipulated by apertures, where each aperture can be considered as a lighting source (Lam 1986). Physical scale models are a sensible method of understanding and manipulating lighting patterns in an interior space.

Physical scale models have considerable resemblance to real buildings in terms of daylighting studies. The physical properties of light are such that daylight penetrates and reflects within a scale model almost identically to how it would in a real size building (Robbins and Dwyer 1981, p.221). They are also an easy and intuitive way to understand daylighting design options, especially in the early stages of design. They can be used for qualitative as well as quantitative aspects of daylighting.

One of the advantages of physical models is to provide information about glare, contrast and the lighting pattern provided in a space through various apertures. Physical models can provide photographic records of the light quality and lighting pattern inside a room in order to study the spatial effect of light and shades. They are specifically a useful method in the early stages of design, in order to give architects or designers a general idea or impression of daylighting ambience in an interior space. This type of daylighting study of interior space by a physical model is employed in a pilot study in chapter 4 (section 4.5.2) in which a typology of daylighting components is investigated.

Physical models can also be used for quantitative aspects of daylighting. Daylighting models can be used for numerical analysis and to record light levels within a model. The models can be tested either under real sky conditions or in an artificially constructed sky. The sunlighting analysis under clear sky can be tested under a sun simulator or heliodon. They can be set to represent the correct sun angle for the site latitude and hour of the day and are used to visualize the movement of the light during a typical day (CHPS 2006, p.205). Small light measuring devices (photocells) can be used to record light levels within the model. This method has been used in chapter 5 where the various exterior factors influencing the reflected lighting through a window will be investigated.

1.3.2. Computer simulations and ECOTECT

Computer simulations give information about the distribution of electric or daylighting across a room. They can calculate light level values and gradients for daylighting studies. Some of these tools such as Radiance can produce realistic renderings of light and space, but they require more modelling time and detail which might not appropriate to use at the early stages of design. On the other hand, there are other simulation programmes such as ECOTECT, which are easier to use by designers and designed to work with minimum modelling requirements.

Among different conceptual building design programmes ECOTECT has been chosen as a simulation tool in this research. ECOTECT is a software package developed by the SQUARE ONE research centre at the Welsh School of Architecture in Cardiff. It has a unique approach to conceptual building design which couples an intuitive 3D design interface with a comprehensive set of performance analysis functions and interactive information displays (Marsh 2003). ECOTECT is driven by the concept that environmental design principles are most effectively addressed during the conceptual stages of design. Therefore, it is a suitable tool to investigate influencing factors of reflected daylighting in classrooms.

Chapter 6 will apply ECOTECT simulation to two different types of case studies: historic and typical modern classrooms in Iran. In The first stage, a typical single study (Hojra) in Iranian historic schools is simulated with ECOTECT and the effects of clerestory and room height on reflected daylighting are studied. In the second stage, a typical Iranian contemporary classroom is simulated and the effects of room height, shape and apertures on the amount of reflected daylight will be measured. The results will highlight some of the factors influencing reflected daylighting in classrooms.

1.3.3. Observational studies

While the experimental methodology (physical models and computer simulations) addresses reflected daylighting and the influencing factors, observational studies will address the second part of research question, which deals with how to inform architects and designers to make high performance daylit schools in a specific climate. Therefore, a number of exemplary contemporary schools have been chosen to identify their successful design solutions in terms of daylighting and other interrelated factors. The observation and analysis will cover examples from warm-dry climate zones in the US and other parts of the world, as well as other climate zones such as the UK for a comparative study. Despite the climatic difference, there are still lessons to be learnt in terms of daylighting in classrooms in all exemplary schools. One reason is the functional requirement of daylighting in classrooms which avoids direct sunlight on the students' working areas to prevent glare and visual discomfort.

1.4. Research outcome and daylighting design guidelines

The results from the physical experiment and computer simulations will elucidate the influencing factors in reflected daylighting in classrooms in warm-dry climate of Iran. However, this research is also concerned with the usefulness of these findings for architects and designers in designing well daylit and sustainable schools for the future. Therefore, a set of guidelines for daylighting design in schools in Iran is intended to be produced as the outcome of the research which will incorporate the above findings. It is intended to address the warm-dry climate of Iran in specific and also other climatic zones of Iran in general.

CHAPTER 2: DAYLIGHTING AND CLIMATIC CONSIDERATIONS

2.1. Climatic classification of Iran

As mentioned earlier, it is important to address the climate as it has a significant effect on daylighting design. In overcast climates, because of the lack of sunlight building designers make the most of available daylight and, therefore, use large glazing to capture as much daylight as possible. On the other hand, in sunny climates there is a challenge of controlling harsh sunlight in buildings and at the same time using natural light to illuminate interior spaces. Therefore, the type of climate has a significant impact on daylighting design strategies.

This chapter, firstly, reviews climatic classification of Iran and her varied climate. It, then, explains why the warm-dry climate of Iran is chosen as the focus of this research. Moreover, it addresses the climatic design and sustainable architecture as they are current significant issues relating to climate and daylighting design. Daylighting design is one of the main components of sustainable architecture and passive solar design. As this research is focused on the warm-dry climate of Iran, daylighting features of warm-dry climates are, then, explored through the vernacular architecture as well as passive solar design features. This will identify basic requirements of daylighting design in such climates. Finally, based on the vernacular architecture of the region, this chapter suggests a holistic approach towards daylighting design which also takes into account other environmental issues such as heating, cooling and natural ventilation.

2.1.1. Geography of Iran and the varied climate

Iran, previously known as Persia until 1935, is the 10th largest country in the world and consists of mountainous rims surrounding the country from the West and North. The main chain is called Zagros Mountains which runs along northwest to southeast of the country. Many peaks of Zagros exceed 3,000 meters above sea level (Microsoft-Encarta 2003). The northern chain of mountains is called Alborz and it is narrow but high mountains covering the south of the Caspian Sea. Volcanic Mount

Damavand (5,671 meters) is in the centre of Alborz and is the highest peak in the country (Fig.2.1).

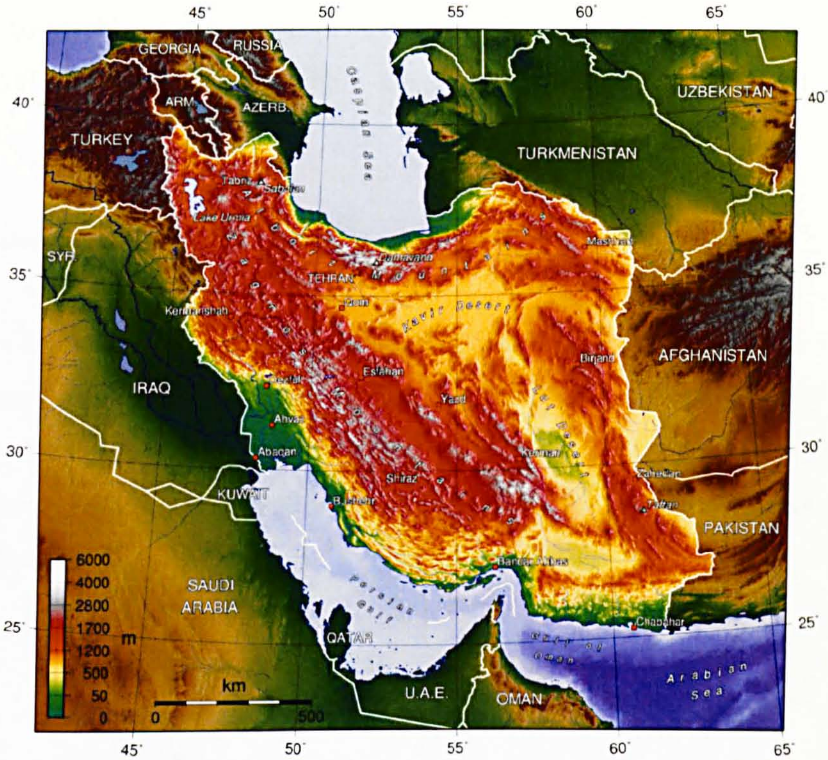


Fig 2.1. Topography of Iran, (Wikimedia-Commons 2007)

The central part of the country consists of flat areas enclosed by mountainous zones called the Central Plateau which are about 900 meters above the sea level. There are two great deserts in Iran which are located at the Central and Eastern part of the country: Dasht-e Kavir and Dasht-e Lute. There are also two expanses of lowland in Iran: the Khuzestan plain in the southwest by the Persian Gulf and the Gulf of Oman as well as the Caspian Sea plain in the North which are both illustrated in Fig 2.1 in green colour.

Due to the variety of land in Iran, such as mountains, deserts and the sea as well as pressure systems affecting the region Iran has a very varied climate across the country. The lowlands by the Persian Gulf and the Gulf of Oman are extremely hot and humid, especially in summer; the arid Central Plateau has cold winters and scorching summers; the Alborz and Zagros mountain chains have cold winters, mild summers and high precipitation; and finally the narrow Caspian plain is a fertile, semitropical area with a mild and pleasant climate.

The climatic conditions of Iran shows a distinct seasonal pattern which is partly because of the variety of the land and partly the weather and pressure systems in the area. Weather systems are especially significant factors in climatic conditions in Iran (Ganji 1968; Gorji-Mahlabani 2002). The following section will explore different categories of Iranian climate.

2.1.2. Main categories of Iranian climate

There are a few methods used for classifying Iranian climate. W. Koppen's method is based on the botanical and plant environmental conditions, while the Olgay methods are based on the bio-climatic chart (Kasmaei 1993). One of the common climatic classifications (Frye 1975) identifies five main areas based on the temperature zones of Iran as follows:

I. Mild & Humid region
II. Very cold region due to high altitude
III. Mild & Dry
IV. Warm & Dry
V. Warm & Semi-humid

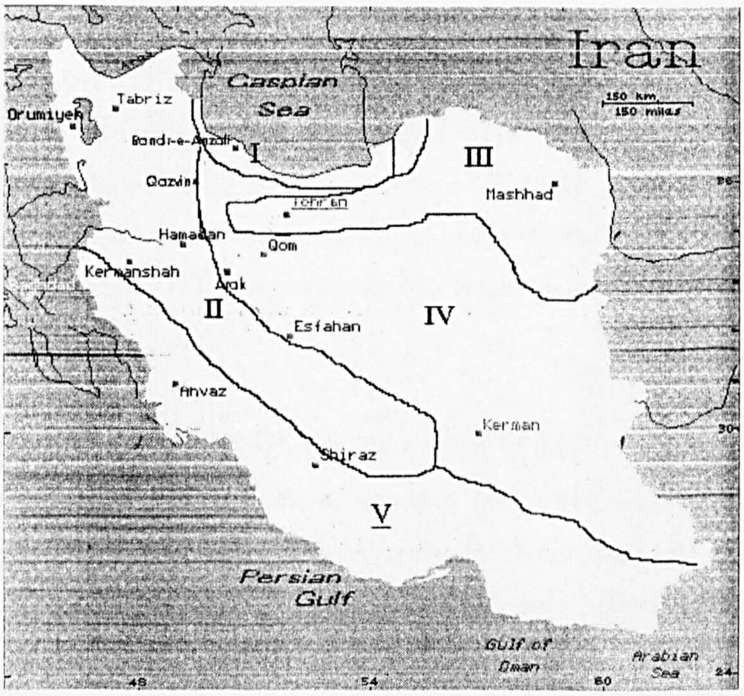


Fig 2.2. Iran climatic classification (source: The Cambridge History of Iran)

The mild and humid area lies to the south and east coast of the Caspian Sea. The average annual temperature is 14.5 °C to 18°C and the average humidity is relatively high, 62.5 to 90 percent. The mountainous area has a very cold winter and moderate to cool summer. The average annual temperature in this area is 11 °C to 14 °C and the average humidity is 45 to 62.5 percent. The third zone, mild and dry, is an area of lower altitude. Winter is relatively cold and summer is warm and dry in this area. The annual average temperature is 13 °C to 17°C The humidity is relatively low and there is plenty of sunshine during all seasons (Gorji-Mahlabani 2002).

The warm and dry area is located in the central, often deserts parts of the country. The average temperature is about 16 °C to 19°C and humidity is relatively low. Daytime temperature in summer can go up to 35°C to 39°C while it falls to 12 °C to 23°C at night time. In winter, the temperature goes up to 16°C and falls to -3°C during the night. The last climate zone, warm and semi-humid, is located in the south along the northern part of the Persian Gulf. The weather in winter is moderate, while it gets hot and semi-humid in summer. The annual average temperature is about 23°C to 27°C with high rates of humidity (ibid, p.22).

The Ministry of Housing and Urban Development (1993) in Iran has developed a more detailed classification of Iranian climate based on Givoni's approach (1998) in which there are 8 main weather categories with 36 sub-categories. Table 4.1 illustrates these 8 main groups and 36 sub-groups as well as some of their climatic design considerations. It also summarises some climatic considerations for designing buildings in such climates. The main 8 climatic group locations are briefly described as follows:

The first group is located in the high altitude regions of the Northwest, which are over 2000m above the sea level. The second group is the largest climatic region and has the greatest number of sub-groups. It is located in the North, Northeast and Northwest of Iran. There are large variations in latitude and altitude of the different areas in this region. The third group lies mainly across the Southern coasts of the Caspian Sea as well as a narrow region around Urmia Lake. The main reasons for its specific climatic conditions are its high latitude, low altitude and the vicinity to water (Gorji-Mahlabani

2002). The fourth group is smaller than the third group and is located along group 3 in two separated regions with higher altitude and a long distance to the Caspian Sea. The fifth group is located in the central part of Iran. The variation of altitude and latitude is considerably higher in this group and there is plenty of sunshine during all seasons. The sixth group consists of low altitude regions and the deserts in the central and Southeast of Iran. The seventh group consists of low latitude areas extended as a narrow band from West to South and Southeast. Low latitude and low altitude are the main causes of high temperature in this area (MHUD 1993). Finally, the eighth group is located in the North coasts of the Persian Gulf and Oman Sea. This group is considered as the 'worst' climatic group due to its very low altitude, low latitude and the location by the sea (ibid). It is very hot and humid in summer and temperate and humid in winter.

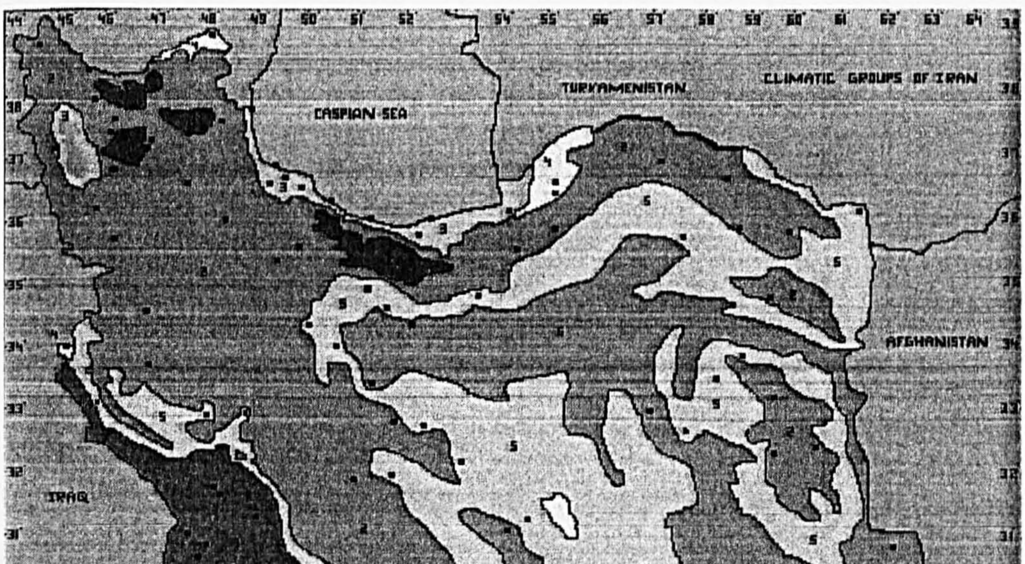


Fig 2.3. Iran Climatic Classification (Source: The Ministry of Housing and Urban Development,Iran)

Climatic conditions in two critical seasons in Iran				
Climatic Group	**Climatic sub-group**	**Winter condition**	**Summer condition**	**Climatic design considerations**
Group 1	1.1	Strongly Cold	Suitable	• No cooling system required • Preventing heat loss
Group 2	2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8	Strongly cold Very cold Very cold Very cold Cold Cold Cold Relatively cold	Temperate Temperate Semi hot Semi hot and arid Temperate Semi hot Semi hot and arid Temperate	• Reduction of heat loss • Reduction of wind effect on the heat loss • Solar energy as heating system • Protection of buildings aginst solar radiation
Group 3	3.1 3.2 3.3	Very cold Relatively cold Cold	Humid Humid Humid	• Wind flow circulation & open plan for comfort reasons • Low U value of external walls
Group 4	4.1 4.2 4.3	Very cold Cold Relatively cold	Hot and humid Hot and humid Hot and humid	• Natural ventilation for cooling • Low U value of external walls
Group 5	5.1 5.2 5.3 5.4 5.5 5.6 5.7	Relatively cold Relatively cold Relatively cold Relatively cold Relatively cold Relatively cold Cold	Semi hot Semi hot and arid Hot Hot and arid Very hot Very hot and humid Very hot	• Using solar energy • Reduction of heat loss of buildings • Preventing the effects of high temperature on buildings • Natural ventilation
Group 6	6.1 6.2 6.3 6.4 6.5 6.6	Relatively cold Semi cold Semi cold Semi cold Semi cold Cold	Very hot and arid Semi hot Very hot Hot and arid Very hot and arid Hot and arid	• Using solar radiation especially in winter • Using shading devices • Natural ventilation like wind towers (Badgir)
Group 7	7.1 7.2 7.3 7.4 7.5	Cold Cold Cold Temperate Temperate	Very hot and arid Strongly hot and arid Strong. hot/semi-humid Strongly hot and arid Strong. hot/semi-humid	• Cooling devices necessary • No heating device required • Protection of buildings against hot temperature and strong solar radiation
Group 8	8.1 8.2 8.3	Cold Temperate Suitable	Very hot and humid Very hot and humid Very hot and humid	• Cooling devices necessary • No heating device required • Using shading devices • Protection of buildings against hot temperature and strong solar radiation • Air circulation & open plan

Table 2.1. Iran climatic classification and weather conditions in two critical seasons

Table designed by F. Ai after Gorji (2002)

2.1.3. Warm-dry climate as the focus of research

We can see therefore that Iran has a variable climate and as a result of the necessity of the research to narrow down its domain, one of the main climate zones was selected, based on two main reasons. In Fig. 2.2, zone IV or warm-dry is the largest zone and it also includes large cities such as Esfahan, Kerman, etc. Zone V, which is also relatively large, has a warm and semi-humid climate. Using the five climate zone classification, the majority of the population of Iran lies in the warm-dry climate group, mainly in the central part of the country, which accommodates a number of populated cities and towns.

Fig 2.3 & Table 2.1 show that group 2 which is relatively cold in winter due to its high altitude and moderate, arid and hot during summer is geographically the largest climatic zone according to the eight climate zone category (MHUD 1993). However, because of its geographical condition and mountainous areas it does not include large and populated cities. As can be seen in Fig 2.3, the warm-dry climate region in general includes more populated urban areas and is a significant climatic zone to focus this research on. Groups 5, 6 and 7 can be considered in the family of warm-dry climate for research purposes. Group 5, central Iran, has a variable altitude and has plenty of sunshine. Group 6, central and Southeast, has low altitude and also includes the deserts. Group 7 has low altitude and low latitude and that is the main reason of its extremely high temperature.

Secondly, apart from the geographic facts that warm-dry climate is the climate for the populated parts of Iran, especially in spring and summer, there is also another significant reason as to why this type of climate has been chosen for this research. This part of the country has plenty of sunshine and whilst it can be a great source of energy and natural lighting in buildings, has unfortunately caused overheating and discomfort, particularly in contemporary buildings. It is mainly because of poor design and technical implementation. This problem is exacerbated with the implementation of European mild climate design solutions, particularly largely glazed buildings, into the warm-dry climate of Iran.

Solar radiation is a great source of energy and with a good understanding of how to use such a valuable resource effectively; buildings can be more energy efficient, use daylight more productively and also be better for the well-being of the occupants. Therefore, based on the above two main reasons, the warm-dry climate zone of Iran is selected to make a more precise research. Having focused on a specific climate zone, it is important to address the climate change and sustainable architecture as they support daylighting from a climatic and environmental point of view.

2.2. Climate change and Sustainable architecture

An understanding of the climate change and its dreadful consequences is essential for architects to take sustainable architecture in general, and daylighting design in specific, into account as they reduce the risks of buildings to the environment and the climate. Climate change is a contemporary concern and refers to variations in global and local climate over time. These changes can be caused by internal processes of the earth such as volcanic emissions, external forces such as variations in sunlight intensity or, currently of main concern, human activities such as the production of excessive greenhouse gases. UNFCCC (United Nations Framework Convention on Climate Change) uses the term '*climate change*' with the presumption of human causation, while the term '*climate variability*' is used for non-human caused variations (Baede 2001). In recent usage, climate change often refers to changes in the contemporary climate particularly the rise of the average temperature of the earth's surface, known as global warming.

Global warming is the observed increase in the average temperature of the Earth's waters and the air near its surface in recent years and its projected continuation. Global temperatures are likely to increase by 1.1 to 6.4 °C (2.0 to 11.5 °F) between 1990 and 2100 according to the International Panel on Climate Change (IPCC 2007). The following chart illustrates the record of global average temperatures compiled by Climate Research Unit (CRU 2007) and the Hadley Centre (2007).

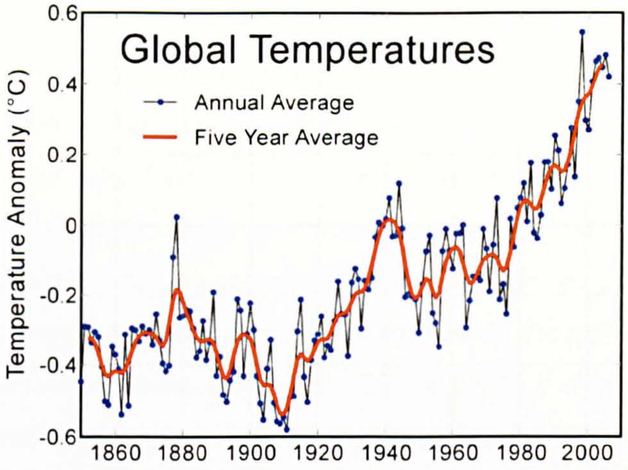


Fig 2.4. Global average temperatures (Source: Hadley Centre, CRU)

An increase in global temperatures can cause other changes such as Arctic ice melting, rise of sea levels and changes in the amount of precipitation, which can in turn cause natural disasters such as floods, droughts, hurricanes, tornadoes, etc. This is increasingly a matter of global concern, with some countries taking a lead and putting it high on their political agenda. The government of the United Kingdom is a leading example and has proposed a climate change draft bill to set legally binding carbon reduction targets (BBC 2007). This plan has a particular emphasis on the use of solar power and renewable energy instead of fossil fuel to reduce carbon dioxide (CO2) emissions as well as utilizing more reliable and sustainable resources for energy.

Reduction of greenhouse gases including carbon dioxide is one of the crucial solutions to save the climate change and global warming. This crucial call leads us to renewable energy or so called '*green*' resources which are more sustainable. The following section clarifies what sustainability and sustainable architecture mean as they are fundamental keys to help remedy global warming and climate change situation.

Sustainability and sustainable architecture

> *Sustainability is a state of organization, at any particular level, that ensures, without discontinuity, an opportunity for evolution, not just now, but well into the future (Varadaan 2006).*

According to the New Oxford Dictionary (Oxford 2001, p.1870) sustainability originates from Latin *sustinere* which is rooted from *sus-* (under) and *tenere* (hold) and it basically means to keep in existence, maintain or prolong. As a definition "sustainability is satisfying basic human needs; privileging quality of life over material standards of living; minimizing resource use, waste, and pollution; taking a lifecycle approach; and it is finally acting with concern for future generations" (Oslo-Symposium 1994). Sustainability is an attempt to provide the best outcomes for the human and natural environments both now and also into the indefinite future. It affects every level of organization, from the local neighbourhood to the entire planet. Sustainability is a broad concept and has different aspects such as social, economic, environmental, ecological and should be considered throughout the building process (DfES 2002, p.57).

Sustainable architecture attempts to reduce the collective environmental impacts during three main stages of buildings: first the production of building components, second during the construction process and third during the lifecycle of the building which includes its heating, cooling, lighting, cleaning, etc (DfES 2002). In other words, it is aimed to minimize the environmental impacts of buildings by enhancing efficiency and moderation in the use of materials and energy. This design practice emphasizes efficiency of heating and cooling systems, alternative energy sources such as passive solar energy, appropriate building siting, reused or recycled building materials, on-site power generation (solar technology, photovoltaic cells, ground source heat pumps, wind power), rainwater harvesting for gardening and washing, and on-site waste management such as green roofs that collect, filter and control rainwater (DfES 2002, pp. 57-60).

Nair and Fielding (2005, p.83) argue sustainable architecture is one of the key aspects of high performance schools in four main ways: firstly, it involves a sensible approach which attempts to minimize the disruption of a site's natural features; secondly, it tries to use natural energy resources from the earth, wind and sun to minimize the consumption of fossil duels; thirdly, it tends to utilize indigenous materials with high recyclable content which do not cause health problems; and finally it tries to minimize the consumption of water within the building by collecting rain water managing recycled water in the site. It is important to mention that daylighting plays a significant element in an attempt to achieve a successful sustainable architecture.

This research is focused on the solar energy, specifically passive solar, as a significant factor in sustainable architecture for two main reasons. Firstly, around 60 percent of energy use in our buildings is taken up by electricity, and as one of the climate change solutions, it is most reasonable to reduce electricity in our buildings and use, instead, the solar energy and, of course, renewable energy (ibid). This lowers our dependence on fossil fuels and, hence, reduces greenhouse gases which are the main causes of global warming. Besides, the reason passive solar is selected for this research, comparing to active solar and photovoltaic cells, is active solar is an expensive technology to use widely in Iran. Secondly, the choice of warm-dry climate of Iran as the focus of research offers a good opportunity to utilize sunlight indirectly and efficiently in buildings.

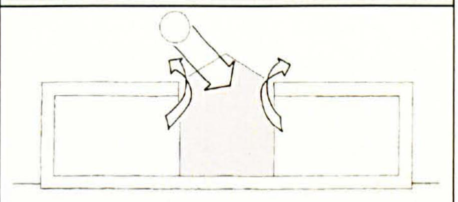
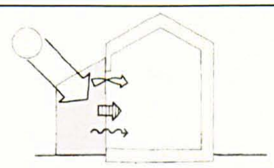
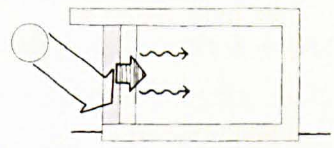
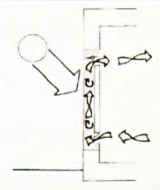
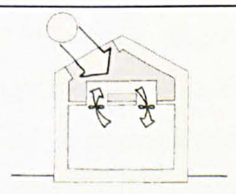
However, it is important to highlight the difference between passive solar approaches in the UK climate and the warm-dry climate of Iran in terms of natural illumination. In the former climate context, the passive solar approach is to use the sunlight to heat and supplement illumination of interiors, while in the latter climate direct sunlight is not usually welcomed due to overheating problems and the approach is to obstruct the harsh sunlight and at the same time use it indirectly for natural illumination.

Finally, as this research intends to contribute to the knowledge of school buildings and educational spaces, it is important to mention in a school setting sustainable design can become an excellent teaching tool. It can become a dynamic model to teach architecture, engineering, construction and environmental science in harmony with nature (Nair and Fielding 2005, p.83). The value of sustainable architecture as a teaching tool should not be underestimated as the exposition of architectural structure in educational spaces can engage students' imagination and encourage learning about buildings as 3 dimensional textbooks (ibid, p.84). Therefore, the next section will elaborate on passive solar schools and their characteristics.

2.3. Passive solar schools

As already discussed, sustainable and passive design buildings is one of the key fields of interest and research in architecture. A passive solar school is a design which uses natural resources and saves energy and also creates pleasant environmental conditions for children. It is difficult to achieve a successful passive solar school design as it needs to consider a number of factors such as building orientation to make the most of sunlight, building material, window design, shading, heating, lighting and ventilation. A passive solar school absorbs and distributes solar energy by means of the form and the fabric of the building. It is worth mentioning that although the idea of using solar energy effectively is not new and can be traced back in vernacular architecture; the application of passive solar concepts to schools is relatively new (DFE 1994, p.6).

There are basic principles in passive solar building design (daylighting, shading, Thermal mass, natural ventilation, etc.) which if applied successfully in a design; the result should be a well daylit building with an energy consumption lower than a conventional design (ibid, p.9). Solar energy usage in buildings can be improved by incorporating passive solar features such as atria and conservatories, etc. The following table (Tab 2.2) illustrates briefly passive solar features and components which could be used to enhance the energy performance of the building. It is important to mention that these features (especially the first two) should ideally be integrated in the design process, particularly in the early stages of design, to produce a successful design solution sensitive to the climate of the region.

Feature/ Component	Description	Illustration
ATRIA	A sun space to provide daylight & fresh air to adjacent places. Two types: courtyard & linear central atrium.	
CONSERVATORIES	An enclosed glazed roof space. Three types: Integral direct, integral indirect & attached isolated.	
TROMBE-MICHEL WALLS	A glazed cavity wall to increase the wall's thermal mass & time delay.	
THERMO-SYPHONING AIR PANELS	A sunlight collector with rear panel absorber to let air pass between glazing & the absorber.	
ROOF-SPACE COLLECTORS	A pitched roof to collect solar energy and provide warm air. Different variations are available.	

Tab 2.2. Features and components of passive solar buildings (Based on DFE 1994, P.21 32)

Among different factors of passive solar design, daylighting is of significant importance. Daylighting has been considered a crucial factor in designing schools that, perhaps, in the design of any other building types (Manning 1967). The provision of daylight and air in schools has become a driving force in the evolution of school design right up to the present day (Baker, Steemers et al. 1993, p.1.8). Phillips (2004, p.65) also argues that it is in the field of educational buildings that some of the most innovative daylight solutions have been developed which will be discussed in chapter 7. He suggests one of the reasons, perhaps, is the education authorities are insistent that in any new buildings for schools the question of energy savings is fully investigated and solutions adopted. Having reviewed passive solar schools briefly, the next section will look into the specific passive solar features of warm-dry climates.

2.4. Warm-dry climate and passive solar design features

The main characteristic of warm-dry regions is a combination of low humidity and high summer daytime temperature which affects human comfort as well as building and urban design (Givoni 1998). Therefore, mitigating the harshness of sunlight especially in summer time is one the main objectives of passive design strategies. This strategy, of course, applies to both the interior as well as the exterior of buildings.

The building envelope and building materials are significant factors in providing the above objective. A more compact building shape and configuration has a low ratio of building envelope to its volume, which in effect reduces the radiation on the envelope and therefore reduces overheating. On the other hand, more spread-out or open shapes and configuration allow better natural ventilation of the building which in turn reduces the indoors temperature (Kasmaei 1993). Moreover, if the air, which is usually dry in the climate zone under consideration, is moistened by passing over ponds or fountains outside or inside the building, it would lower the temperature and makes the ventilation more pleasant for human comfort. Although, it might appear contradictory to employ the above two building envelope types in one building, it is possible to have the benefit of both arrangements in one building during the summer day time by indented porches (Givoni 1998, p.341). Fig 2.5 illustrates this solution.

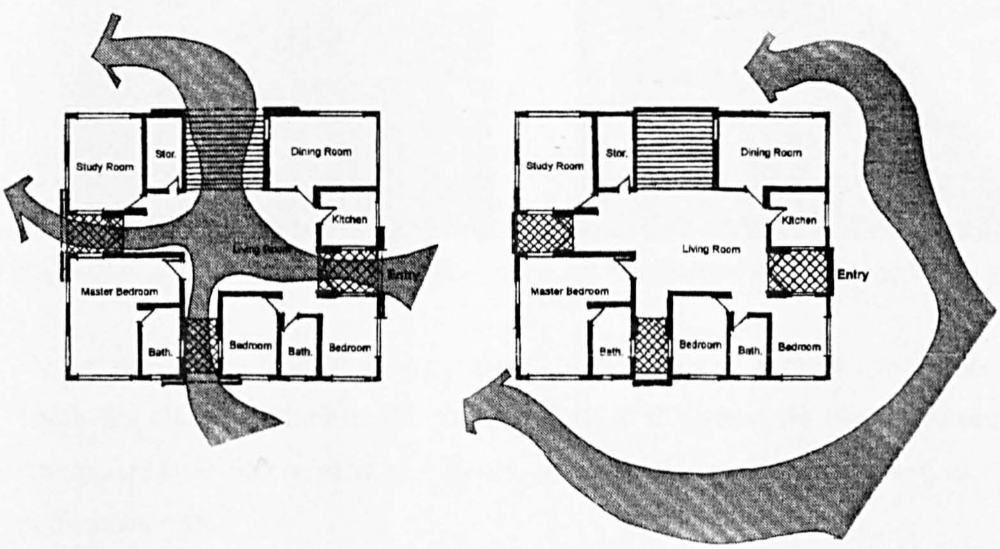


Fig 2.5. An example of a compact and yet open configuration with intended porches closable by insulated shutters (After Givoni, 1998: 341)

Another important factor in tackling problems of comfort design in a warm-dry climate is the microclimate around the building. Foliage and vegetation can have a significant effect on the shading and cooling the temperature around the building which in turn provide more pleasant environment for the building occupants (Kasmaei 1993; Givoni 1998). Ponds and fountains, as mentioned earlier, could also alleviate the excessive heat at the hot times of the day and also moisten the air and make the natural ventilation of the building more pleasant. These factors can help create a mediated environment around the building, and defeat the evident problems of such a climate. This mediated environment can be incorporated within the building through the incorporation of the traditional courtyard or patio configuration in warm or hot-dry climates. Figures 2.6 and 2.7 (photos © F. Ai) illustrate typical examples of courtyards in traditional Iranian schools which are equipped with ponds and large areas of greenery. Courtyard configuration forms an important part of vernacular architecture solutions in such climate and will be explored more in detail in the next section.

Fig 2.6. Microclimate in Khan School, Shiraz

Fig 2.7. Microclimate in Chaharbagh School, Esfahan

Before moving on to daylighting features of this climate, a more specific aspect of warm-dry climates which is the main concern of this research, the above section is summarized as follows. The main issues of warm-dry climate in terms of its thermal performance are:

- Reduction and slow rate of heating during summer daytime;
- Fast rate of indoor cooling in summer evenings

Therefore, as exemplified some potential solutions to the above issues are:

- Good natural ventilation in summer evening;
- Foliage, vegetation and ponds to provide shade and amelioration of the microclimate around the building

2.5. Daylighting issues of warm-dry climates

The above section addressed briefly the thermal performance issues and some potential solutions in warm-dry climates. Daylighting and sun lighting strategies, as the focus of this research, are strongly affected by the thermal performance of the building in this climate. It is, however, worthwhile to address the difference between sunlight and daylight as they will be frequently used in the research. Sunlight is direct sun rays emitted from the sun and scattered through the atmosphere where it could be reflected, absorbed or passed through the receiving objects. On the other hand, daylight is the diffused light or the indirect and reflected light in the atmosphere.

The sky is clear throughout most of the year which increases solar heating during daytime through direct as well as indirect solar gain. Direct sunlight is harsh in this climate particularly in summer time and causes overhearing issues. The bright sky is also a source for discomfort glare. Besides, sunlight reflection off the ground together with the reflection from building's walls may produce intense glare and consequently visual discomfort and significant radiant heat load for windows and walls (Givoni 1998, p.334). Therefore, the main strategy of daylighting in such climates is to prevent glare and visual discomfort which, in the first instance, means keeping the harsh sunlight off the windows. However, not only the first radiation of sunlight should be avoided in terms of the direct lighting of a room, but also the second source of radiation, namely the reflecting surfaces, should be controlled as they can also cause glare to the occupants in a room (Givoni 1998). Therefore, reflected sunlight seems to be a good solution for daylighting in such climate (Givoni 1998; Gorji-Mahlabani 2002) whether it is controlled first-source reflecting surfaces or second-source reflecting surfaces. Sunlight and daylight also depends on the sky types.

2.6. Standard Skies and Daylighting

Daylight availability is usually measured under CIE overcast sky which is the current model and is based on restricted conditions and locations (Kittler, Hayman et al. 1992, p. 173). There are very limited data on clear and diffuse sky conditions. Therefore, the Commision Internationale d'Eclairage (CIE) in cooperation with other organizations such as WMO and IDMY have initiated a program which intends to gather data for other sky conditions (ibid, p. 173). Kittler, Perez and Darula (1997) have analysed and compared sky luminance distributions sets in more than hundred selected cases in different climates and have proposed a new range of standard skies. It is a set of mathematical equations describing 15 standard skies which is set to determine sky luminance distributions characteristic of intermediate skies between the two already standardized clear and overcast sky distributions (ibid, p. 370). The following table summarises 15 standard skies changing from overcast to clear skies.

	Sky Type	Short Description
1	Overcast, steep gradation, azimuthally uniform	Including CIE overcast sky
2	Overcast, steep gradation, slight brightening toward sun	No direct sunlight, sometimes darker or brighter skies
3	Overcast, moderate gradation, azimuthally uniform	No direct sunlight, sometimes darker or brighter skies
4	Overcast, moderate gradation, slight brightening toward sun	No direct sunlight, exceptionally darker skies
5	Overcast overall, uniform sky	No direct sunlight
6	Partly cloudy, moderately graded, slight brightening toward sun	No direct sunlight, exceptionally darker skies
7	Partly cloudy, moderately graded, brighter circumsolar effect	Filtered direct sunlight, exceptionally darker skies
8	Partly cloudy, rather uniform, clear solar corona	Filtered or no direct sunlight
9	Partly cloudy, shaded sun position	Filtered or no direct sunlight
10	Partly cloudy, brighter circumsolar effect	Filtered direct sunlight
11	White-blue sky, clear solar corona	Direct sunlight
12	Clear sky with low turbidity	Corresponding to current CIE clear sky standard
13	Clear sky with higher turbidity	Corresponding to current CIE polluted sky standard
14	Cloudless turbid, broader solar corona	Direct sunlight
15	White-blue turbid sky, wide solar corona	Direct sunlight

Tab 2.3. A set of 15 basic sky types representing Sky Luminance Distributions

2.7. The vernacular and the strategies of daylighting in warm-dry climates

Having addressed briefly daylighting issues of warm-dry climates, it is important to find out how the vernacular architecture of the region has dealt with this issue. Vernacular architecture is an appropriate basis on which one can explore a variety of design issues as it has developed over centuries adapting to people's needs and available material (Givoni 1998). It holds lessons of sustainable design because of the way that it has evolved specifically in relation to the place and climate. A configuration which has a special role in the warm-dry climate is the internal courtyard or patio. Although, there is a common notion that this type of configuration maintains a cooler indoor temperature, it should be recognized that courtyard houses were built in response to different needs and limitations, and climate was only one of these factors (Givoni 1998). Other factors influencing its development are cultural and social, in particular the need to provide a high degree of privacy, particularly for women. However, the focus of this section is the benefits of using sunlight appropriately within such configurations. This is to see what lessons may be translated to the subject of the thesis, i.e. the design of schools.

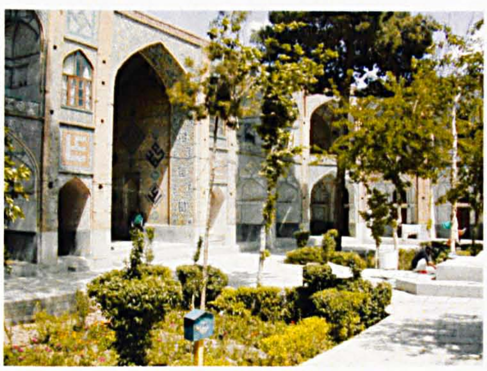


Fig 2.8. Nimavard Religious School, Esfahan

Fig 2.9. Darolfonon School, Tehran (photos © F. Ai)

As discussed in the previous section, reflected lighting is a suitable way of daylighting in this climate. The internal courtyard is a configuration which blocks or limits direct sunlight from the windows, depending on its proportions, and allows reflected and filtered light to illuminate the rooms naturally. As the ratio of the height of the building surrounding the courtyards to its width at the roof's level increases, less sun can penetrate into the ground level of the courtyard (ibid, p.344). This increases the shaded area of the patio and reduces the radiant temperature. Apart from the shading of the building, trees and plants can have a significant effect in shading the internal courtyard and further reducing the temperature. The foliage of trees also filters the harsh sunlight and makes it less glaring inside the rooms surrounding the courtyard (Fig 2.8 & 2.9). Another feature of the vernacular architecture of the region to control harsh sunlight in such a climate is latticed screens which usually have geometric patterns. Wherever the use of reflected light is not possible, these screens reduce the glare significantly and make it possible to look at the clear bright sky from within the room.

Fig 2.10. Examples of geometric latticed screens as filtering solutions of harsh sunlight, Khan School, Shiraz, Iran, (Photos © F. Ai)

There are other elements such as porticoes, clerestories, building material and colour, etc. which have been used sensibly in the vernacular to make the building more environmentally friendly and self-sufficient, these will be discussed more extensively in chapter 6. Nevertheless, one of the interesting findings of the vernacular architecture observational study is that daylighting is only one element in understanding how buildings have evolved to relate to their climatic context. Other factors such as the cooling or heat loss in the cold season, as well as natural ventilation and air circulation in the hot season, are not of less importance in the configuration of buildings. Therefore, a holistic approach can be drawn from the vernacular as a valuable lesson for climatic design.

2.8. The Holistic approach

A holistic approach is characterized by understanding the parts of something to be intimately interconnected and explicable only by reference to the whole (Pearsall 2001, p. 874). It is based on the principle of '*Holism*' which was concisely summarized by Aristotle in *Metaphysics*: *"The whole is more than the sum of its parts."* Holism is defined in the New Oxford Dictionary (ibid: 874) as follows:

> *The theory that parts of a whole are in intimate interconnection, such that they cannot exist independently of the whole, or cannot be understood without reference to the whole, which is thus regarded as greater than the sum of its parts.*

In this context, daylight is, therefore, treated as a part of a whole, which is architecture, and cannot be fully assessed and understood without its relations to other architectural elements such as heating or ventilation, materials and configuration, and so on. This is a lesson to be learnt from vernacular architecture and will be discussed in more detail in chapter 6. The following sections will briefly discuss the natural lighting, heating/cooling and ventilation of the vernacular architecture of the region to understand the interrelationship.

2.8.1. Daylighting

Having studied 15 exemplary historic schools in the warm-dry climate of Iran (Appendix A), it appears daylighting conditions are not appropriate for a learning environment in the most of the Hojras (study rooms around the courtyard). Levels of illuminance and its uniformity could have been more satisfactory had the design been different. The reason is that other comfort factors, such as the reduction of room temperature and air circulation, had prevailed over the consideration of daylighting. This explains the limited and restricted apertures of the rooms especially those facing the south or west (see Appendix A).

2.8.2. Heating/ Cooling

Cooling strategies during the hot summer time, as well as the reduction of heat loss during the cold season nights, are important factors in climatic design in warm-dry climates. This issue has been resolved quite sensibly in the vernacular architecture. Thick masonry walls delay the absorption of daytime heat during summer and also delay the loss of the interior heat during cold nights (Givoni 1998). Ponds in the courtyard have a positive effect in reducing the air temperature which, in turn, will flow in the surrounding rooms. Cooling is more of a concern in such a climate. Cooling is also related to natural lighting as uncontrolled sunlight causes overheating.

2.8.3. Ventilation

Natural ventilation is particularly of significance during hot days or nights. The flow of air reduces the room temperature and brings about a pleasant sensation as it dries out the perspiration caused by the hot weather on the skin. An open plan configuration, where the building is spread out and narrow rather than compact with deep plan, allows air to circulate more efficiently, while such an open plan might not be appropriate for avoiding heat gain during day time (Givoni 1998, p.341). Although it might sound contradictory, there are some design solutions which allow both ventilation and low heat gain rate possible such as the example in Fig 2.5.

Finally, it is important to understand the above separate elements of climatic design should be studied and analyzed while taking the effect of the others into account. This research suggests a holistic approach by which neither of the above elements is totally independent of one another, but is seen as interconnected in a successful building design. Although, they can be studied individually, as this research intends to study the daylighting issue, the influence on other elements should be taken into account as they all together, and not separately, create a sustainable architecture.

2.9. Summary and Conclusion

This chapter started with a general description of the geography of Iran. The Main categories of Iranian climate were identified and discussed. A comprehensive classification divides the climate into 8 main groups and subsequently 36 subgroups. It shows Iran has a very varied climate extending from hot dry to cold wet climatic zones which is due to the mountains, the seas and deserts, as well as varied weather systems. This means there may be different design solutions for energy efficiency and sustainability depending on the locality within the country. However, due to the vast area of warm-dry climate and its coverage of the main populated cities, this climate is chosen as the focus of the thesis.

Concepts such as climate change and sustainable architecture were then introduced briefly and passive solar design features of warm-dry climates are examined. Passive solar schools and their features and components were, then, briefly introduced. From the various elements of passive solar design element, daylighting is chosen for further research as it is a significant factor, particularly in this climate, and its various issues were introduced in relation to the warm-dry climate. Other climatic elements such as heating/cooling and natural ventilation were also briefly explored in the context of such climate and it is established that they are basically interconnected. This research suggests a holistic approach whereby the effect of other elements should be taken into account during an individual study of a climatic element.

It can be concluded that Iran has a varied climate of which the warm-dry zone covers some of the most populated cities. The bright sunshine in such a climate is usually filtered or blocked to avoid discomfort glare as well as overheating issues particularly in hot seasons. It has been used appropriately in the vernacular architecture of the region, although much of the weight has been given to the thermal performance rather than natural illumination of the historic schools. There are lessons which can be drawn from it for designing new buildings. An important lesson is the holistic approach which does not separate different elements of climatic design but studies their interconnected effects.

CHAPTER 3: DAYLIGHTING AND SCHOOL DESIGN

3.1. Introduction

This chapter is about the importance of daylighting design on the overall quality of the school and educational environments. First of all, it introduces the school curriculum in Iran briefly. Then it discusses the idea of paradigm change in educational systems and its effects on the curriculum. The history and development of daylighting in schools and the change of lighting standards will be an introductory section to the rest of this chapter about the issue of daylighting in schools.

The chapter will then argue, based on a number of research findings, that natural light has beneficial effects on the learning environment and student performance. It also deals with other implications of daylighting in schools such as energy performance etc. Finally, it will conclude with the specificity of daylighting design in schools and special features of daylighting in educational buildings which designers should be aware of.

It is important to mention that in this chapter climate is not considered a significant factor as it simply explores the effects of natural light on the learning environment in general and identifies particular parameters of lighting and daylighting in schools. The fact that natural light is beneficial to students and their performance in schools seems to be a universal notion and is valid in different climates. This chapter brings together research from different parts of the world to support the argument. However, in further stages of the research (chapter 5 & 6) will particularly focus on the design challenges in a warm-dry climate and will investigate the relevant solutions.

3.2. School Curriculum in Iran

School curriculum in Iran is based on a class group organisation which is divided by student's age group. There are usually between 30-40 students in each classroom. Traditional Western methods of education have been adapted to the Iranian curriculum; this influence started in a high school called "Darolfonon" in Tehran in 1851 (Mozaffar 1997, p.202).

Although there have been some changes in the educational system since the adoption of the Western model, the method of education is still based on the concept of a traditional approach which assumes children are inactive and submissive toward education. This traditional method can be regarded as teacher-centred and the emphasis is usually on 'what is to be learned'. Moore (1974) elucidates the idea of traditional method of education as follows:

> *"Education is thus represented as a sort of translation between a full and an empty vessel. The teacher is a full man, a repository of socially important knowledge and skills and attitudes whereas the pupil is empty and needs to be filled up".* (Moore 1974, p.20)

However, the educational approach in Iran is trying to accommodate a change toward this attitude and incorporate more a '*student-centred*' approach, based on Western examples.

3.3. Paradigm shift in school design

Paradigm is a useful concept to capture the state of educational change over the last century and today. The paradigm is an accepted model or pattern and the term is used metaphorically from its original technical way defined by Thomas Kuhn, who revolved the philosophy of science with his notion of paradigm shift in 1962 (Kuhn 1970, p.24). Education and its exemplification in buildings and environments has always been concerned with radical ideas set in new settings and the need to encompass ever-changing educational theories and paradigms (Dudek 2000, p.xiii).

The traditional paradigm in education can be called the industrial model of education or the factory model. The "*Factory model*" grew out of the industrial societies of the late 19^{th} and the earlier decades of the 20^{th} century. This is characterised as a school reflecting the mass production methods of the industrial time which was supposed to provide a future workforce with basic skills and submissive attitude (OECD 2001, p.64). However, after the waning of the industrial time a change was needed in educational systems and paradigms.

The *knowledge-based paradigm* did not start with the advent of computers and the fall of factories in the West; it began over a century ago in the US with John Dewey's notion of *'out-of the-Box'* thinking (Lackney 2001). Dewey (1859-1952) understood the problems with a crowded curriculum, the passive student as container, and the limitations of the building in facilitating learning. In response, he invented the idea of a laboratory school which was a small cooperative society where children learned to solve problems themselves (ibid, p.4). He recognized the importance of stimulating children's senses as a part of the educative process as he stated '*...the boy flying a kite has to keep his eye on the kite, and thus to note the various pressures of the string on his hand. His senses are avenues of knowledge not because external facts are 'conveyed' to the brain, but because they are used in doing something with a purpose.*' (Dewey 1916 reprinted 1967, p.142)

This is when the concept of a new knowledge-based paradigm was conceived, and a change began to emerge from teacher-centred to learner-centred attitude in educational systems. Lackney (2001) argues that the factory model is still the dominant school design paradigm, and that is unfortunate. Standardisation of the curriculum, large group instruction, and teacher-centred classes with the table at the front of the room are the typical results of the traditional system and remain familiar to most children in school today. There is, instead, more room for small group project-based learning and cooperative learning in the new system (ibid, p.5). This change in learning methodology should in return influence the design of schools.

Based on changes to teaching methods, there seems to be a new paradigm emerging for school design. The result of this new paradigm is called self-directed learning environments where students direct their own learning, and teachers are there to facilitate it. The new paradigm is no longer about delivering information as in the factory model schools, but it is about nurturing a broad array of learning styles and experiences (Nair and Fielding 2005, p.78). This new model challenges spatial standards and guidelines in schools. A comprehensive set of area guidelines and standards have been established and published in the UK (DfEE 1996) according to Education Regulations 1996, but they do not particularly address the new knowledge-based learning environment. However, the recent Building Bulletin 95 *"Schools for the Future: Designs for Learning Communities"* (DfES 2002) addresses the new educational paradigm and the new spatial requirements for schools. It is a relatively young subject area, with designers across the world only beginning to conduct design experiments about the idea of schools for the future and their physical features (Lackney 2001; DfES 2002; DfES 2002; CABE/RIBA 2004; Nair and Fielding 2005; DfES 2006; DfES 2006).

Nair and Fielding, however, have developed a system of 18 modalities of learning such as independent study, peer tutoring, team collaborative work, project-based learning, etc. which challenges the traditional spatial standards (Nair and Fielding 2005, p.20). This approach challenges the schools' terminology and addresses classrooms as learning studios, corridors as learning streets and schools as community learning centres (CLC) (ibid). The 18 modalities approach is focused on the activities which could happen in a school and is influenced by Multiple Intelligence theory by Howard Gardner. Howard Gardner's Multiple Intelligences (MI) theory suggests that all human beings possess eight intelligences such as linguistic, logical/mathematical, musical, bodily /kinaesthetic, spatial, naturalist, interpersonal and intrapersonal smart (Hoerr 2000). Even though Gardner developed MI as a theory of the mind, it has naturally influenced the realm of education and the classroom design (Nair and Fielding 2005, p.70). It is suggested that it is more likely to create interesting and exciting learning environments if as many of the above intelligences as possible are accommodated (ibid, p.71).

One of the successful examples of the new paradigm schools is the project '*Classrooms of the Future*' run by the Department of Education and Skills in the UK (DfES 2002). This project aimed to challenge current thinking on school design and 12 pilot projects were developed by local education authorities across the UK to test new ideas with innovative design of classrooms in schools for the future. The result is imaginative designs which aim to stimulate and inspire children; they will be discussed extensively in the exemplary schools in chapter 7. Another approach is '*The language of space in school design*' (Nair and Fielding 2005) in which 25 design patterns for 21st century schools are explored based on the concept of Alexander's '*A Pattern Language*' (1977). The above successful examples will be analysed in chapter 7. Having discussed factors that influence school design, it is time to address daylighting as an important factor in school design.

3.4. The history and development of daylighting in Western schools

> *It is well known that the rays of the sun have a beneficial influence on the air in the room, tending to promote ventilation, and are to a young child very much what they are to a flower. Acting on this known fact the builders of some schools have sought to secure as much sun as possible and produced results of light and glare painful in hot summer weather, either to teachers or pupils or both.* (Robson 1874)

Daylighting in schools has been a subject of interest ever since school design became a specialist area of architecture. In the eighteenth century, the single room building was perhaps the typical school classroom in Western societies, and it had to include the instruction of the whole school simultaneously (Seaborne 1971, p.8). But this style of school building came to an end with the increase in the UK school population and separate classrooms for children of different age began to appear. Robson (1874) was one of the first to make suggestions about the layouts of school and the interior environment. He suggested the best source of light for classrooms is the steady light of the north. He even advised designers as a rule of thumb '*A classroom is only well lit when it has 30 square inches of glass to every square foot of floor space*' which is about 20% glass to floor area which is related to current standards (DES 1997). During the 19^{th} century schools were predominantly designed to take advantage of north light and therefore the problem of glare from south or west facing windows were avoided (DFE 1994, p.7).

From 1900 up to 1930s, there was an increase in awareness of the importance of fresh air and sunlight to health in education which resulted in the open-air school movement (Dudek 2000). It started as an improvement to the stuffy, and often gloomy, typical classrooms of the late nineteenth century. The new plan was essentially a row of classrooms connected to a hall by open corridors and verandas, showing a new obsession with light and air. In spite of their large area of glazing, these schools did not suffer excessively from overheating since the fabric was massive and the generous room height permitted useful stratification and ventilation (Baker, Steemers et al. 1993, p.1.10).

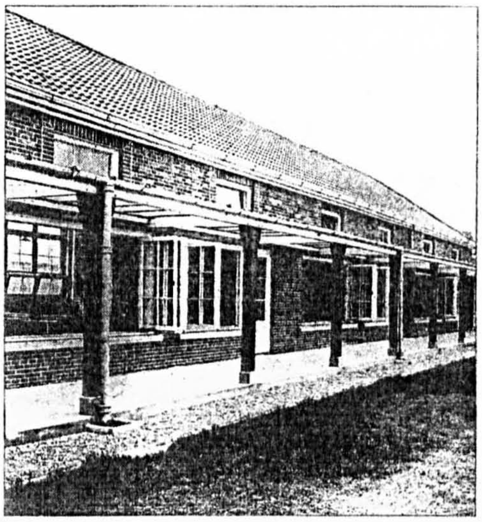


Fig 3.1. A 1930s open-air school (DFE 1994, p.7)

Open-air schools were usually oriented towards the south, and by using sliding or folding windows exposed teaching areas to fresh air and direct sunlight. Waldram (1914) also placed an emphasis on the effects of the open-air movement in his review of the history of daylighting in schools since 1866. Due to the importance of facilitating sunlight penetration into classrooms in the 1940s, the bilateral daylit classrooms became a standard form to maximise daylight (DFE 1994, p.8). Bilateral daylit classrooms received daylight from two opposite sides, usually the south and the north. Figure 3.2 illustrates a typical 1940s classroom which receives maximum daylight from south-facing glazing as well as the north light via the clerestory over the corridor. This example was a good solution to overcome the dark end of classrooms.

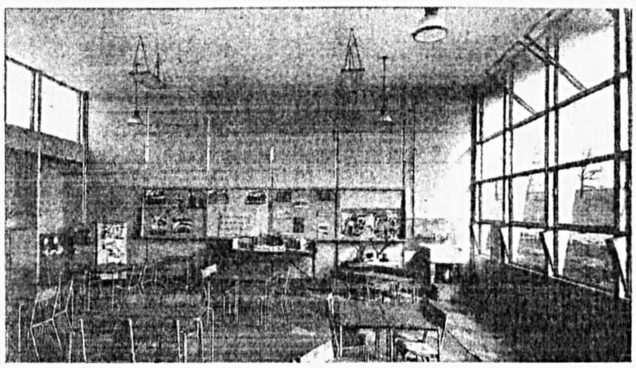


Fig 3.2. A typical 1940s classroom to maximise daylight (ibid, p.8)

Daylight was regarded as the principal source of illumination in the regulations for school design. A minimum 2% 'sky factor', and where possible 5%, was recommended for classrooms (British-Standards-Institution 1945). Sky factor refers to *uniform* sky luminance distribution and is a more demanding factor than currently known daylight factor as it only takes daylight directly from visible sky into account whereas with daylight factor, reflected exterior and interior daylight are also included, as defined in chapter 4. Therefore, many schools constructed in 1950s and 1960s had large windows and unfortunately, due to the lightweight building structures which where thermally inefficient, they suffered overheating in summer and heat loss in winter as well as glare discomfort. Largely as a result of the large glazing area, the thermal environment presented major problems, high room air temperatures in summer being aggravated by direct sunlight falling on the occupants sitting close to a window (Baker, Steemers et al. 1993, p.1.10). These problems caused by highly glazed facades, led to the start of the design of energy efficient schools which were built with compact plans and reduced size of windows. Most schools of 1960s reduced their window size due to summer overheat and winter heat loss and also the reduction of excessive glare.

The reduction of window size in school buildings sometimes went too far, especially in the USA where fluorescent lighting became normal in classrooms (Wu and Ng 2003). Natural ventilation was replaced by air-conditioning and engineers suggested that smaller windows could improve energy efficiency (Kay 1963; Brown and Hult 1967). Consequently, many classrooms had small windows and little daylight. The window size reduction went even further with the oil crisis.

The oil crisis occurred in 1970s and due to concerns over energy shortages, schools had to reduce their energy consumption. There were two main approaches taken toward energy efficient schools: the *exclusive* and *selective* model (Wu and Ng 2003). The exclusive approach restricted the window size even further or totally excluded windows from school buildings. In the UK, some local education authorities were no longer commissioning the previous type of design with large glazing areas and were beginning to adopt heavyweight systems with small windows and a deep plan, necessitating artificial lighting and mechanical ventilation (Baker, Steemers et al. 1993, p.1.11). The majority of schools especially in the US were built with minimum glazing or without any windows (McDonald 1961; Lynes 1968). In the US, Florida, there was even a legislation passed which required all schools to be air-conditioned and windowless (ibid).

There is a considerable amount of research evidence inquiring the existence of windowless classrooms and its effects on students. Graves and Pearson (1993) studied an example of the interior of such windowless classrooms in the US in 1960s. Karmel (1965) studied the psychological effects of windowless classrooms by asking more than 1000 secondary students aged 14-15 to draw a picture of their school. The results revealed that students in the windowless schools drew windows significantly more frequently than those in windowed schools. Subsequently, Tikkanen (1970) investigated the reactions of over 3000 students in eight schools (windowed & windowless) in California to see whether they preferred classrooms with or without windows. The results showed 94% of students in windowed schools preferred classrooms with windows while only 4% preferred windowless classrooms. In another research project conducted a few years earlier, Tognoli (1973) found students chose the presence of a window more pleasant than its absence. Larson (1975) also found the increase of absenteeism in windowless classrooms and established students desire for windows in their classrooms.

The second approach to energy efficiency is known as *selective*, by which sunlight is selectively admitted into the school but with careful control of its admission. Based on passive solar design principles, this permitted direct sunlight penetration into classrooms, and yet avoided heat loss as well as using solar energy as a heating source. Contrary to the '*exclusive*' school model which resulted in windowless schools in 1970s, a '*selective*' model would make more effective use of ambient daylight (Crisp, Littlefair et al. 1988).

The first energy efficient sustained attempt to design a school based on passive solar design principles in the UK is St Mary's in Wallasey (Fig 3.3) which was built in 1961 (DFE 1994, p.8). It is a good example of experimental attempts to provide a thermally comfortable classroom by means of solar gain, occupancy gain and interior artificial lighting. It is important to mention here that the main research consideration in St. Mary's school was thermal performance, and daylighting was not taken into account substantially (Davies and Davies 1971; Davies 1979). These studies suggest that designers of passive solar buildings should be at least as concerned with the interior visual effects of glazing as with the interior thermal effects (ibid). Since 1980s a number of schools with passive solar features have been built in Europe and the US to make the most of natural resources. Large windows were used again to maximize daylighting as well as solar gain for heating.

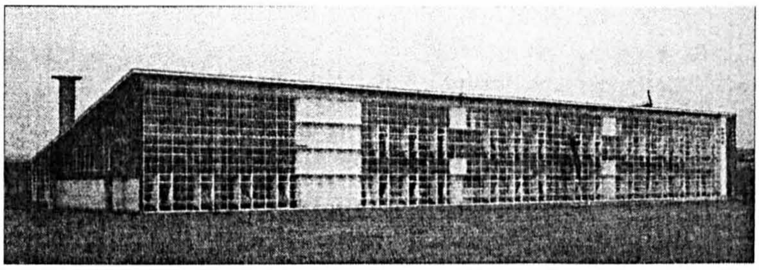


Fig 3.3. St Mary's in Wallasey, UK first passive solar school (DFE 1994, p.8)

During 1970s 1990s, fluorescent lighting has been improved in terms of energy efficiency and having wider lighting spectra and therefore has been universally adopted in schools (DFE 1994, p.8). This has resulted again in neglecting daylighting planning of schools and as a consequence, electric lighting demands formed a significant portion of the total energy consumption (ibid). In contrast, a good passive solar design involves the optimum balance of daylight whilst avoiding overheating and glare. Table 3.1 summarises the above section.

Period	School Model & Daylight	Goals	Issues & Problems
18th Century	Single-room house	inclusiveness	Deep plan & Stuffiness
19th Century	North facing classrooms	Even daylight to avoid glare & overheating	Heating/ no solar energy usage
1900-1930s	Open-air School Movement South oriented classooms	Increase light & fresh air	Glare/thermal inefficient
1940s	Bilateral lit classrooms	Maximise daylight	Glare/thermal inefficient
1950s-1960s	Large glazed classrooms Lightweight structure	Maximise daylight	Thermally inefficient heat loss/glare
1970s	Exclusive vs. Selective Compact schools	Window size reduction Energy Consumption reduction	Oil crisis Limited/non-daylit school
1980s	Compact design Or Passive solar schools	Avoiding heat loss	Reliance on fluorescent light & unawareness of daylight planning
1990s onwards	Passive solar schools	Optimum Daylighting & sustainability	Incorrect usage & overheating

Tab 3.1. A summary of the history of daylight in schools in the UK & Western societies

3.5. The history of daylighting standards in Western schools

Daylighting standards in schools have considerably changed over the last century in the UK. The first change of standards in the literature dates back to late 19th century when minimumexternal openings were defined in *the London Building Acts 1894:*

> *'Every habitable room shall have one or more windows opening directly into the external air, or into a conservatory...equal to at least one-tenth of the floor area of the room...but a room having no external wall, or a room constructed wholly or partially in the roof, may be lighted through the roof by a dormer window...equal to at least one-twelfth of the floor area of the room...' (Dicksee 1906, p.113)*

However, Waldram (1914) declared that the minimum requirements of the London Building Act 1894 are frequently adopted as maxima and should be discarded for schools in favour of a glass area of one-fifth the floor space for vertical lights. Although Robson (1874) acknowledged the beneficial influence of sun rays in schools, he criticized schools which pursued as much sun and daylight as possible because of the risk of glare and overheating in summer. In 1945, the British Standards Code of Practice recommended a minimum of 2% 'sky factor' in classrooms.

As mentioned earlier, sky factor is a more demanding factor comparing to daylight factor as the latter is an accumulation of the former as well as internally and externally reflected daylight. The above terms, daylight factor and sky factor, and their difference with lux and other units of lighting were explained in the previous chapter. In 1954, the legal requirements for schools specified that in all teaching accommodation the daylight factor on the working plane should not be less than 2 per cent, and where possible 5 per cent, and also the minimum illumination levels should be at least 100 lux (DES 1954).

The values of illuminance quoted in this section in terms of lux address the lighting level of working areas in classrooms in general and electric lighting levels in specific. Therefore, lux value mainly refers to electric lighting while daylight factor represents daylight. As daylight levels can not be guaranteed to maintain consistently due to weather changes during school hours, electric lighting should be supplemented and, therefore, the history of daylighting standards are interrelated with electric lighting standards.

In 1977, the CIBS Lighting Code recommended a minimum illumination on the working plane of at least 300 lux (CIBSE 1977). Daylight levels discussed in this section are recommendations for classrooms, as there is less daylight requirements in non-task based areas of a school. In 1981, the School Premises Regulations announced a minimum fluorescent illumination of 300 lux on horizontal surfaces. It was suggested schools should be daylit where possible and the minimum light level should be 350 lux if artificial and daylight are combined (Education-Regulations 1981). These illumination levels were not changed in the Code for Environmental Design and Fuel Conservation in Educational Buildings (DES 1981) nor in the CIBSE code for Interior Lighting (CIBSE 1984). The CIBSE code for Interior Lighting in 1994 again did not make any changes to the minimum illumination requirements but declared that they are under review (CIBSE 1994, p.77-78).

In 1997, the Constructional Standards of Building Bulletin issued by the UK Department of Education made recommendations based on average daylight factor of 4-5% (DES 1997). A minimum glazed area of 20% of the internal elevation of the exterior wall was also suggested to provide adequate views. Finally, in 1999, Building Bulletin 90 clarifies that interiors with an Average Daylight Factor of 5% or more are considered well daylit and normally do not need electric lighting. Interiors with an Average Daylight Factor between 2% and 5% will need some electric lighting and interiors with less that 2% ADF will require frequent use of electric lighting (DfEE 1999, p.15). In terms of electric lighting standards, Building Bulletin 90 recommends a minimum of 300 lux illuminance for general teaching spaces Table 3.2 summarises the above changes in lighting levels standards in the UK, showing the increasing lighting levels over the last century.

In comparison with the lighting regulations in the UK, regulations in the USA require higher levels of illumination in schools (Kaufman 1984; Kaufman 1987). During 1980s, the Illumination Engineering Society of North America (IESNA) recommended 50 footcandles (equal to 538 lux) for working areas in classrooms and twice as much for the chalkboard illumination (ibid).

Date / Code	Code	Recommended Daylight in classrooms	DF %	Lux
1894	The London Building Acts	1/5th of the floor space for vertical lights in classrooms 9 footcandles	-	**91**
1945	British Standards codes of Practice	A minimum 2% daylight 'sky factor' in classrooms 5% sky factor where possible	**>2–5<**	-
1955	IES Lighting code	Illuminance levels in classroom not less than 10 footcandles (100lux), daylight factor not less than 2%	**> 2**	**100**
1977	CIBS Lighting code	Minimum illuminance on working plane not less than 300 lux	-	**300**
1981	The Education Regulations	Minimum task illuminance not less than 300 lux If combined with artificial light not less than 350 lux	-	**300-350**
1984	CIBSE code 'for interior lighting'	Minimum task illuminance not less than 300 lux	-	**> 300**
1994	CIBSE code 'for interior lighting'	Minimum task illuminance not less than 300 lux	-	**> 300**
1997	Guidelines for environmental design in school	Minimum task illuminance not less than 300 lux Average daylight factor between 4-5 %	**>2-4<**	**> 300**
1999	Building Bulletin 90	Minimum task illuminance not less than 300 lux Average daylight factor between 2-5 %	**>2-5<**	**> 300**

Tab 3.2. A summary of the history of daylight regulations & standards in Britain (after Wue 2003)

3.6. Aspects of lighting design and schools

There are a range of different and possibly conflicting requirements when lighting design is considered in relation to classroom design (DfEE 1999). Fig 3.3 illustrates briefly these different aspects.

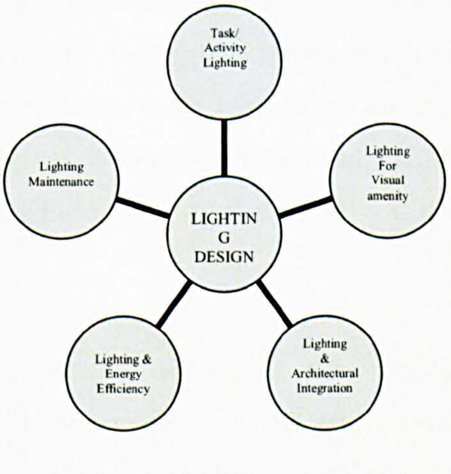


Fig 3.4. A framework for a aspects of lighting design (DfEE 1999)

First of all is the functional aspect of lighting or task lighting which allows occupants to carry out their tasks and activities without any visual discomfort. It mainly requires minimum levels of illuminance and a relatively high level of illuminance uniformity over the task area, while avoiding discomfort glare (ibid, p.3). There are actually two types of glare concerning daylighting: disability and discomfort glare.

Glare is usually caused when the balance of luminance distribution in an interior environment is disturbed by excessive contrast. Disability glare can be caused when the luminance of the sky seen through a window is very high and it is visible from a work place of much lower luminance (DfEE 1999, p.19). For instance, a window on the chalkboard wall should be avoided because of the likelihood of disability glare. On the other hand, discomfort glare can be experienced when some parts of an interior have a much higher luminance levels than the general surroundings (ibid, p.20).

Discomfort glare from daylight is a more common problem than disability glare. There are different ways to reduce discomfort glare in a room and specifically in a classroom. One way is to reduce the contrast between the window and its surroundings by using splayed light-coloured window reveals or by increasing the brightness of the window wall by increasing its reflectance or lighting it from a window in an adjacent wall (ibid, p.20). However, the reduction of sky luminance by horizontal or vertical shading devices is the major consideration especially in bright sky climates. Discomfort glare can also be caused by electric lighting. It is controlled by the luminance and the size of the glare sources, its position in the field of view and the visual adaptation given by background luminance (ibid, p.24). These factors should be below the Limiting Glare Index in table 3.3 according to CIBSE Technical Memorandum No 10. However, it should be noted that CIBSE TM 10 Limiting Glare Index is now superseded by European Legislation and a Unified Glare Rating (UGR) system is used instead.

UGR method serves as a practical discomfort glare evaluation system for use in interior lighting conditions (Sendrup 2001). UGR values are on a scale from 10 to 30, where low values indicate no glare and high values indicate intolerable glare. The visual field in the UGR method is divided into fields of 'glare sources' and 'background' (ibid, p. 243). Maximum allowed UGR in offices and working areas is 19. As can be seen in table 3.3, there is another important factor in daylighting in schools which needs addressing: uniformity ratio.

The distribution of light in a space has a considerable impact on the appearance of the room. It is believed that a uniform distribution of light is favorable in teaching spaces as it enhances concentration on the task (Heschong-Mahone-Group 2003). However, some directional light can give character and interest to non-task based parts of a classroom as it provides variety and visual contrast (DfEE 1999, p.26). The following table illustrates task lighting consideration levels in different areas of a school.

Spaces \ Levels	Standard illuminance/ lux	Uniformity Ratio	Glare Index
General Teaching Spaces	300	0.8	19
Teaching spaces with detailed work e.g. crafts rooms	500	0.8	19
Circulation spaces:			
corridors, stairs, lobby…	80-120	-	19
Waiting areas	175-250	-	19
Reception area	250-350	-	19
Atria	400	-	19

Tab 3.3. Illuminance, Uniformity ration and glare index levels for schools (DfEE 1999, p.23)

Lighting for visual amenity is as important as task lighting and it enhances the appearance of the space. Although uniform light is recommended by task lighting, a degree of non-uniform lighting pattern is desirable by visual amenity lighting. Fielding (2005, p.77) even claims that uniform illumination levels in the classroom was sensible for students in the *factory model* schools. Fielding (2000) argues that uniform light can be monotonous. It seems acceptable that with the flexibility in student arrangement in new classrooms a variety of lighting will be required and accent lighting can accompany uniform lighting to enrich the quality of illuminated space. Spaces with some areas of light and shade are generally liked by students, but the variation in brightness should not disturb the visibility in working areas as it would cause visual discomfort (DfEE 1999, p.5). Whilst direct sunlight is generally avoided in the task based lighting, it could be used in the non-task based areas of the school such as circulation spaces etc. to enhance the visual amenity of the educational environment by the appearance of sunlit areas and the changing shading patterns it provides. This aspect of daylight will be explored more in detail in section 3.7.

Architectural integration of natural and electric lighting is also an important issue to take into account especially in the early stages of design. The pattern of light can enhance the building form and space. The new British Library in London is a good example of the designer's attempt to create a symphony of daylight and electric light in harmony with the interior space and building forms. Appendix C explores the integration of daylight and artificial light and their harmony with architectural form and space in the library. There are, of course, a number of examples where daylighting and its patterns have enhanced the appearance and aesthetics of the space. Appendix B also represents a few examples of Modern architecture which are known by their daylighting novelty.

Fig 3.5. Interior space of the New British Library (Photos © F. Ai)

Lighting and energy efficiency is also another important aspect of lighting design in schools as an efficient use of energy reduces primary energy consumption and hence lower carbon dioxide emissions. And finally, lighting maintenance should be considered in lighting design as well. Poor maintenance reduces the illumination levels of the luminaires and also causes energy waste.

3.7. Aspects of daylight and schools

There is a significant amount of research on the impact of learning environment and more specifically the impact of daylight on student performance. This section reviews the literature on these issues and then reviews other aspects of daylight and schools such as the energy performance of daylit schools.

3.7.1. Learning environment and student performance

> *Good design is not just about the aesthetic improvement of our environment, it is as much about improved quality of life, equality of opportunity and economic growth ...Good design does not cost more when measured across the lifetime of the building or place ...* (CABE 2002)

Feilden (2004) advocates the need for evidence to demonstrate that '*well designed*' new educational buildings provide better academic results than '*poorly designed*' ones to ensure that new schools offer genuine value for money through improved functionality, performance of pupils, and recruitment and retention of staff. This section attempts to bring together the evidence from research findings in support of the correlation between school buildings and student performance particularly in respect of daylighting. Jago & Tanner (1999) argue that the visual environment affects a learner's ability to perceive visual stimuli and this, in turn, affects his/her mental attitude which consequently should affect their performance. Daylighting is clearly an important factor in the visual environment.

It is important to mention that typical school buildings and classroom layouts vary between countries as they respond to local understanding and philosophies of education and material resources (Alexander 2000). In a study of 30 primary schools in five countries, Alexander finds some interesting and consistent differences among schools. For instance, he identifies the contrast of *'a great deal of light'* in all the Russian classrooms comparing with some British and American classrooms *'so inadequately fenestrated that they require artificial light throughout the day'* (ibid, p.185).

However, most of the published research concerned with the effect of the learning environment on students has tended to be carried out in the Western Europe and, particularly, in the USA (Higgins, Hall et al. 2005, p.10). Clark (2002, p.8) acknowledges that there is as yet no equivalent body of research in this field in the UK as that in the US. There is not enough evidence in the UK of the way in which design or architectural ideas directly affect school performance except a few generalized projects (CABE 2002; CABE/RIBA 2004).

Although recent building bulletins produced by DfES promote more imaginative school buildings, it seems many of the new buildings are planned along conventional lines. Jamieson et al (2000) argue that this conservatism is due to the lack of participation of users in the design of educational facilities. Therefore, in response, a number of instruments and tool kits have been devised to encourage students' and staff's participation in the design process (Seymour, Cottam et al. 2001). Although the participation of students and staff in the school design process is an important issue to address, this research is more concerned with physical factors of learning environment, and thus discuss primarily on US research.

The fundamental aspects of physical environment such as heating, acoustics and lighting have been mostly researched in isolation. Many reviews of the effect of the physical school environment on learning such as Weinstein (1979), Gump (1987), Fisher(2001), Clark (2002), Schneider (2002) and Earthman (2004) have researched a specific factor of the physical environment in schools and have drawn conclusions about the effects of the particular physical characteristic on the learning environment. However, it is important to consider the possible interactions of different factors as they all contribute to the whole learning environment (Hygge and Knez 2001). In addition, it is also important to be aware of some conflicting recommendations which could arise from individual research on physical environment factors.

3.7.1.1. Temperature and air quality

Temperature and the air quality are related to daylighting as they are all related to windows in general. They are important factors affecting students' comfort and their performance. Earthman (2004) considers temperature, heating and air quality as the most important individual elements for student achievement. There are a number of research findings highlighting the importance of temperature and air quality and its likely effect on student performance (Fisher 2001; Schneider 2002; Young, Green et al. 2003; Buckley, Schneider et al. 2004). Most of these studies have been conducted in the USA and considering the given climates (which are generally hotter than Europe in the summer) an increased use of air conditioning has been recommended. However, it is important to remember that air-conditioning, ventilation and heating systems could contribute to the levels of noise in classrooms which is not desired

(Schield and Dockrell 2004). This is an example of conflicting recommendations from individual studies on physical elements.

The inadequacy of air quality in classrooms has been an issue which is addressed in a number of surveys and reports (Khattar, Shirey et al. 2000; Kimmel, Dartsch et al. 2000; Lee and Chang 2000). The effects of such inadequacy have been also correlated to ill-health of students (Ahman, Lundin et al. 2000). Air-related health problems is investigated more thoroughly and in a study by Rosen and Richardson (1999) poor air quality has been correlated with absenteeism. They found out that improving the air quality in a nursery school by clearing the air and reducing its particles resulted in a reduced child absence. However, the demand of fresh air into classrooms can conflict again with the outside noise which should be taken into account.

3.7.1.2. Noise and Acoustics

Noise is also related to daylighting as it is also a factor associated with windows and openings. There is considerable literature regarding the effect of noise on human functioning, with some related to children in noisy learning environments. Such research addresses noise annoyance, distraction and direct masking of cognitive process (Poulton 1978; Salame and Wittersheim 1978). Stansfeld and Matheson (2003) discuss the possibility of noise-related psychological and health problems and conclude that '*the evidence for effects of environmental noise on health is strongest for annoyance, sleep and cognitive performance in adults and children*' (p.253).

There is supporting research which addresses the link between noise and its effect on children in learning environments. Hygge (2003) reports that various noises such as recordings of road traffic, trains or aeroplanes appear to interfere with the encoding stage of memory. In a study on children exposed to aircraft noise in a learning environment, some evidence of raised blood pressure and signs of learning distraction was found (Cohen, Evans et al. 1980). As a result of these studies as well, as other supporting research such as Evans & Maxwell (1997), Haines et al. (2001), and Lercher et al. (2003), it can be concluded that noise and acoustics are important factors in a school environment. Schneider argues that in general the research is consistent and convincing and summarizes that good acoustics are fundamental to good academic performance (2002, p.6).

Good acoustics, of course, calls for design solutions to absorb and dampen the noise. Examples are increased carpeting, sound amplification systems and ceiling hangings to dampen reverberation (Maxwell and Evans 2000). It is interesting to mention that ceiling hangings have been used as early as 1831 in the UK (Seaborne 1971). However, in 21st century there are a number of ways of dampening the sounds in a classroom such as perforated profile metal absorbers, acoustic fibreboard panels, suspended baffle noise absorbers, acoustic strandboard and general acoustic absorbers (DfES 2006, P.40).

3.7.1.3. Colour

Colour is also a significant factor of the physical environment which affects students in different ways. It is also related with daylighting as means of perceiving and accentuating colour. Different colours are considered stimulating depending on the age of children. Engelbrecht (2003) argues that younger children prefer bright colours while adolescents prefer more subdued colours. On the other hand, Pile (1997) warns against using intense primary colours for young children while he suggests using strong warm colours instead.

Research findings in the literature indicate a positive correlation between colour in classrooms and students' behaviour and performance (Bross and Jackson 1981). The colour of surroundings has a distinct impact on children's mood and behaviour through changing perceptions to room size and temperature (Sundstorm 1987). It is also asserted that colour and ceiling height affect children's cooperative behaviour (Read, Sugawara et al. 1999). Engelbrecht (2003) argues that the colour of walls in a classroom can affect productivity and accuracy and, more specifically, Brubaker (1998) maintains that cool colours help concentration of students. Other research carried out by Hamid & Newton (1989) suggest children demonstrate more physical strength and positive mood in a pink coloured room rather than cool colours such as blue. On the other hand, Schauss (1985) argues pink has tranquilising effect on adults and it can be used to prevent aggression in individuals.

Although there might be some conflicting findings on the effect of colour and children's mood in the research, there is no doubt it is an important factor in a classroom's physical environment. In a study, Burke and Grosvenor (2003) emphasise the importance of colour and children's preference for colours in their classrooms. One of the common problems reported in the classrooms is eye fatigue which could be relieved with a better understanding of colour in schools. Engelbrecht (2003) suggests that the end wall of the classroom behind the teacher should be a different colour from the other walls. Pile (1997) also supports the idea and suggest the other walls could be neutral colours. It is also suggested that the use of yellow, beige or off-white surface colours can stimulate learning while light blue, green and lavender can be calming, but some vibrant colours can over-excite and have a negative effect on learning (DfES 2002, p.36)

On the other hand, Nair and Fielding (2005, pp.77-82) challenge some general notions about the use of colour in schools. They believe children are wonderfully sensitive and responsive to nuances in colour and lighting and they are particularly attuned to the colours of nature and human skin tones (ibid, p.80). Therefore, they argue the use of primary colours in schools is harsh and should be used with caution. They also debunk the notion of using neutral colours in learning environments and argue it has resulted in *a period of architectural history often considered as soulless* (ibid, p.81). Nair and Fielding (2005) innovative approach toward the use of colour in learning environments is mainly based on their design experience at FNI (Fielding Nair International, one of the leading change agents in school design) and are not substantiated through research evidence. Therefore, there is a need for more research in colour aspect of schools to make the most of its effects on student's mood and performance.

3.7.1.4. Lighting

One of the most critical characteristics of the physical environment of classrooms is lighting. Dunn (1985) insisted that the lightning of a school should be considered an active element of the total educational environment. The research in lighting area relates to two different kinds of lighting; daylight and artificial. There is extensive research on daylight and its effect on student performance which will follow in the next section. However having daylight solely in a classroom is not practical due to weather changes and early morning and dusk-time classes.

Benya (2001, p.1) suggests that for *'lighting to be effective, daylight should be supplemented by an automatically controlled electric lighting that dims in response to daylight levels'*. In addition to the type of light source, there is also the way light is admitted, either directly or indirectly which were defined in previous chapter. Barnitt (2003) suggests that good lighting can only be achieved by a combination of direct and indirect lighting. Such combination creates variety and interest which should be aimed rather than an even flat light (DfES 2002, p.37). In terms of artificial light, full spectrum lighting is preferable as it has higher Colour Rendition Index (CRI) comparing to fluorescent lamps. However, polarized lenses are designed to filter fluorescent lamp and improve its quality. Fluorescent lamps can now even be provided with a high-frequency solid-state ballast which completely removes the flicker problem (Stone 1992, p.59).

Karpen (1991) supports the combination of full-spectrum lamps with polarized lenses as the result resembles daylight in terms of spectral energy distribution and light polarization characteristics. *"The lighting has been found to match natural daylight so closely that one cannot tell the difference between the artificial illumination and any light entering the windows. There is none of the eyestrain and fatigue typical of conventional cool-white illumination, which dives fluorescent lamps with core coil ballasts in unpublicized fixtures."* (ibid, p.36) The main problem, though, is they are quite costly and have not been widely accepted commercially.

Nonetheless, research in schools favours daylight over artificial lighting as its light quality is more appropriate for human visual tasks (Heschong-Mahone-Group 2003). Light quality is a holistic term and includes a number of attributes of the lit environment that are generally considered to be favourable. For example, daylight has better distribution of light, better colour rendition, and there is no flicker comparing to electric light (ibid, p.26). These factors highlight the importance of using daylight in classrooms.

Lighting is also related to occupants' health issues in the research review. The most common complains of children in classrooms such as headaches, eyestrain and fatigue are related to inappropriate lighting conditions (Higgins, Hall et al. 2005, p.20). In terms of electric lighting, Karpen (1993) suggests the use of full spectrum polarised lighting which is free from glare and flicker to overcome above symptoms. The idea of glare free electric lighting is important due to increased use of ICT in schools (Barnitt 2003). In terms of daylight, glare issue and ways of overcoming it are not a new concern and has been addressed frequently over the last century. Donovan (1921) gave suggestions of desks alignments and use of blinds to overcome glare issue. There is more evidence on the impact of daylight on students' health and performance which will be discussed in the next section.

3.7.2. Daylight and student health and performance

Daylight has long been associated with health and well being in general. Inappropriate lighting quality could cause health problems. The phenomenon of Sick Building Syndrome (SBS) is particularly associated with deep plan air-conditioned buildings, and lighting quality, particularly spectral composition, flicker and glare, is thought to be one of the combination of contributory factors (Baker, Steemers et al. 1993). However, the lack of quantity of light also could cause serious health concerns. Seasonal Affective Disorder (SAD) is directly related to light deprivation. Daylit buildings, due to the non-uniformity of illuminance in both time and space, usually provide sufficient illuminance to trigger the physiological processes necessary to avoid the syndrome (ibid, p.18).

There is extensive research on the impact of daylight on student performance. This supports the idea that natural daylighting provides a learning environment in which students are more productive academically and even stay healthier. Perhaps the largest study in this area of knowledge has been conducted by Heschong Mahone Group (1999) in which a positive correlation has been established between daylight and students' performance.

This study focused on skylights, as a way to isolate daylight as an illumination source from other qualities such as view that are associated with side windows. The test score results for over 21000 elementary students from three districts in the USA were analysed and it was found that students with the most daylighting in their classrooms progressed 20% faster on math tests and 26% on reading tests in one year compared to those with the least daylight. Students in classrooms that had a well designed skylight which diffused the daylight across the room and in which the amount of light was controllable improved 19-20% faster than those students without a skylight (ibid, p.2). These results support the proposition that there is a valid and predictable effect of daylighting on student performance (ibid, p.3).

One specific finding of the above research is its focus on the daylighting aspect alone. It attempts to exclude other attributes of windows such as view, communication, ventilation, etc. The findings of the research (Heschong-Mahone-Group 2003) strongly suggest that there is a specific effect attributable to daylight as opposed to a window effect in general, and that the amount of daylight provided in classrooms is important.

In addition, there are some rigorous studies carried out in Europe which investigate the impact of daylight on the behaviour and health of primary school children. In Sweden, Kuller and Lindsten (1992) investigated the health, behaviour and hormone levels of 88 primary school students in four classrooms over the course of a year. The classrooms had different daylight and electric light conditions. They found significant correlation between daylight levels, hormone levels, and student behaviour and concluded that windowless classrooms should be avoided. They concluded *'work in classrooms without daylight may upset the basic hormone pattern, and this in turn may influence the children's ability to concentrate or co-operate, and also eventually have an impact on annual body growth and sick leave'* (ibid). Hathaway et al (1992) goes further on the aspect of lighting and found a correlation between lighting and incidences of dental cavity and gains in height and weight. They have also linked lighting to absenteeism (although Heschong Mahone Group (2003) does not support the link between lighting and student attendance).

In an earlier study, Tikkanen (1970) examined 400 students averaging 16 years old in five Swedish schools. He found that in the northern classroom environment of mixed daylight and electric light, the reported incidence of eye fatigue was significantly higher than in a classroom with only skylight compared to a classroom with regular side-window at eye level sitting position. This study highlights the importance of other attributes of daylight such as the view from windows, in terms of student performance.

The view element of the window and its content also has an impact on student performance. In a study on the behaviour and attitude of the school students towards daylight and fenestration in 350 primary schools in the UK, Stewart (1981) found that a significant proportion of the students chose to sit or work near windows, with the main determining factor being the amount of daylight. However, he also found that the view content and the visual and thermal comfort were also important factors in choosing the favourite window of the classroom. Visual comfort, in this research, is associated with natural scenery and greenery compared with a view to urban buildings. All in all, the impact of daylight on student performance is one of the main reasons to encourage designers and stakeholders to consider daylight as the main source of illumination in schools. Other reasons will be discussed in the next section.

3.7.3. Daylit schools and energy performance

Natural daylighting not only provides better learning environments, but also provides schools with dramatic energy savings. According to the US National Centre for Educational Statistics, 72 percent of the cost of energy in educational buildings is consumed on electricity of which the majority (56 percent) goes toward lighting (Digert 2002). Therefore, by using daylighting as the main source of illumination in schools in combination with lighting controls and dimming systems, schools can reduce or eliminate electric lights during daylight hours. These findings are not directly transferable to other climates and countries.

As an example, a study analyzed the energy performance and cost of daylit schools designed by Innovative Design in Johnston County, North Carolina, where a series of schools replaced electric lights with daylighting (Nicklas and Bailey 1999). The daylit schools in the study indicated energy cost reductions of 22% to 64% as compared to typical schools (ibid, p.4). The study concluded daylighting, even excluding all the productivity and health benefits, is worth investing in from a financial point of view. Daylight measures cost less than one percent of the construction budget which is paid back with three years of school life while the long term benefits to schools and students are enormous (ibid).

3.8. Specific features and principles of daylighting in schools

There are specific features about daylight in schools that makes it different from other buildings. The reason behind the specificity of daylight in schools is the educational nature of the building which requires appropriate illumination for reading and writing as well as providing a healthy, stimulating and inspiring space for children to learn. One of the first principles of daylighting in schools is to avoid glare in teaching spaces (DfEE 1999). This requires preventing direct sunlight penetration and avoiding other sources of glare such as a glaring view such as the bright sky or a contrastive window wall colour. Instead, a uniform and gentle daylight is preferred for teaching and task based spaces.

On the other hand, Lam (1977) argues that a constant and even light condition does not benefit the human state and also omni-directional light, especially top-light, is also identified as being negative to how people work as it affects focus and concentration and has even been described as lowering mood. So it is important to avoid a constant and even daylight distribution in all school spaces. Non-uniform daylight and patches of sunlight could enhance the appearance and visual amenity of non-task based spaces such as corridors or atria. The National Best Practice Manual (CHPS 2006) elaborates on the principles of daylighting in schools which is summarized in table 3.4.

The location of daylight apertures has significant impact on causing glare as well as distribution of light throughout the classroom. When daylight apertures are located in the ceiling, the likelihood of glare is reduced as long as the glazing cannot be seen directly from normal viewing positions. Besides, the evenness of distribution of light is increased. It is more difficult to achieve uniform illuminance with windows as there is more quantity of light next to them (CHPS 2006). While The National Best Practice Manual tends to suggest skylights and general top lighting for classrooms because of their efficiency in terms of an even distribution of light, Building Bulletin 90 in the UK highlights the importance of the directional properties of light from side windows to provide a better quality of light.

	Basic Daylighting Principles	Reasons & Practical Solutions
1	Prevent Direct Sunlight Penetration	To avoid visual & thermal discomfort Except in non-task based areas
2	Provide Gentle, Uniform Illumination	Balanced diffuse daylight across the space Use walls & ceiling as reflective surfaces Use light coloured surfaces to help reflection Use daylighting systems such as light shelves
3	Avoid Glare	Avoid excessive high contrast which causes glare Obscure bright views by blinds, louvers, etc. Place daylight apertures next to reflective surfaces Use splayed window reveals or skylight wells Avoid punched small windows in the middle of a wall
4	Provide Control of Daylight	Devise variable apertures that respond to daylight changes or use blinds and shades inside or outside Provide teacher's access to blinds or shades controls
5	Integrate with Electric Lighting Design	To create high quality lighting & produce energy savings
6	Plan the Layout of Interior Spaces	Locate work areas where appropriate daylight exists from sides or above

Tab 3.4. Basic daylighting principles and practical solutions, after (CHPS 2006)

The flow of light across the room provided by side windows should not be underestimated as it is a significant attribute contributing to the modeling of the interior space, including objects within it and of course surface textures (DfEE 1999, p.19). It is worthwhile at this stage to compare and contrast the National Best Practice Manual daylighting principles in Tab 3.4 with the daylighting design guidance suggested by the Building Bulletin 90 in Tab 3.5.

There are more similarities than differences between table 3.4 and 3.5. Avoiding glare, providing a balanced luminance distribution in classrooms and providing sunlight control are the main principles in common between two sets of guidelines. However, the National Best Practice Manual daylighting principles (Tab 3.4) emphasizes on the provision of a uniform and even distribution of daylight in classrooms while the Building Bulleting 90 (Tab 3.5) points out the directional properties of sunlight should not be underestimated as it gives a unique character and variety to the quality of the daylit environment. This should be carefully applied in classrooms as excessive directional sunlight could increase the contrast in the learning environment and hence could cause discomfort glare.

	Daylighting Design Guidance	Features & Practical Solutions
1	Provide sufficient daylight quantity	Use of rooflights and clerestories to improve distribution of light in the space
2	Daylight quality	Offering a unique character to an interior Distribution of light enhances the visual field Directional properties of light from side windows are a significant attribute contributing to the modeling of the interior and providing brightness to vertical surfaces
3	Avoid Glare	Avoid glare to provide a balanced luminance distribution (some contrast but not excessive) Windows on chalkboard wall should be avoided Reduction of sky luminance by shading devices Reduce the contrast between the windows and their surroundings by using, for example, splayed light coloured reveals or increasing the brightness of the window wall by increasing its reflectance or using a window in an adjacent wall
4	Sunlight control	Using shading devices to provide some protection from excessive direct heat and glare Solar control devices should be placed outside the window for optimum sun protection
5	Exterior visual contact	To avoid claustrophobia and provide visual relaxation & view

Tab 3.5. Daylighting Design Guidance, after (DfEE 1999, pp 19-22)

Having discussed the specific features and principles of daylight in schools and specifically classrooms, the next question is how daylight is applied to schools and classrooms. In other words, having known the principles of daylighting in schools what daylighting systems are available to be utilized.

3.9. Daylighting systems in schools

There are generally three main ways by which daylight is admitted to a room: through the side of the room namely as *sidelighting*, through the ceiling namely as *toplighting* and also through another lit area of a building such as atria namely as *borrowed lighting*. Sidelighting, however, can be divided into view windows and clerestories (Fig 3.6). Side windows have the advantage of a view to the outside when the sills are beneath eye levels. A general rule of thumb for daylight penetration in a room is about 1.5 times the window head height; therefore, a separate high side window can be used to bring the daylight deeper into the room.

Clerestory windows (b in fig 3.6) admit light from the brighter part of the sky and therefore, it increases the contrast between inside and outside which could cause glare (DfEE 1999, p.9). Rooflights (c in fig 3.6) admit the light from the highest part of the sky which is generally unobstructed. They also need careful consideration in terms of glare from contrast if the glazing is visible from normal viewing positions. Exterior or interior shading devices should, then, be used to obstruct the direct view to the bright sky. However, they provide more even daylight when equipped with shading or diffusing devices. And finally, borrowed light can contribute to the light levels in darker areas of the rooms away from window walls. Daylighting components and further categorization of them have already been discussed in chapter 4 while specific systems which enhance reflected daylighting will be discussed in chapter 5.

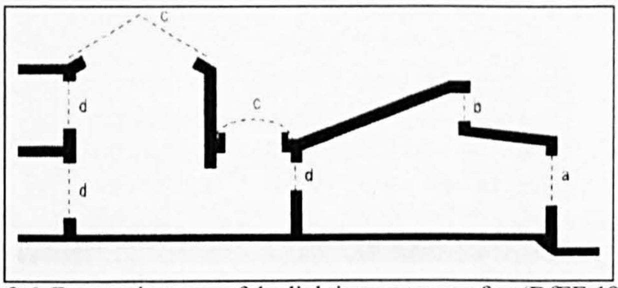
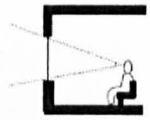
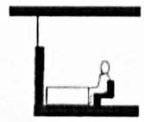
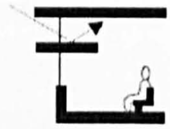
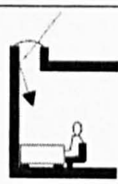
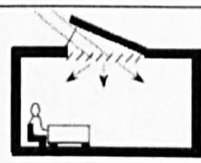
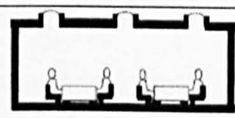
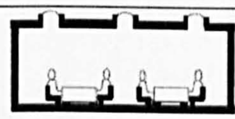
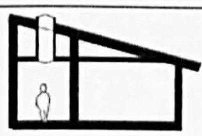
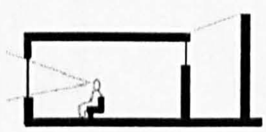


Fig 3.6. Four main types of daylighting systems, after (DfEE 1999)

The above daylighting systems are a general description and can apply to different buildings including schools. However, daylighting systems and classifications can be more specific because of the nature of schools and classrooms. The national best practice manual (CHPS 2006) provides a detailed daylighting guide for schools, with their applicability to different parts of a school as well as different climates of the United States. The climatic classification is varied from cold and humid, temperate and humid, hot and humid, hot and dry and cool and dry. It is comparable to the varied Iranian climate which is already discussed in the previous chapter.

Although it identifies 8 types of sidelighting and toplighting strategies in schools, it does not address borrowed lighting which is an important option for deeper and darker parts of classrooms. Borrowed lighting is, therefore, added to the National Best Practice Manual classification which is summarized in Table 3.5. The table describes each daylighting system briefly and shows which part of a school building they can be applicable. Most of these systems need to be considered in the early stages of design to provide their full benefits.

	Daylighting Systems	Description & applicability	Illustration
SIDELIGHTING	**1. View Windows**	Vertical glazing at eye level Essential in most school spaces Applicable in all climate regions	
	2. Clerestory (High Sidelighting)	To increase daylight penetration Can be used in all school spaces Applicable to all climate regions	
	3. Clerestory With light Shelf	To improve daylight distribution It keeps the contrast and glare low Applicable to most school spaces and all climate regions	
TOPLIGHTING	**4. Wall Wash Toplighting**	Daylight through a linear skylight or monitor to wash an interior wall To balance daylight from window walls Applicable to classrooms, libraries, etc. Applicable in all climate regions but must be planned in schematic design	
	5. Central Toplighting	To provide high levels of even daylight Daylight is diffused by glazing or baffles Applicable to single story or top floor classrooms, libraries, multipurpose spaces & administration offices Applicable in all climatic regions	
	6. Patterned Toplighting	To provide low glare even illumination across large spaces such as the gym, or Library, multipurpose or cafeteria Applicable in all climatic regions	
	7. Linear Toplighting	To provide high intensity daylight Suitable for walkways or large spaces Applicable in all but hot climate regions unless provide diffused or shaded light	
	8. Tubular Skylights	Clear domes skylight with reflective ducts, Suitable with areas with deep roof cavities, Applicable to small spaces such as toilets, kitchen, etc. All climates	
	9. Borrowed Lighting	To illuminate the deep end of classrooms remote from window wall Applicable in spaces near an atrium and all climatic regions	

Tab 3.6. Daylighting systems in schools, based on (CHPS 2006)

3.10. Conclusion

This chapter has emphasized the importance of daylighting design on the overall quality of schools. Having reviewed the history and development of daylighting in schools, it has explored different aspects of daylight influencing schools such as student health and performance as well as energy performance of the building in general. It has finally delivered some guidelines and principles of daylighting in schools which is useful for school designers. This chapter is finished with a specific daylighting system classification which is suggested to be used in school buildings.

Next chapter will review different approaches to daylighting including quantitative vs. qualitative or typological vs. phenomenological and will propose an integrative approach which intends to bridge the gaps in individual approaches.

CHAPTER 4: APPROACHES TO DAYLIGHTING

4.1. Introduction

> *Daylight is a gift of nature. As civilised man learns to use artificial light sources which free him from total dependence on daylight, he also learns to appreciate the value of daylight and become aware of its special advantages .*

Natural light was the main source of illumination in buildings before the advent of electricity. It has always played a dominant role in architecture, both to reveal the architecture of the building and to create a particular atmosphere as well as to provide the occupants with visual comfort and functional illumination (Baker, Steemers et al. 1993). Daylighting remained the primary means of lighting to all types of building until the early twentieth century when the primary role of daylighting was beginning to be questioned in relation with electric light (Phillips 2004).

By the beginning of 20^{th} century daylight was in competition with the various forms of artificial light, up to the point when it appeared to be irrelevant, having as its nadir the development of '*Burolandschaft*', when buildings lit by artificial light sources could be of indefinite depth and, as we have seen, some schools were built without any windows at all (ibid, p.xix). By 1960s the concept had grown that artificial lighting would supplant natural light as the primary source during the day in many situations including schools. It was not until the energy crisis, and the realization that our reliance on fossil fuels had limitations, that people started to question this high energy approach, and began to look at ways to reduce the electricity load in building; one of more obvious ways was to return to an understanding of the natural resource of daylight (ibid, p.5).

There are many reasons for the renewed interest in daylighting. The most convincing reason is the increasing cost of fossil fuels and the realization that sources of electricity have a finite life; but perhaps even more important are the less tangible aspects of daylighting which relate more to the human spirit and the need for the quality of life (ibid, p.xix). Steemers (1993) reinforces these two factors in favour of daylighting: The first, he argues, is the growing understanding that the energy use involved in the provision of artificial lighting contributes significantly to global environmental pollution, and secondly that the deprivation of daylight may have detrimental physiological and psychological effects on the occupants of buildings (ibid, p.1). Philips (2004, p.5, 6) draws attention to the importance of daylight and the association with natural environment in his study by highlighting still more reasons for using natural light. These can be summarised as follows: the need for functional light for visibility; the aesthetic appearance of natural light and space; an innate desire for variety and the changing light; the sense of natural orientation and wayfinding; the natural view and its content; the experience of natural colour and light; and the use of natural ventilation.

4.2. Historical Background

> *"...Architecture is the masterly, correct and magnificent play of volumes brought together in light... The history of architecture is the history of the struggle for light."*
> (Corbusier 1989)

Philips (2004) also argues the history of architecture is synonymous with the history of the window. The initial crude opening was the vehicle for the introduction of daylight, letting in light, air, heat and cold. The window has developed over the centuries, but its purpose of letting in daylight has remained its primary role (ibid, p.3). It has developed through centuries and has allowed different admissions and applications of light to buildings through history.

The earliest civilisations had a relationship with light that is still with us today. At the fundamental level the seasons are controlled by direct light – the sun's changing path throughout the year is as much a part of the cycle of the year as the seasons themselves (Hodges 2002). In Ancient Egypt, too, there was a strong relationship with the sun – spaces that allowed shafts of light only to penetrate at the particular times of year and the use of gilding and other bright materials underline the importance that such things had in the religious rites (Mann 1993). Light was a metaphorical element that focussed worshippers on the power of higher things, and its importance in rites were well understood.

The significance of light was again highlighted in Baroque architecture, in which light is a central concern. Baroque architecture enables a more imaginative control of light introduced between the overlapping layers of the enclosure. The use of mysterious light and indefinite special enclosure signifies transcendence (Baker and Steemers 2002). Indirect natural lighting is explored extensively in Baroque architecture where the sources of light are not visible and it creates a dramatic effect.

Fig 4.1. Toledo Cathedral in Spain, Narciso Tome (Plummer 1987)

A further innovative means of daylighting was developed for the lighting of the Baroque churches of Southern Germany, where 'indirect' daylight onto the ornate decorations and ornaments of the church is gained from windows concealed from the direct view of the congregation (Phillips 2004).

Fig 4.2. Pilgrimage Church in Zwiefalten, (Plummer 1987)

The invention of glass had a crucial influence on the evolution of the window in the pre-industrial period. Windows began to be larger and by the 16th century the widespread celebration of the window can be seen (Baker, Steemers et al. 1993). The industrial revolution brought the most rapid changes in both the requirements and the solutions for daylighting. A whole architecture of light and air was born. However, the development of fluorescent lighting marked the end of an era where daylighting was at least a design aim. Fluorescent lighting gave at least a fourfold increase in lighting efficiency over tungsten lighting, thus reducing running costs and heat gain sufficiently for designers to abandon daylighting altogether. High artificial illuminance together with the move to open plan, led to the monotonous working environment of the air-conditioned office (ibid, p.15).

In summary, 70s and 80s could reasonably be described as the dark ages in non-domestic buildings since daylighting design became a neglected if not forgotten art. Many technical developments have occurred in the last decade, which increase the application potential of daylight. These include innovative component design such as light ducts and light-shelves, and also new materials which can be used to control and redirect light (ibid, p.17). These innovative daylighting components will be expanded in the next chapter.

4.3. Principles of light and daylighting

By the time of the Renaissance two words were used to describe light: *Lux* and *Lumen*. Although the terms have quite distinct and clear definitions today, in the past they were defined more ambiguously as follows (Barker 2002, p.14):

> *Lux is the natural property of luminous bodies that imparts a motion similar to that of the body to which it belongs. This movement is its essence and does not depend on anything else intrinsic in the body. Lux was given its existence by the Creator at the act of Creation of the world...Lumen namely the illuminating light is the image of the light itself that is to say of lux, and its derivation is of a primary nature (Ronchi 1970).*

In these terms Lux signifies the emotional and phenomenal response to light and cannot be measured. Lumen on the other hand refers to the light one can see and which thus can be measured, and is more tangible than Lux. *Lumen* and *Lux* could be constructed to represent the rational and the emotional, or the scientific and the poetic aspects of light (ibid, p.14). This dualistic aspect of light has been a fundamental debate throughout the ages. However, with the advancements in science and human knowledge since Renaissance, there are various scientific units and terms for quantifying light in our modern time.

Light is a flow of energy and is a part of electromagnetic spectrum. As there is no one-to-one link between the spectral distribution of radiation and human perception of brightness and hue, light is uniquely defined by the response of the human eye (Tregenza 1998). However, it has its own set of units which allows it to be quantified. These units are four interrelated units which describe the flow of light or luminous flux (Lumen), its intensity in space or luminous intensity (Candela), Illuminance at a point (lux) and the brightness or luminance of a surface (cd/m2) (ibid, p.3-5). Illuminance is the density of a luminous flux incident on a surface which is measured in lux (lumens per square meter) whereas luminance or brightness is the product of illuminance and reflectance which is measured in candela per square meter (Moore 1985, p.19).

In other words, *lumen* is the unit of light/energy as perceived by the human eye and *lux* is the unit of *illumination*, or spread of light. The spread of light is measured across horizontal surfaces, the working planes, and while this is an excellent indicator of such spaces it gives less insight into the experience of the spaces (Hodges 2002, p.7). Demers (1997, p.48) argues that the horizontal plane is inapplicable to spaces that were about the spiritual. Hopkinson also points out the deficiencies of the mere scientific approach and describes the use of the human being as a meter from which information can be collected (Hopkinson 1963). There is another factor which is important to describe for quantifying daylight in a room, namely the daylight factor.

4.3.1. Daylight Factor (DF)

> *Daylight factor is the percentage of the horizontal diffuse illuminance outdoors from an unobstructed sky hemisphere which is received at a point indoors under a CIE Standard overcast sky (DfEE 1999, p.15).*

As a window does not give a steady flow of light, unlike electric lamps, the illuminance in a room depends on the brightness of the sky (Tregenza 1998, p.37). Therefore, the level of daylight in a room is specified by *the percentage of interior to exterior illuminance* which is called daylight factor (DF) (ibid). Moore (1985, p.22) defines daylight factor as *a ratio of interior to exterior illuminance under an overcast, unobstructed sky* (measured in a horizontal plane at both locations and expressed as a percentage) and remains constant regardless of changes in absolute sky illuminance. The daylight factor is usually calculated on the horizontal working plane. It is a valuable factor as it can predict the likelihood of daylit appearance of an interior space.

Daylight factor has three components: first component is directly received from the sky known as Sky Component; second component is received by reflection from external surfaces (Externally Reflected Component); and the last component is received by reflection from interior surfaces (Internally Reflected Component) (DfEE 1999, p.15). Daylight factor varies depending on a number of parameters such as the size and disposition of the window, the dimensions of the space, the reflectance of interior surfaces and the level of external obstruction. If the average daylight factor is 5% or more, the interior is considered well daylit and no electric lighting is requires. On the other hand, if the average daylight factor is below 2% it is not sufficiently daylit and the interior is dependant on electric lighting. However, if the average daylight factor is between 2% and 5% then some electric lighting will be required in autumn and winter (ibid, p.15). Figure 4.3 illustrates the concept of daylight factor and its three components.

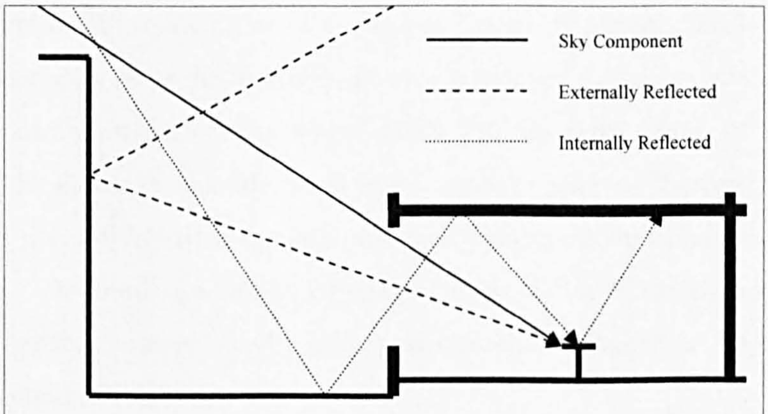


Fig 4.3. Daylight factor components, after (DfEE 1999, p.15

As daylight factor is described as a percentage ratio, it ensures constancy between the light outdoors and the light indoors. Therefore, it expresses the efficiency of the lighting of an internal space. However, daylight factor is insensitive to both the prevailing local climate and building orientation. The next section introduces advanced climate-based daylighting modelling which can replace daylight factor.

4.3.2. Useful Daylight Illuminance

Daylight factor approach offers only a limited insight into true daylighting performance of buildings because it is based on a measure of illumination under the CIE standard overcast sky (Mardaljevic and Nabil 2005, p.41). Daylight factor is invariant to building orientation as it does not take into account the illuminance from the sun and non-overcast skies. Despite its lack of realism, daylight factor has been used extensively in design manuals and CIBSE guidebooks over the last 50 years (ibid, p.41). However, advances in computer simulations allow a new approach to daylighting measurement and analysis which is based on hourly (or sub-hourly) predictions of internal illuminance for a full year (Mardaljevic 2000).

Hourly, or sub-hourly, predictions of daylight illuminance under variable sky and also sun conditions can provide a realistic measure of the true daylighting performance for an internal space (Mardaljevic and Nabil 2005, p. 42). This new schema for assessing daylighting potential is called 'Useful Daylight Illuminance' or UDI and is based on time-varying annual illuminance data of internal spaces. The new schema abandons the notion of target illuminance such as 300 lux for general teaching spaces and, instead, determines the occurrence of a range of illuminance levels across the working plane. For example, if the daylight illuminance is below a minimum in a classroom, it may not be useful in performing visual tasks. On the other hand, of the daylight illuminance is above a maximum, it may cause visual or thermal discomfort. Illuminances that fall between the minimum and maximum are called *useful daylight illuminances*. The minimum and maximum illuminance levels are based on a survey of occupant behaviour in daylit office environments under a wide range of illumination conditions (ibid, p.47).

Daylight illuminances below 100 lux are considered insufficient as the only source of illumination, while illuminances between 100 and 500 lux are considered effective either as the only source of illumination or in conjunction with artificial lighting. Daylight illuminances between 500 and 2000 lux are perceived as desirable or at least tolerable, while illuminances levels over 2000 lux are intolerable. Therefore, in evaluating time-varying daylight illuminances across the working plane, *useful daylight illuminance* is said to occur whenever all the illuminances fall within the range of 100-2000 lux (Mardaljevic and Nabil 2005, pp.48-49). The UDI paradigm is ideally suited for the assessment of any building design where daylight redirection is a feature (ibid, p.55).

4.4. Approaches to daylighting

4.4.1. Quantitative vs. Qualitative

Two broad approaches to daylighting can be identified: the quantitative/scientific and the qualitative. There has been a considerable amount of research undertaken in the scientific field of daylighting in recent decades. Most of these studies focus on the amount of light required on the working plane in different work places, and are thus mainly concerned with the quantity of light. On the other hand, some design orientated researchers focus on the phenomenal impact natural light might have on the occupants; these are more concerned with the qualitative aspect of light. The second approach explores the patterns of light in space and their impact on human perception, while the first attitude is mainly objective and deals with figures and numbers rather than people's moods and the inspirational and psychological use of light. Therefore, there is a gap between these two main bodies of daylighting research which has been addressed in a few recent studies. Thus, Demers (1997) investigates on how to bridge this gap between the art of light and science of lighting.

Robins (1986) asserts that daylighting is both an art and a science which means daylight is both an environmental system as well as a design element. As an environmental system, it should be subjected to the same level of rigorous analysis and review that any environmental system receives. As a design element, it can enhance aesthetic and qualitative aspects of a building. To work as a design element, it must be made an integral part of one's design philosophy (Robins 1986, p.3).

4.4.1.1. The Quantitative approach

Part of the quantitative approach is already covered in the principles of daylighting section (4.3) as it is concerned with the measurement of light in a space in relation with the human eye requirements. The science of lighting is a relatively modern development and is geared toward better understanding of the nature of light in order to allow better lighting of different spaces. The work done in these fields has fed into guides and regulations for lighting for different building types. The direction of such analysis is generally concerned with the working environment, comfort of vision and the sufficiency of light to perform tasks (Hodges, 2002, p.6). The primary goal of this approach is not architecturally engaging or concerned with beautiful execution of that solution, but it merely conforms to providing the quantity of light required (ibid, p.6).

Lighting specifications aim to provide a particular quantity of light at a 'horizontal working plane' – for writing or reading, for example. It is also dedicated to avoiding glare to produce spaces with comfortable or acceptable lighting, often characterised by a constant light level that does not have great variations in brightness or cause glare (ibid, p.8). Extensive investigations into visual comfort and the use of light were carried out and informed codes such as those used by CIBSE which is now superseded by Society of Light and Lighting (SLL) Code for Lighting (2006). The CIBSE *Code for Interior Lighting* sets out that the lighting should fulfil three basic functions (CIBSE 1994): *Ensure safety of people in the interior; Facilitate the performance of visual tasks; and Aid the creation of an appropriate visual environment.* The third function addresses the quality of light which gives a particular unique character to an interior and is beyond providing the right quantity of light (DfEE 1999, p.19).

4.4.1.2. The Qualitative approach

During the last century a shift from a qualtative understanding to a quantitative understanding of lighting has occurred. In the past, the lighting of buildings was derived from experience or recognised good practice. In the last 80 years in particular, engineering principles of illumination have been applied to the problems of both daylight and artificial lighting in works by notable lighting scientists such as Hopkinson, Petherbridge and Longmore (1966).

Parpairi (1999) addresses the lack of literature on the quality of light and investigates the quality through perceived effect on the everyday users of a daylit space. She suggests that daylighting quality is a balance between three main parameters: *Quantifiable parameters* such as illuminance, luminance, codes and standards; *Architectural parameters* such as views out, shape of room, reflectance, etc; as well as *Personal parameters* such as expectations, control and opportunity. Although this research suggests an understanding of a whole variety of factors influencing daylight quality, it does not offer solutions to be applied in the design of daylighting.

In a research study, Demers (1997) aimed at reconciling the worlds of lighting art and science, developed computer-based methods of analysis and representations. This is one of few attempts to bring scientific methods into the field of qualitative light. As qualitative light analysis is a subjective matter, it is based strongly in the thoughts and beliefs of the individual. To ensure that objectivity remains it is necessary to bring scientific methods to analyse lights and spaces. It may never be possible to turn the emotive qualities of space to the pure rationale of science but the methods of analysis should be thorough, legible and consistent, thus enabling a blurring of the edges between art and science. The next section is an example of a qualitative approach to lighting and is only focused on the first impression people get by seeing and experiencing images of well daylit spaces.

4.4.2. Impression of light: Survey no. I

The idea behind this survey was to address the qualitative aspect of lighting and to show understanding light is complex and multi-faceted. The purpose of the survey was to find out the variety of the vocabulary people use to describe the effect of light on them. This survey was undertaken by the author at the Sheffield school of Architecture in 2003. A group of students as well as the staff (about 50 subjects) were given 15 interior images of buildings in which natural lighting seems to be a significant element in the design and the perception of the space. The images were chosen from a variety of buildings such as religious, educational and commercial as well as different styles such as Baroque and Modern to include a wide range of conditions of light in space. Subjects were asked to describe their first impression about the quality of light in the pictures with one or two adjectives. There were no multiple choices or a list of words and subjects were free to express their impressions.

However, some patterns began to emerge after organising the data, which went beyond the initial purpose of the survey. The results emphasize the relationship between physical characteristics of architectural spaces and the emotive and perceptual aspect of light. Flynn (1992) addresses this relationship and argues that emotive and perceptual aspects are related to some physical and morphological characteristics of light in space. In other words, the morphology of space related to a system of apertures may create specific lighting effects on occupants.

Having analysed the results of the survey, three groups of adjectives were identified in the data: descriptive, physiological and psychological. It will be discussed after illustrations. The following analyses of the first 8 images shows the variety of adjectives which are grouped in three mentioned groups. The numbers next to the adjectives are the frequency of the words used among the subjects. Further discussion and analysis will follow after the illustrations. Table 4.1 illustrates thumbnails of 15 chosen images. Table 4.2 to 4.9 illustrate the results of the survey for 8 images which are almost inclusive of all 15 images.

Tab 4.1. Thumbnails of 15 images of light impression survey

	Adjectives (Impressions)						
Pilgrimage Church	**A. Descriptive** Light Sources physical feature		**B. Physiological** Visual stimulating		**C. Psychological** Subjective response		
	diffused	5	bright	6	soft		6
	architectural	1	contrasting	6	heavenly		4
	incandescent	1	glaring	3	mysterious		4
	natural	1	illuminating	2	dramatic		2
	sidelight	1	dazzling	2	romantic		2
	unbalanced	1	atmospheric	2	grandeur		2
	varied	1	brilliant	1	relaxing		2
	indirect	1	clear	1	delicate		2
			cloudy	1	dull		2
			harsh	1	dusky		2
			hazy	1	attractive	ambiguous	1
			light	1	calming	caressing	1
			luminous	1	carefree	cold	1
			obstructive	1	dreamy	cool	1
			overexposing	1	enhancing	eerie	1
			piercing	1	epic	fearful	1
			radiant	1	ethereal	fresh	1
function-related adjectives:			semi-bright	1	fantastic	gentle	1
sacred 2			shadowy	1	grand	secretive	1
spiritual 1			sharp	1	moving	subdued	1
celestial 1			shining	1	mystical	subtle	1
			sparkling	1	profound	unpleasant	1
			strong	1	promising	welcoming	1
					royal		1
					sublime		1

Tab 4.2. Three groups of adjectives used to describe the impression of light in the pilgrimage church

	Adjectives (Impressions)						
Toledo Cathedral	**A. Descriptive** Light Sources physical feature		**B. Physiological** Visual stimulating		**C. Psychological** Subjective response		
	dawn light	1	contrasting	4	warm		9
	diffused	1	bright	3	soft		4
	emphasizing	1	glowing	2	calm		2
	exaggerating	1	intense	2	artistic		1
	focused	1	atmospheric	2	ascending		1
	indirect	1	yellow	2	attractive		1
	natural	1	golden	2	elevated		1
			dominant	1	enlightening		1
			foggy	1	ethereal		1
			illuminating	1	gentle		1
			mellow	1	grand		1
			piercing	1	heavenly		1
			radiant	1	inspiring		1
			revealing	1	inviting	dark	1
			shadowy	1	magnificent	dim	1
			strong	1	mysterious	dull	1
			unclear	1	mystic	effective	1
					mythical	hegemonic	1
function-related adjectives:					nice	moody	1
spiritual 4					sublime	powerful	1
sacred 1					subtle	reflexive	1
divine 1					theatrical	smooth	1
holy 1					transcendental	touching	1
celestial 1					uplifting	unpleasant	1
metaphysical 1							

Tab 4.3. Three groups of adjectives used to describe the impression of light in Toledo Cathedral

	Adjectives (Impressions)						
	A. Descriptive Light Sources physical feature		B. Physiological Visual stimulating		C. Psychological Subjective response		
Ronchamp Chapel	Variable	4	bright	5	dramatic		4
	diffused	4	intense	3	interesting		4
	complex	1	atmospheric	2	gentle		3
	eclectic	1	contrasting	2	heavenly		2
	fragmented	1	glaring	2	mysterious		2
	framed	1	piercing	2	artistic		2
	intermittent	1	blur	1	cool		2
	multi-faceted	1	clear	1	ambiguous		1
	patchy	1	dazzling	1	becoming		1
	restricted	1	distracting	1	dreamy		1
	selective	1	dominant	1	effective		1
	sporadic	1	gazing	1	emotive		1
	unmanaged	1	glistening	1	ethereal	bland	1
			harsh	1	evocative	cold	1
			hazy	1	infatuating	fearful	1
			light	1	intimate	frightening	1
			permeating	1	inviting	light	1
			shimmering	1	nice	obscure	1
			well-lit	1	promising	sad	1
					provoking	soft	1
					romantic	unattractive	1
					serene	unpleasant	1
function-related adjectives:					soothing	warm	1
spiritual 2					subdued		1
sacred 1					thoughtful		
religious 1							

Tab 4.4. Three groups of adjectives used to describe the impression of light in Ronchamp Chapel

	Adjectives (Impressions)						
	A. Descriptive Light Sources physical feature		B. Physiological Visual stimulating		C. Psychological Subjective response		
Myyrmaki Church					modern		5
	complex	2	bright	11	spacious		4
	vertical	2	clear	4	cool		4
	background	1	ambient	2	pleasant		3
	diffracted	1	hard	2	calming		3
	diffused	1	blue	2	cold		3
	directionless	1	airy	1	floating		2
	electric	1	chilled	1	celebratory		2
	floodlight	1	colourful	1	relaxing		2
	high-tech	1	constant	1	nice		2
	industrial	1	even	1	interesting		2
	mechanical	1	functional	1	absolute		1
	natural	1	gleaming	1	beautiful	comfortable	1
	omnipresent	1	glowing	1	chic	ethereal	1
	volumetric	1	illuminating	1	clean	expansive	1
	well-balanced	1	light	1	clinical	fascinating	1
			mellow	1	crisp	glorious	1
			pale	1	deep	harmonic	1
			shaded	1	delightful	marine	1
			sharp	1	epic	inanimate	1
			sufficient	1	formal	musical obscure	1
			transparent	1	good	normal	1
			uneven	1	placid	ordinary	1
function-related adjectives:					sensitive	romantic	1
modern sacred 1					soft	uninteresting	1
					uplifting		1

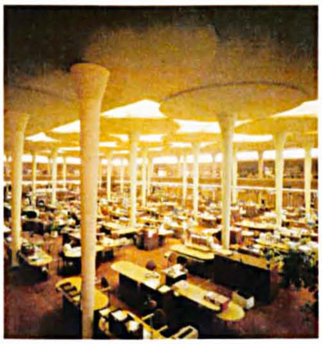
Tab 4.5. Three groups of adjectives used to describe the impression of light in Myyrmaki Church

Riola Parish Church	Adjectives (Impressions)						
	A. Descriptive Light Sources physical feature		B. Physiological Visual stimulating		C. Psychological Subjective response		
	controlled	5	even	5	soft		4
	open	2	airy	3	calming		3
	diffused	2	bright	2	gentle		3
	bold	2	adequate	1	nice		3
	commercial	1	ambient	1	comfortable		3
	concealed	1	appropriate	1	clinical		2
	direct	1	clear	1	dull		2
	filled	1	dark	1	relaxing		2
	floodlight	1	environmental	1	warm		2
	mixed light	1	illuminated	1	clean		1
	natural	1	intense	1	cool		1
	non-obstructive	1	light	1	crisp		1
	proportional	1	mild	1	delicate		1
	reflective	1	plain	1	depressing		1
	restricted	1	pure	1	dramatic		1
	simple	1	shaded	1	elegant		1
	variable	1	shining	1	fresh		1
			stark	1	good	cosy	1
					interesting	modern	1
					inviting	quiet	1
					neutral	serene	1
					ordinary	silent	1
					pleasant	supportive	1
					smooth	thoughtful	1
					sterile	unsubtle	1

Tab 4.6. Three groups of adjectives used to describe the impression of light in Riola Parish Church

Sir John Soane's Museum	Adjectives (Impressions)						
	A. Descriptive Light Sources physical feature		B. Physiological Visual stimulating		C. Psychological Subjective response		
	top-light	4	bright	9	cold		3
	natural	2	clear	3	cool		2
	naturalist	2	contrasting	2	warm		2
	angelic	1	radiant	2	wonderful		2
	cascade	1	revealing	2	powerful		2
	concentrated	1	ambient	1	ambiguous		1
	conductive	1	brilliant	1	animating		1
	direct	1	dominant	1	artistic		1
	emphasizing	1	even	1	attractive		1
	far-reaching	1	gaudy	1	awe-inspiring		1
	flowing	1	shadowy	1	boring		1
	focused	1	spectral	1	calming		1
	indirect	1	spreading	1	dramatic		1
	layered	1	uniform	1	glorious		1
	one-directional	1	unimposing	1	good	admiring	1
	open	1	well-lit	1	graceful	grandeur	1
	pouring	1			heavenly	nice	1
	volumetric	1			inspiring	normal	1
	white	1			intimidating	ordinary	1
					relieving	subdued	1
					religious	sublime	1
					senseless	subtle	1
					striking	unifying	1
					thoughtful	unpleasant	1
					weak	uplifting	1

Tab 4.7. Three groups of adjectives used to describe the impression of light in Sir John Soane's Museum

Johnson Wax Admin Building	Adjectives (Impressions)						
	A. Descriptive Light Sources physical feature		**B. Physiological** Visual stimulating		**C. Psychological** Subjective response		
	diffused	5	bright	4	comfortable		2
	artificial	2	even	3	gentle		2
	natural	2	clear	3	subdued		2
	unnatural	2	oppressive	3	subtle		2
	industrial	2	functional	3	surreal		2
	balanced	1	consistent	2	active		1
	dispersed	1	flat	2	bad		1
	external	1	harsh	2	boring		1
	indirect	1	hazy	2	depressing		1
	light fall	1	imposing	2	eerie		1
	simple	1	intense	2	ethereal		1
	sky like	1	abundant	1	grandeur		1
	well-distributed	1	brilliant	1	harmonic		1
			cloudy	1	imminent		1
			floating	1	infinite		1
			forcing	1	intimidating		1
			glaring	1	modern		1
			glowing	1	mundane		1
			homogenous	1	murky	cold	1
			penetrating	1	non-dramatic	dark	1
			practical	1	pleasant	dull	1
			uniform	1	sickly	live	1
			useful	1	spacious	nice	1
			warning	1	steady	ordinary	1
			yellow	1	sterile	relaxing	1

Tab 4.8. Three groups of adjectives used to describe the impression of light in Johnson Wax Building

Westgate School	Adjectives (Impressions)						
	A. Descriptive Light Sources physical feature		**B. Physiological** Visual stimulating		**C. Psychological** Subjective response		
	diffused	2	bright	13	clean		3
	open	2	glaring	4	bland		2
	white	2	harsh	3	cheerful		2
	artificial	1	disturbing	2	clinical		2
	controlled	1	too much	2	cool		2
	dispersed	1	intense	2	inviting		2
	free	1	sharp	2	modern		2
	greyish	1	airy	2	refreshing		2
	invariable	1	abundant	1	calm		2
	mechanistic	1	brilliant	1	lovely		2
	natural	1	clear	1	active		1
	reduced	1	dazzling	1	attractive		1
	structural	1	functional	1	cold		1
	translucent	1	hard	1	comfortable		1
	two-sided	1	light	1	fresh		1
			overexposing	1	inspirational		1
			radiant	1	nonsense		1
			well-lit	1	quiet		1
					refined		1
					spacious		1
					splendid		1
					sterile		1
					uncomfortable		1
					absolute		1
					warm	pleasant	1

Tab 4.9. Three groups of adjectives used to describe the impression of light in Westgate School

Discussion

As can be seen in the above tables some of the adjectives describe the physical features of the light source. This group of words tells us about the physical attributes of the light such as being direct, indirect, diffused, sidelight, etc. The second group of adjectives are those which seem to describe the effect of the visual stimulation of the viewers. For example, descriptive words such as bright, glaring, glistening or shimmering are the visual impressions of the viewers from the sources of light or lit surfaces in the space. This group is considered as the physiological impressions since they are mostly related to the stimulation of nervous systems in the eyes as well as the lightness or the darkness of the room.

On the other hand, the third group of words express the psychological effect of light on the viewers. Adjectives such as mysterious, romantic, inspirational etc. do not only refer to the quality and the quantity of light in the space; they also address the viewers' symbolic and emotional response. They are the subjective responses of the beholders, whereas the first group of words are objective responses dealing with the physical characteristics of the light source and the second group is closer to the first group in terms of the objectivity of the description.

The first finding of this survey is the variety of adjectives is higher in the second group than the first group and the highest in the third group. This finding highlights the significance of lighting design and its direct effect on human conditions. The second finding establishes the relationship between emotive and perceptual aspects and some physical and morphological characteristics of light in space (Flynn 1992). It is the author's personal interpretation that there seems to be a correlation between three groups of words in the above tables. For example, in table 4.2 there are a few adjectives in the first group of words such as 'diffused' or 'indirect' which are related to some of the words in group B such as 'dazzling', 'atmospheric', or 'radiant' as diffused light usually creates an atmospheric impression in a room. The second group of words are also related to some of the words in the third group such as 'delicate', 'mysterious', 'soft', or 'romantic' in terms of their subjective interpretation. Another example can be seen in table 4.4 where adjectives such as 'variable', 'complex', or 'selective' in group A are related to 'distracting' in group B and also to 'ambiguous' or 'obscure' in the third group of words.

This brief survey suggests that there is a relationship between emotive and perceptual aspects of light and some morphological characteristics of light in space. Therefore, a classification of different lights or a typology of light could be an informative and an inspiring source for designers to achieve their goals in terms of creating more human responsive and richer interior spaces. The above discussed survey is only a preliminary investigation toward a compilation of inspiring typology of light which is not in the scope of the research, but nonetheless acts as a useful pointer towards the relationship between the design and perception of light.

4.4.3. Classifications of light

A classification of light types could give an insight to designers and architects into a better understanding of the nature of light and its impact on the occupants in architectural space. Although there is some research on physiological aspect of vision and perception (Gregory 1972; Bloomer 1990) as well as emotive aspects (Flynn 1979), there have been fewer attempts to define light in terms of ambience and atmosphere. One of the exemplar classifications of light is the Four-lights of (Ciriani 1991). He suggests a classification that originates from the qualitative aspects of light. His classification of Four-lights is summarised as follows (Ciriani 1991, p.77-79):

1. *Feeling-light*: the light-that-moves-us. The aim of feeling light is to hold the attention and thus induce concentration.
2. *Lighting-light* or hygiene-light: "good old sunshine that fights TB and feeds us with vitamins has steadily replaced light-that moves-us...but by doing away with feeling-light, architecture was deprived of much of its capacity to move us, and difficulties thus arose...Its aim is to create the illumination that the inside is still the outside. It stands for progress whereas feeling-light stands for God."

3. *Radiant light* is another variant of lighting light. It represents too much light. While lighting-light refers to the notion of progress, radiant light is "artistic, cerebral...White enables this radiation of light, and gives maximum internal intensity."
4. *Pictorial light* "was born of the will to build what the artists were painting...It isn't just 'coloured feeling-light'. Being pictorial means imagining being in the space of a painting...In the same way as a painting on a wall transforms the wall, pictorial light has the capacity to transform matter, to set it free from material conditions."

The light-that moves-us is a central concern in religious architecture, since it is often regarded as a symbol of divinity. Le Corbusier's Ronchamp chapel is a good example of *feeling light,* where the unusual fenestration of the building creates a mysterious ambience inside the church. Natural light qualities such as glitter or glare are one of the main stimuli involving the viewer's eyes and minds. On the contrary, *lighting-light* is the functional light which only satisfies the visibility inside a building and does not go further. It is the standard natural illumination required for a building to enable the inhabitants to see or read.

Fig 4.4. Chapelle de Notr-dame du Haut, Ronchamp (Photos © F. Ai)

Von Meiss (1990) describes four types of light that represent the typical conditions of illumination at the basis of numerous possible combinations. His classification relates to Arnheim's theory (1974) of the attribution of light sources to lit object. Arnheim (1974, p.303) argues that the brightness of objects on earth is seen basically as a property of their own rather than as a result of reflection. This approach differs from Ciriani's classification since it relies almost entirely on the morphological aspects represented in four conditions of space related to the source: Light-space, light as an object, light from a series of objects and light from surfaces. While Von Meiss classifies light types in relation with the objects and surfaces occupying a space, Hogarth (1981) refers to light sources as well as the quality of light spread across a room.

Hogarth's studies of light from pictorial representations (1981) establish an empirical classification. Hogarth's order initially differentiates the type of sources that affect modelling, suggesting five categories of light based on types of light source. The types of sources are as follows: Single source light (direct light), double source light, flat diffused light (overcast days) and sculptural light (an invented light). Five types of light are therefore described as follows: Textural light, Transparent light, Fragmentation light, Radiant light and Expressive light.

Richard Kelly (US lighting designer 1940-50s) identified three types of light based on his understanding of '*light energy impacts*': *focal light* of highlight, *ambient luminescence* or graded washes, and the *play of brilliants* or sharp details (Kelly 1952). Kelly considered three types of light as a palette from which designers could mix and compose to achieve their desired results. He considers the order of imaginative planning in lighting design similar to the creation of a watercolour painting, although any of the above light types could dominate. *First, major highlights are imagined – then, graded washes of different luminosity are added and – then, the detail of minor lightplay makes the idea clear and entertains the eye* (Kelly 1952). He believed that visual beauty is an interplay of all three kinds of light, though one is usually dominant (ibid).

The above classifications (Ciriani 1991, Von Meiss 1990, Hogarth 1981, Kelly 1952) have three main types of light in common: direct, diffuse or indirect light and radiant light. Table 4.10 summarises the three discussed classifications of light in terms of direct, diffuse and radiant light. Having discussed classifications of light in terms of qualitative lighting which could partly be considered as intangible, the next chapter is focused on the tangible classification of architectural forms which admit or conduct light into a space. Such a formal classification is considered as typological approach as it only deals with the formal aspects of a building in regard to daylighting.

Proposed Classification	CIRIANI	VON MEISS	HOGARTH	KELLY
Direct Light	Feeling-Light (or Moving Light)	Light Space Light from a series of objects	Textural light: (Single source light) Sculptural light (Double source light)	Play of brilliants
Diffuse Light	Lighting-Light (or Hygiene Light) Pictorial Light	Light from surfaces	Transparent light Expressive light	Ambient luminescence
Radiant Light	Radiant Light	Light as Object	Radiant Light Fragmentation Light	Focal glow

Tab 4.10. Comparison of classifications and the three main types of light

4.5. Typological approach

Architectural precedents are usually inspirational resources for architects. Antoniades (1992) discusses in *The Poetics of Architecture* how didactic architectural precedents can be taken from the remote past, as well as from the recent, and they can enhance the design process. Architects can learn lessons from exemplar buildings, whether to improve positive features in new designs or else not to repeat their mistakes. However, due to the complexity of architectural examples there is a need for a design tool to analyse them and make them easier to understand and use for designers. Many people believe that the intuitive methods of design traditionally used by architects are incapable of dealing with the complexity of the problems to be solved and that without sharper tools of analysis and classification the designer tends to fall back on previous examples for the solution of new problem (Colquhoun 1981, p.43).

In his essay on *Typology and Design Method,* he argued against both pure functionalism and mere intuition as methods of design, and instead for an idea that rigorous analysis could offer suggestions but not necessarily solutions to architectural problems. These '*type-solutions*', which are only design suggestions rather than solutions, are considered as typologies. The importance of typologies is that they allow an understanding of the structures and principles around which things are built. They are not a set of instant answers, but instead a method by which to aid understanding (Hodges 2002, p.64).

Typology in architecture is the study or systematic classification of formal types. It plays a creative role by allowing the designer to begin the cycle of analysis and revision from a reasonably confident position (Hawkes 1976, p.466). By the analysis and classification of buildings, based on their formal differences, one can explore different types of approaches which, in the end, give a better understanding to the designer.

Aldo Rossi identified the nature of type through the writings of Quatremere de Quincy, who strongly rejected the ideas of 'type' as being something merely to be copied. The reasons for this were predominantly the understanding that the 'type' is vague and lacks the precision of the design model. Writing on typologies within the urban landscape, Rossi added: *"Thus typology presents itself as the study of types of elements that cannot be further reduced..."(Rossi 1981).* He develops such a typology through as analysis of the formal characteristics of architecture and a classification method which proceeds into a series of types.

However, the risk with typology lies in its tendency to reduce the whole building or the complex experience of space into a limited number of types. Colquhoun (1981) shows that a reductionist theory, according to which the problem-solution process can be reduced to some sort of essence, is untenable. He argues that a typological approach should not be based on a process of reduction, but rather on a process of exclusion. If we look at the allied fields of painting and music, we can see that in the work of a Kandinsky or a Schoenberg, traditional formal devices were not completely abandoned but were transformed and given a new emphasis by the exclusion of '*ideologically repulsive iconic elements*' (ibid, p.49). Therefore, for Colquhoun (1981, p.50) the process of exclusion enables us to see the potentiality of forms as if for the first time.

This research takes typology as a design tool to incorporate daylighting studies into architectural design. The following sections investigate the application of the typological approach to daylighting components in the literature.

4.5.1. Typological classification of daylighting components

This section explores different types of daylighting components which admit daylight into the interior spaces. The reason behind this exploration is an understanding of the morphology of light according to apertures and space allows the designer to manipulate light with more ability and encourage greater explorations of different alternatives of penetration, distribution, quantity and quality of light (Egan 1983). Daylighting components include a range of building elements such as windows, apertures, atria, etc. This section first examines what a typological method is and compares two recent methods of classification. Subsequently, it will extensively explore two main types of daylighting components which are admitting and conducting elements.

The typological method can be seen as architectural composition theory developed as a cumulative design tool (Baker et al 1993, p.11.1). The stored repertoire of forms and types can be used by architects to select the appropriate design solution. However, there is a need to analyse the repertoire of forms to make them more useful and easier for architect's selection in the design process. The approach of the typological method is one in which building researchers structure the experiment of an architectural grammar, which can then be used by designers on a selective basis. The grammar which is proposed by Baker et al (1993) consists of a set of compositional rules and a repertoire of architectural types. It proposes a set of transformation rules to fit the types to a specific site and programme. Thus, the typological grammar collects good examples of daylit buildings into a repertoire of building types.

The proposed typological grammar is based on the analysis of a room as the basic unit of a building. The room represents the lighted space and is the main object of daylighting analysis. The elements which shape the room are: the floor, the walls with openings and the ceiling with openings. The floor can be considered as the lighted area, while the walls and ceiling are lighting areas which can be divided into three sub-areas: the windows as light sources, the surfaces as diffusers and the dark surfaces (ibid, p.11.5).

The morphological box (Los in Baker et al. 1993) offers a useful scheme for analysing daylight in existing buildings, but does not constitute a typology in itself, since it does not succeed in identifying major types or categories. However, it succeeds in distinguishing two main types of daylighting components which will be discussed in the next section; namely as admitting and conducting components. Nonetheless, there are few attempts in the literature review, such as the following example, which address different types of building in regards to their daylighting.

In a recent study (Hodges 2002), light types in churches are investigated and 16 types of light are found out depending where natural light is admitted to the altar or nave of the church. As many of these types are closely related and are most likely members of '*family*' groups within the typology, they are simplified and compressed to 6 group as follows (ibid, p.93-94):

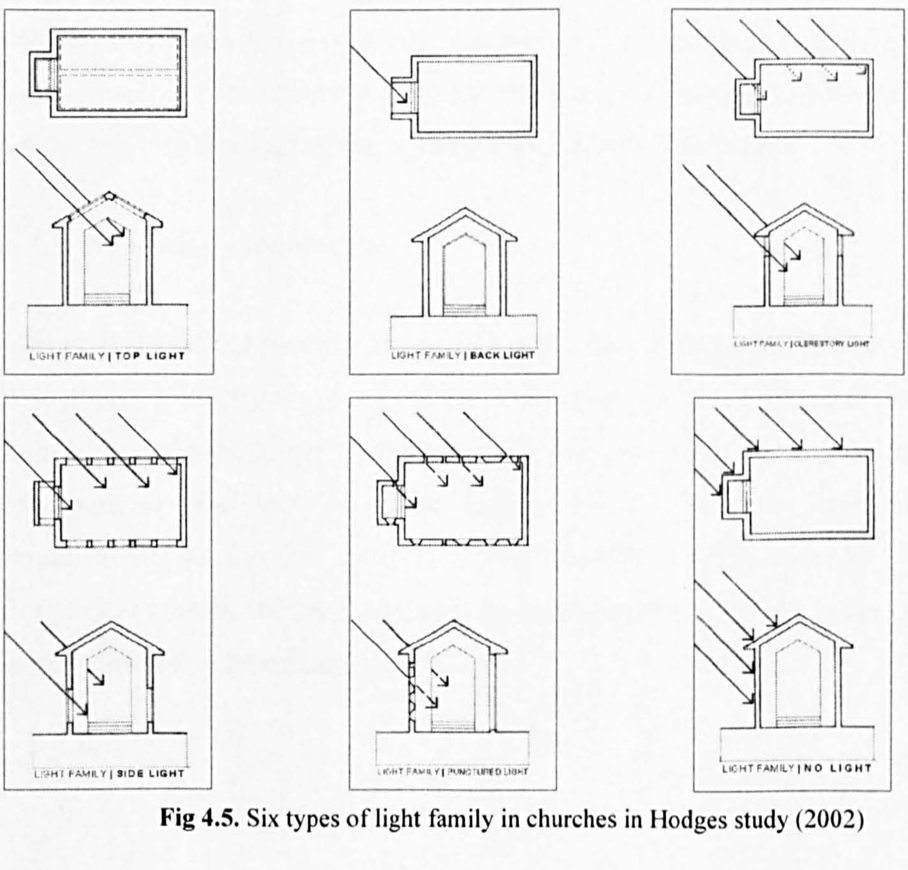


Fig 4.5. Six types of light family in churches in Hodges study (2002)

In the above study, the initial types of light identified have been grouped into family groups with shared characteristics. The idea of a family group allows related, but not identical, light types to be understood more closely. It is a family in the sense of close and distant relationships and takes into account of the manner in which individual buildings, whilst not identical, share strong common ground in their use of light (ibid, 95). The above visualisation diagrams are based in part on similar clear diagrams used by Urs Buttiker (1993) in *Louis I Kahn: Light and Space*. Buttiker used it as a method to easily visualise the methods that Kahn used to bring light into his projects.

The main problem with Hodges' study is that indirect light, which is an especially important source of light in churches, is not included. The important 'borrowed' light from other spaces could not be taken fully into consideration as it cannot simply be added to the lists of light types. The reason is the light can be 'borrowed' from a variety of sources, specially designed surfaces to transmit or conduct light. Nevertheless, it is an appropriate example of classifying light types in churches by reducing them to a limited number of groups, although an essential source of light has been excluded. Having discussed the typological method and its application in daylighting in buildings as an example, the following two sections will elaborate on two main components of daylighting (admitting & conducting) in buildings and their sub-components. An understanding into the variety of daylighting components will, then, inform any typology of daylighting components in buildings.

4.5.1.1. Admitting components

Baker et al (1993) put forward two main components of daylighting: pass-through and conducting. Pass-through components which can also be referred to as admitting components, of which the window is the most important, are devices designed to allow light to pass from one light environment to another. Each pass-through component can incorporate a set of control elements which are devices designed to admit and/or control the entry of light into a building (ibid, p.5.1). Three basic types can be identified in admitting components:

Group I: *Lateral pass-through components* permitting lateral penetration of light; Group II: *Zenithal pass-through components* allowingtop -lighting to the space below; and Group III: *Global pass-through components* permitting a lateral and zenithal entry of light (ibid). These elements can be analysed by their geometric characteristics such as size, location and shape. The following table summarises admitting components and their subgroups:

LATERAL	ZENITHAL	GLOBAL
Balcony window	Clerestory	Membrane
Translucent wall	Monitor roof	
Curtain wall	North-light roof	
	Translucent ceiling	
	Skylight	
	Dome	
	Lantern	

Tab 4.11. Admitting or pass-though daylighting components and their subgroups, from (Baker, Steemers et al. 1993)

It is important to mention that admitting daylight components are not only the features of a building which affect daylight; all the solar control elements surrounding the apertures also need to be considered. Baker et al study (1993, p.5.3) has identified 5 types of solar controllers which are *separator surfaces, flexible screens, rigid screens, solar filters*, and *solar obstructers*. *Separator surfaces* are devices to permit light or view through while not admitting air in the building. *Flexible screens* can allow diffused light and air to pass through the window. *Rigid screens* are designed to redirect or obstruct direct solar radiation. *Solar filters* cover the entire surface of an opening and obstruct the view, while solar obstructers can entirely block the light (ibid, p.5.3-5.25). The following table summarises control elements and their examples.

Separator surfaces	Flexible screens	Rigid screens	Solar filters	Solar obstructers
Conventional division	Awning	Lightshelf	Jalousie	Shutter
Optical division	Curtain	Sill	Louver	Blind
Prismatic division		Overhang / Fin	Brise-soleil	
Active division		Baffle		

Tab 4.12. Control elements and the examples as part of admitting daylight components, from (ibid)

Another important factor in the admitting component's performance is the orientation toward the sun. South-facing openings receive high levels of light and somewhat variable illumination, high energy gain in winter and medium in summer; while North-facing windows receive low levels of light but constant illumination throughout the day and poor energy gain. East-and west-facing windows receive medium levels of light, high energy gain in summer and low in winter. Depending on the orientation of the building and each opening, one or a combination of the above solar controllers will be necessary to control the harsh sunlight during warm times of the year as well as moderating the effects of low-level sunlight in winter. The effect of orientation will be discussed thoroughly in chapter 5.

4.5.1.2. Conducting components

Conduction components can be identified as spaces designed to guide or distribute daylight towards the interior of a building. Baker et al (1993) identified two groups of conduction components: *Intermediate light spaces* which are part of the perimeter zone of a building and *interior light spaces* which distribute daylight into specific zones of a building. The following table summarises the examples of the above two group of conducting components:

Intermediate light spaces	**Gallery**	A covered light space attached to a building as an intermediate living space which admits daylight to the inside parts of a building. It provides a decreased and less contrasting light level to the inside zone adjoining the gallery. Depth from 0.8 to 4 m.
	Porch	A covered light space attached to a building at ground level open to the exterior environment. Depth normally 1 to 5m.
	Greenhouse	A space attached to a building by one or more of its faces permitting the entry of light and direct solar radiation. It provides an inside luminous level similar to outside.
Interior light spaces	**Courtyard**	An enclosed space by the walls of one or several buildings and open to the exterior at the top. Courtyards have luminous properties similar to exterior space but daylighting and natural ventilation are reduced. The finishes of the enclosing walls influence the illumination performance of the courtyard.
	Atrium	A laterally enclosed space by the walls of a building and covered with transparent or translucent material. It is an inside living space and normally occupies the total height of the building. The interior finishes should have high reflectance to ensure good daylight penetration into adjacent spaces.
	Light-duct	It conducts natural light to interior zones of a building which are not linked to the outside but are not far from the exterior. Its surfaces are finished with light-reflective materials in order to direct and diffuse natural light downwards. The section is usually between 0.5*0.5m and 2*2m
	Sun-duct	A light space designed to reflect solar beams to dark interior spaces, it may also provide ventilation. Surfaces are covered with highly reflective finishes, such as mirror, aluminium, etc in order to reflect solar radiation. Typically dimensions between 0.5*0.5m and 1.2*1.2m. The length may be greater than 15m.

Tab. 4.13. Conducting components' groups and examples, after (Baker, Steemers et al. 1993)

Some of the components such as porches and courtyards have been used extensively in vernacular architecture and will be discussed thoroughly in chapter 6, while some of them are fairly new developments of the modern technology in construction such as sun-ducts. Atria have human as well as environmental advantages (Philips 2004). From The human point of view, by getting daylight into the centre of deep plan buildings, this provides the occupants with a sense of orientation, information on the time, weather and the world outside the building; together with a sense of space and views which may compensate for the lack of external views. Besides, from an environmental viewpoint, there is a potential for savings of energy, assistance with the problems of ventilation, and a reduction in the need for air-conditioning (ibid, p.25).

4.5.1.3. Conclusion

> *A deeper understanding of the behaviour of light is necessary to take full advantage of all the benefits offered by daylighting.* (Baker et al, 1993, p.5.1)

There are three ways to convince designers of the advantages to be gained by improving the daylighting performance of their architectural projects (ibid, p.11.1). The first way is to show them the architectural possibilities through exemplary case studies. This method is usually undertaken individually at the first stages of design studies. Antoniades (1992) argues in *Poetics of Architecture* how architects and designers refer to their visual memory, which consists of their personal experiences and studies of architectural precedents. Therefore, this method is the most common way of learning architectural possibilities through exemplary cases, consciously or sub-consciously. The second way is to provide analyses and information describing the relevant aspects and lessons learnt from the case studies. This is a more analytical method and needs to be undertaken rigorously in order to reveal the lessons to be learnt. The third way is to make available to architects the tools that can assist them in the design and analysis of daylit buildings.

There are already a number of tools available to designers to simulate and evaluate the lighting condition of a building such as Luminance, Ecotect, etc; however, Baker et al (1993) argue that what we need to equip architects with generative as well as analytical tools. He suggests that up-dated precedents of building types which embody effective daylighting concepts and principles are required. Generative methods are useful in providing examples of design and help designers choose or combine suggested examples. In this context, typology and typological methods are means that can be used to help build such a generative tool for designers.

The above discussed typologies of light by Hodges (2002) and particularly Baker et al (1993) are examples of approaches toward classifying different sources of daylight in a building. However, they do not offer possible alternatives which could be generated from the suggested types. They are appropriate examples of a reductionist approach towards building apertures and sources of daylight which have concluded into a limited number of choices available to designers. The problem with typological approaches arises at this point which is going to be discussed in the next section; the critique of typological approach.

However, before concluding the typological approach section of this chapter with the critique, it is worthwhile to address and discuss the author's attempt in an experiment to explore daylighting components in rather a 'generative approach'. This approach is different from the typological approach as it is a 'process of inclusion' of as many alternatives as possible, while in typology the 'process of exclusion' is dominant.

4.5.2. An exploration into a typology of daylighting components: Survey no II

In the early stages of this research in 2003, the author undertook a pilot study to explore daylighting components and the possibility of suggesting a typology on the basis of a model study. A single room without a specific function was used as the starting point. Before doing the model study, some hand drawings were made to explore different ways of admitting light into the assumed room.

The drawings were only a brainstorm into the explorations and the next step was to model the room either by computer simulations or cardboard model making and digital photography. Simple cardboard models were made with 1/20 scale at the lighting laboratory of the School of Architecture in Sheffield. The surfaces were matte white which helped reflecting light. The room was assumed a square in plan with 25 m² area and 3 meter height. Two corner walls and the roof were exposed to outdoors and could admit daylight. It is presumed that all models are exposed to sunlight at the same time of day and also at the same time of year.

The following photos were taken with a micro-camera installed in the model at the human eye level. Fig 4.6 illustrates the first attempts to admit daylight through the four corners of one of the corner walls. It explores unconventional ways of admitting light into a room from only one side wall which is exposed to outdoors.

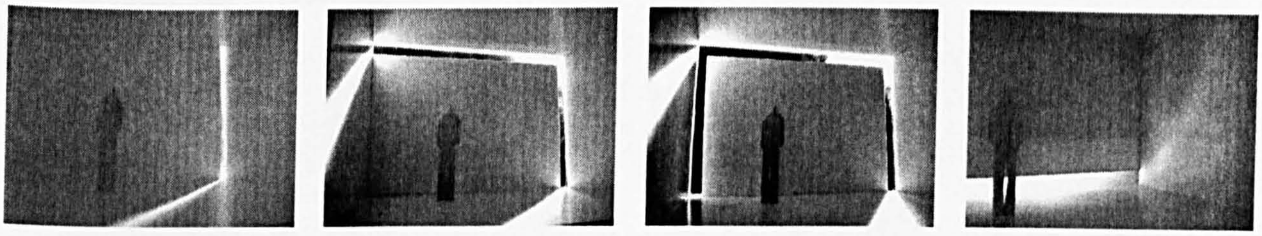


Fig 4.6. Lateral study of unconventional ways of admitting daylight

Fig 4.7 explores a few varieties of a horizontal window with either horizontal or vertical louvers to control daylight. The second and fourth photos from left shows the same types of windows accompanied by some extra light from the gap between the ceiling and the wall. The second photo clearly shows how effective the wall washing effect by the extra top lighting is to reduce the contrast on the window wall and therefore the reduction of the glare for people inside the room. Besides, the depth of daylight penetration inside the room is improved by the addition of the narrow top lighting.

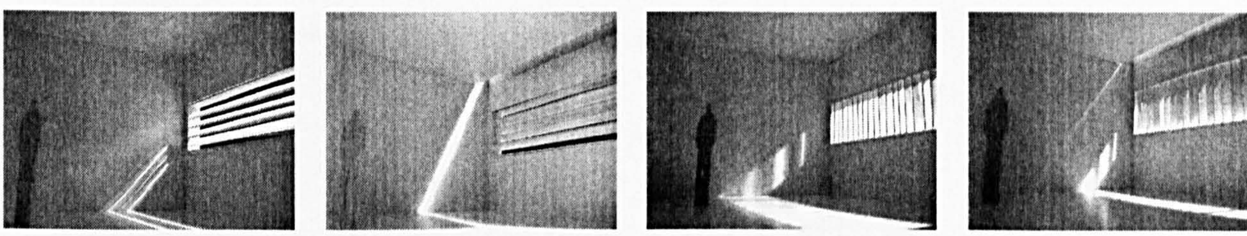


Fig 4.7. Lateral study of conventional ways of admitting daylight with diffusers

Next, narrow top lighting is studied and compared with the various use of horizontal and vertical louvres. Fig 4.8 shows the effect of light diffusers and the angle of sunlight on the illumination of the room. As can be seen the left photo with horizontal louvers has a better effect of wall washing since louvers are placed parallel to the wall being washed and the sunlight is directly reflected upon them. Therefore, the horizontal position of louvers provides more illumination to the right side of the room and also provides more reflected light penetration deep into the room. However, at some sunlight angles direct sun rays could pass through the louvers and could cause overheating or glare. Nevertheless, if louvers orientation angle could be controlled automatically or manually by the users, the problem of direct exposure to sunlight can be resolved.

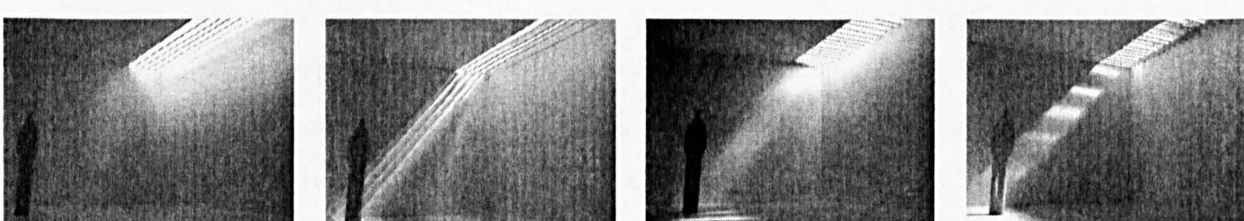


Fig 4.8. Horizontal and vertical louvers lighting performance in top-lighting

The same issue has been studied for clerestories, which are the windows high on the wall located under the ceiling (Fig 4.9). The first photo on the left is a limited clerestory which looks like a gap between the wall and the ceiling. It illustrates how effective a clerestory, even with a limited area of opening, can be in terms of an even distribution of light across the room. However, it has still the previous issue of direct sunlight in the room. The right photos in Fig 4.9 show larger clerestories which are equipped with horizontal and in another case vertical louvres to redirect and diffuse sunlight. As can be seen in the photos, horizontal louvers are more effective in terms of redirecting sunlight to the ceiling and then back into the deeper part of the room. On the other hand, vertical louvers are more effective in terms of controlling sunlight penetration from side angles when the sun is at a lower angle in the sky.

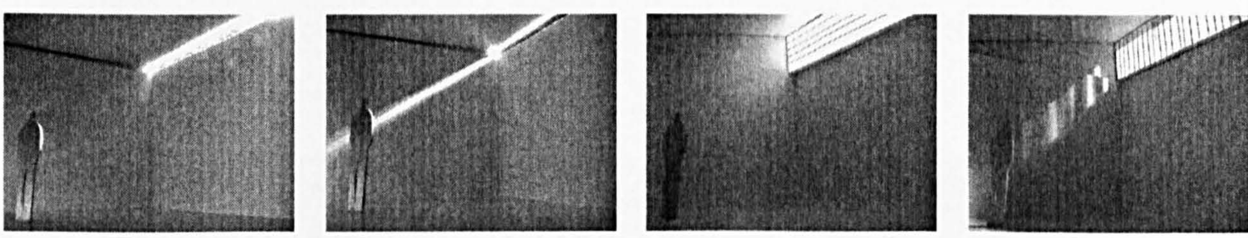


Fig 4.9. Clerestories and the effect of horizontal and vertical louvers on their light distribution and control

Top-lighting is studied in the next set of photos (Fig 4.10). There are a number of ways to admit sunlight through the roof which will be discussed in further sections, but this pilot study only studies top-lighting alternatives by admitting sunlight through a skylight. The main advantage of top-lighting is the possibility of an even distribution of light across a room in comparison with side-lighting. However, depending on the light control devices, such as baffles in this study, or the angle of sunlight, the room can be exposed to a large amount of direct sunlight which could be a nuisance in classrooms, for instance. The following photos illustrate how different ambiences can be created by top-lighting along with shading devices. If properly controlled and diffused, it can create a lively room for study and learning (right photo). But if not controlled or diffused it can create an animated and vivacious space for non-reading spaces in a school, for instance.

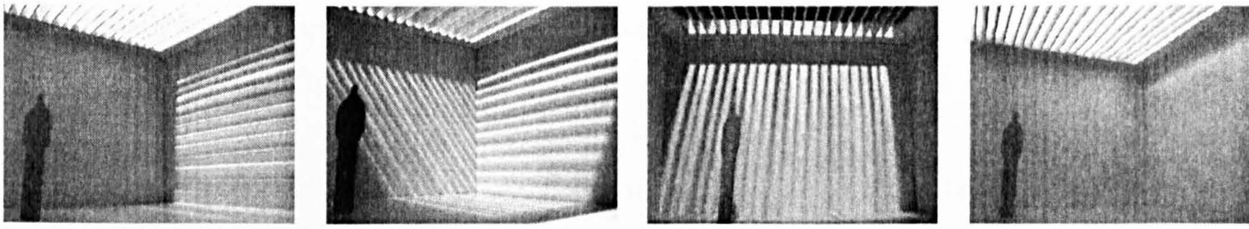


Fig 4.10. Top-lighting and its potentials for creating different light ambiances in connection with shading devices

The last part of this study explores the 'unconventional' ways of admitting light to a room to create dramatic daylighting effects. Fig 4.11 illustrates such possibilities of manipulating the envelope walls to allow daylight penetrate a dark room in more creative and complex ways. Different manipulations in walls in Fig 4.11 or those in the ceiling in Fig 4.12 or a possible combination of them show that there are numerous ways designers could admit daylight into buildings for different purposes.

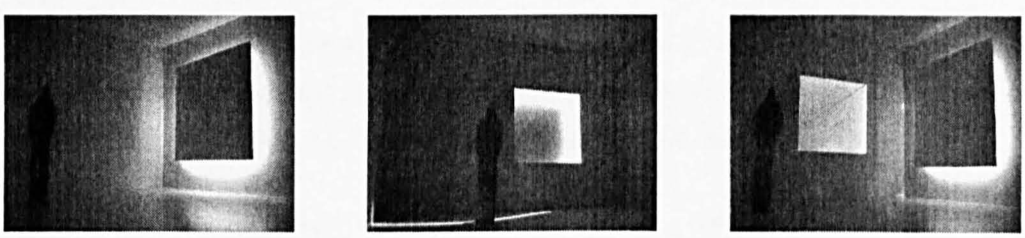


Fig 4.11. Dramatic daylighting effects by manipulating side walls fenestration

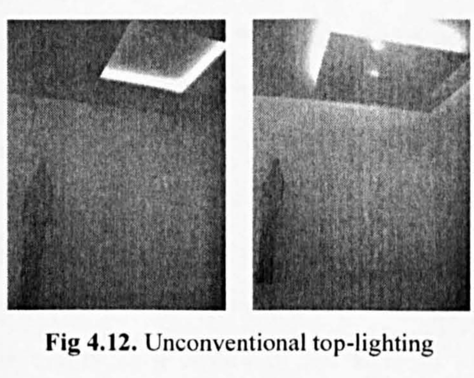


Fig 4.12. Unconventional top-lighting

Finally, this pilot study experiments with a few ways of admission of light into a room and shows most of daylight sources in room can be classified on the basis of the surface from which light is admitted into the room. There are two main types of entries for sunlight discussed in the study: Side-lighting and top-lighting in general as well as their effects when are used with shading or light redirecting devices. This experiment is obviously not comprehensive as it does not cover all aperture types and borrowed lighting.

As discussed in previous sections, Baker et al (1993) have developed a detailed typology of daylighting components based on their admission type and other variables which can be used as an analysis tool for daylighting designers. Hodges (2002) also has suggested a typology of light in Modern church buildings. However, as mentioned at the end of previous section, there is a main drawback with typological approach which is discussed in the next section.

4.5.3. The Critique of typological approach

> *When we treat architecture analytically, we miss the concrete environmental character, that is, the very quality which is the object of man's identification, and which may give him a sense of existential foothold (Norberg-Schultz 1980).*

The observations and classifications are interesting, but it seems they miss an important point; Systems of rule are idealizations that abstract away from complicating aspects of reality (Pinker 1954). Places can not simply be described by means of analytical or 'scientific' concepts in which case the everyday life-world is lost, which ought to be the real concern of man in general and planners and architects in particular (Norberg-Schultz 1980, p.6). Typological approach, as discussed previously, is an analytical tool by which the subject of study is reduced to a number of types. Typological approach can also be compared with reductionist approach in which a complex system can be explained by reduction to its fundamental parts (Jones 2000). Norberg-Schultz (1980) argues a reductionist approach toward analysis of architectural space or its components loses the essential character of the space and the true experience of architecture in its all richness. He suggests a phenomenological approach to maintain the character of space in our attempt to understand and explain architectural elements.

4.6. Phenomenological approach

> *Phenomenology of architecture is a theory which understands architecture in concrete, existential terms...after decades of abstract, 'scientific' theory, it is urgent that we return to a qualitative, phenomenological understanding of architecture (ibid, p.5).*

Phenomenology is a philosophy that considers the individual's experience and has proved particularly influential in architecture mainly due to its emphasis on perception and cognition; although the ultimate aim is producing a solid basis for knowledge (Hale 2000). Seamon (1993) also argues that the ultimate aim of phenomenological approach is not merely idiosyncratic descriptions of the phenomenon, though such descriptions are often an important starting point for existential phenomenology. "*Moreover, the aim is to use these descriptions as a basis from which to discover underlying commonalities that mark the essential core of the phenomenon*" (Seamon 2000, p.3).

The phenomenological approach offers a way of looking at the person-environment relationship and for identifying and understanding its complex, multi-dimensioned structure. It provides a useful conceptual language for bridging the environmental designer's more intuitive approach to an understanding with the academic researcher's more intellectual approach. Phenomenology, therefore, can be identified as a form of qualitative inquiry but involving a particular conceptual and methodological foundation (ibid, p.3-4).

Seamon (2000) argues that "*The rigorous application of a phenomenological perspective to the built environment entails a critical analysis of the design process to ensure that the primacy of experience is not lost to the complexities or scale of the development and...to the lure of geometry as an end in itself. In particular, phenomenology entails a critical distinction between lived-space and geometric space, between the experience of place and the geometric simulations which are a means to its effective transformation*". The difference between lived-space and geometric space is crucial in the phenomenological approach as many typological architectural analysis focus on the geometrical and structural issues and, therefore, exclude the lived-space aspect which deals with the perception of people experiencing the space. A number of studies such as Thiis-Evensen (1989) explore the perceptual and existential aspects of architectural space, which is essential to any phenomenological approach.

Through a hermeneutic reading of many different buildings in different cultures and historical periods, Thiis-Evensen (1989) suggests that there are three basic architectural elements which are common to all architectural styles and traditions: the *floor*, *wall* and *roof*. The essential existential ground of these three elements, he argues, is the relationship *between inside and outside*. The floor, wall, and roof, just by the way they are, automatically create an inside in the midst of an outside, though in different ways: the floor, through *above* and *beneath*; the wall, through *within* and *around*; and the roof, through *under* and *over*. Natural light plays an important role in the inside/outside division as it brings a sense of the outside and nature into the inside of the building. Therefore, daylighting can be considered an important element of a phenomenological approach to architecture as it is a strong stimulus to human senses.

4.6.1. An architecture of the seven senses

The world around us is perceived through our five natural senses (faculties of sight, smell, hearing, taste and touch) and yet there are more senses involved in experiencing architectural space. Every touching experience of architecture is multi-sensory; qualities of matter, space, and scale are measured and understood by *eye*, *ear*, *nose*, *skin*, *tongue*, *skeleton* and *muscle (Pallasmaa 1994).* Architecture, according to Pallasmaa, involves seven realms of sensory experience which interact and infuse each other. His *Eyes of the Skin (1996)* also proposes that our other senses have an interconnected nature that can be developed and utilised. This is an opportunity for architects and designers to create buildings which involve human senses and enrich their experience of space. As an example the Chapel of Nôtre Dame du Haut Ronchamp by Le Corbusier (1954) might be seen to have reached an architecture of the seven senses.

> *Above contrasting textures (extremely rough plaster against concrete) the concave ceiling appeared moulded by light, space, and the upward thrust of the thick walls...The inclined floors, following the natural slope of the hillside, engaged body*

movements...Ronchamp's paradigm of light and space is nearly the inverse of the Pantheon. While one has a mysterious rhythm in a concave, curvilinear space scattered with colour, the other is a symmetrical abyss, a hollow purity in black and white (Holl 1994).

Fig 4.13 Chapel of Nôtre Dame du Haut Ronchamp by Le corbusier (1954), (Photos © F. Ai)

In his first visit to the Pantheon in Rome, Holl (1994) describes how his senses were engaged by the qualities of the space under the dome:

In the tremendous space of the Pantheon, I first felt the passion, the forceful capacity, of architecture to engage all the senses...Each day, its appearance varied with the dramatically changing shaft of light that passed through the open oculus...Its silent clarity, ordered by light and darkness, embraced my imagination with its abstract inversion of interior and exterior space (ibid, p.122).

Holl (1994) argues that a single work of architecture is rarely experienced in its totality (except in graphic or model form) but as a series of partial views and synthesized experiences. It can be compared to a city which can never be seen as a totality, but as an aggregate of experiences, animated by use, by overlapping perspectives, changing, light, sounds and smells (ibid, p.130). Pallasmaa (1994) also argues that "*an authentic architectural experience consists of approaching, or confronting a building rather than a façade; of the act of entering and not simply the frame of the door, of looking in or out of a window, rather than the window itself" (ibid, p.35).* Therefore, it can be seen that a phenomenological approach toward the experience of architecture not only considers the seven senses and the human sensual engagement in its assessment, but also implies the understanding that buildings are not an end in themselves; rather, *they* *frame, articulate, restructure, give significance, relate, separate and unite, facilitate and prohibit (ibid, p.35).* The perception of light is an important factor in this understanding and phenomenological experience.

An architecture of seven senses goes hand in hand with the *Multiple Intelligence theory* of Howard Gardner as well as the *"mind map"* theory coined by Tony Buzan in the late 1960s in terms of learning environments (Hoerr 2000). The brain-based learning research suggests that students learn best is rich environments which stimulates a variety of senses (Nair and Fielding 2005, p.114). Interaction of the brain with its environment suggests that the more enriched the environment, the more enriched the brain and therefore, enhancing learning levels (Lackney 1999). Kotulak (1996) also advocates enriched environments which stimulate learners' senses and emphasizes that an enriched environment can contribute up to a 25% increase in the number of brain connections both early and later in life. Therefore, the benefits of a phenomenological approach to educational space design (stimulating and involving a variety of learners' senses) can be supported, to some extent, by the above research evidence.

4.6.2. Phenomenology and experiential aspects of lighting

Light cannot merely be considered as an isolated visual entity, because it has more complex effects with architectural space. For instance, daylight has complex interconnections with perceptions of sound, heat, scale and other qualities of architectural experience that are easily forgotten in the cold, rational world of the Lux level (Hodges 2002, p.12). The experience of light in a space is interconnected with other human senses as well as vision. Therefore, the experiential aspect of lighting in a space is a key element in architectural design, taking into account the phenomenological approach and creating an architecture of the seven senses.

Texture, colour and material are all elements of a building that have a decisive effect on lighting. Plummer (1987) writes vividly of the effect that building form and surface relief can have. Chiaroscuro, the sculpting and texturing of a surface is given particular emphasis;

> *"...entangle and harbour light deeply within the textural pores of a substance, filling hollows with pooled shadows and skimming peals with lambent rays...such a light is wedded to a substance, settling and steeping into the physical anatomy." (Plummer, 1987, p.29)*

The poetic description of light, either visually through paintings and photography, or linguistically can be considered as one aspect of the phenomenological approach. Henry Plummer's *Poetics of Light* (1987) is an essay using linguistic description to directly describe light and its effects.[1]

Gaston Bachelard in his *Poetics of Space* (1994) refers to the way light affects and moves people, and the way it "inhabits" a space. Christian Norberg-Schulz, whose writings are philosophical as well as poetic (Norberg-Schultz 1980; 1996), emphasizes what light means; the dynamic of light, shadow and space. This is not to say that the needs of the user are ignored, instead light can be seen to enhance our spaces in ways beyond simply being able to read or see clearly (Hodges, 2002, p.6).

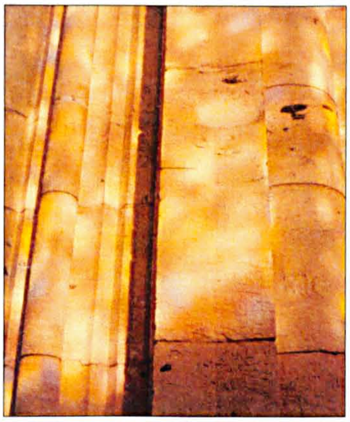


Fig 4.14. St Ouen Cathedral, Rouen

Fig 4.15. Ronchamp, Le Corbusier (1954) Window detail

4.6.3. Perception issue and daylighting design

Hale (1989) defines perception as a process in which an organism detects the external world to interpret and be aware of it through its senses. In other words, perception is

[1] Inspired by Plummer's work, the author studied the relationship between light, shadow, lightness and other spatial ingredients in Japanese architecture and the Zen Buddhism school of thought
Ai, F. (2004). "Light-Shadow-Lightness and other spatial ingredients: Learning from Zen Buddhism." A+T (Architecture & Technology) **3**. The article is attached to the thesis in Appendix B.

an active process through which we make sense of the world around us (Lawson 2001). Holl (1994, p.134) values perception as a model for architectural thought and believes the art of seeing brings a certain joy in engaging with the world, and the way it is revealed to us.

Studying the mechanism of perception shows the importance of vision among other senses in terms of perceiving space. The fact that 2/3 of nerve fibres going to the central nervous system are from the eyes indicates the importance of visual perception (Lawson 2001, p.42). Visual perception involves far more that a passive and mechanistic response to patterns of light: it is a complex, active process of information selection, filtering, interpretation, and storage. It is important to note that context, prior experience, and expectations are combined with incoming sensory data to create meaningful perceptions (Lam 1977). In his book *"Perception and lighting as Formgivers for architecture"* Lam suggests there are three aspects of perception: the *attributive*, the *expectant*, and the *affective* which are inextricably interwoven in real life (ibid, p.34).

The *attributive* establishes links to prior experience, activating expectations and provoking emotional responses. *Expectations*, in return, influence what will be chosen as the next object of sensory attention; while the *affective* component is concerned with how each stimulus affects our emotional or evaluative responses to stimuli (ibid, p.34). As an example, people expect a particular pattern of lighting for a space as well as certain behaviour in a space (Tregenza 2002). Patterns of brightness are not sensed through a purely photometric process. On the contrary, they are perceived in the context of experience and become part of a behavioural setting (ibid).

Lam (1977) proposes an approach to lighting from perception and adaptation point of view, identifying expectation and combinations of direct and diffuse light as additional factors in design of spaces. Lam seeks a balance between the scientific quantitative environment, where lighting requirements are set out in purely numerical terms, and the subjective descriptions of light to 'create a mood'. He argues that performance criteria should be based on perceptual needs. Most importantly Lam identifies lighting for need, not simply to satisfy regulations:

"All spaces should be designed and lighted to satisfy specific needs, not just engineered to meet code requirements - different lights, as it were, for different sites." (ibid, P.12)

William Lam argues that lighting regulations and designers should base their principles of lighting on human perception. This, he argues, will lead to better environments for users, designed around perceptual needs. This includes combinations of diffuse and direct light, adaptable local lighting and working with colour, texture and view.

The problem Lam identifies with regulatory requirements for lighting is they are often over-engineered and promote high illuminance which often is at the expense of the quality of the lighting in space:

"...we discovered that, when we switched over from indirect lighting with very low levels to direct lighting with the new fluorescent tube and increased light levels by three times perhaps, we did not really change or improve vision at all. Although the light went up by three, the contrast, generally speaking, went down..." (ibid, p.64)

High levels of illumination, therefore, do not guarantee a better quality of light. In fact, it is the pattern of light sources and the nature of their relationships to other elements in the visual field which largely determine the overall quality of the luminous environment (ibid, p.5). Lam (1977) indicates that there are different factors determining the quality of light which are briefly as follows: *the quantity of light*; *the experience and attention of the observer*; *the characteristics of object, size, colour, texture, etc.*; *simultaneous contrast*; context such as information content, patterns, figure/background; *adaptation*; *illumination qualities such as geometry, consistency, etc* (ibid, p.52).

Cuttle (1971) also develops the idea of lighting pattern, emphasising on the relation between the quantitative and qualitative aspects of light according to visual rendition. He elaborates on the idea of lighting pattern and suggests that there are three types of lighting pattern: the illumination pattern, the shadow pattern and the highlight pattern. An illumination pattern will be provided on any solid object, but highlight and shadow patterns are evident only when the surface textures are suitable (ibid, p.173).

Pallasmaa (1994) argues that homogeneous light paralyzes the imagination in the same way that homogenization eliminates the experience of place. He suggests that deep shadows and darkness are essential, because they dim the sharpness of vision and invite unconscious peripheral vision and tactile fantasy (ibid, p.34). Nonetheless, Arnheim (1974) suggests that distribution of brightness helps to define the orientation of objects in space and it gives unity and order not only to the shape of single objects, but equally to that of a whole setting (p.313). Therefore, it is important to understand the perceptive differences between directional and diffused light to use various lights in different places appropriately. The author has explored various lights in a contemporary case study, the new British Library, and studied the relationship between light and form in the building as perceived by him (Ai 2004). The full article is enclosed in appendix C.

Visual perception & Brightness

Arnheim (1974) argues that the brightness of objects is perceived basically as a property of their own rather than as a result of reflection. For instance, the brightness of a wall washed by daylight through hidden clerestories is usually perceived as the property of the wall itself rather than the reflection of light from another source. The brightness we see depends on a number of complex factors. It depends on the distribution of light in the total situation, on the optical and physiological processes in the observer's eyes and nervous system, and on the object's physical capacity to absorb and reflect the light it receives. In other words, there is perceptually no direct way of distinguishing between reflecting power and illumination, since the eye receives only the resulting intensity of light but not information about the proportion in which the two components contribute to the result (ibid, p.315). This 'sensation' not only depends on the luminance of the object and the viewer's eyes, but also on the experience and the mood of the viewer as well as the environmental luminance of the surroundings (Steffy 2002, p.21).

The psychology of lighting depends not only on the light intensity, pattern and colour, but also on the viewer's previous experiences, culture and mood (Steffy 2002, p.20). Different viewers might agree on the level of visual comfort for instance, but their perceptions can vary to a great extent. Therefore, the psychology of light is less tangible than the physiology of light (ibid). However, a number of studies over the years indicate that lighting influences perceptions in a meaningful and, to some extent, predictable way (Collins 1993). Flynn and his colleagues concluded that the experience of lighted space is somewhat a shared experience (Flynn 1973).

Flynn (1992) has developed three different types of brightness and suggests a relationship between the type of brightness and the mood and ambience it could offer. He asserts that light is a medium that communicates spatial ideas and moods and has the potential of creating impressions such as sombreness, playfulness, pleasantness, and tension among many qualities. Light influences psychological impressions such as intimacy, privacy and warmth.

He recognises three brightness parameters affecting subjective impressions of observers: *brightness uniformity*, *brightness location* and *brightness intensity*. Brightness uniformity or the distribution of luminance (uniform versus un-uniform) influences *spaciousness*; brightness location or the location of luminance (peripheral versus overhead) influences *pleasantness and spaciousness*; and the brightness intensity or intensity of luminance (bright versus dim) influences *visual clarity* (Steffy 2002, p.20). Therefore, various combinations of these three patterns may structure specific impressions of *spaciousness*, *relaxation*, *privacy*, *pleasantness*, and *visual clarity*.

Conclusion

Perception theories and visual perception studies about light and brightness, as discussed above, challenge the customary numerical approach to daylighting design. To design good quality, appropriate, and relevant luminous environments, it is counterproductive to state oversimplified objectives in purely numerical terms and also not sufficient to state vague objectives such as '*create a mood*' (Lam 1977, p.5). Lam suggests that designers must develop and accept a *new vocabulary and grammar of form*, phrased in *visual and perceptual rather than numerical terms*. He argues that a new process of design would be far more important than any numerical criteria.

> *Regardless of specific activity needs, people have important biological needs for orientation, order, and continuity, which demands that there should be common denominators and reference points in related spaces* (ibid, p.83).

He asserts *positive objectives* in daylighting design as opposed to the *conventional objectives*. Positive objectives such as the creation of positive *focus, sparkle, orientation*, and *guidance*, and lighting for *biological need* are, he says, more important than conventional objectives of eliminating glare, providing adequate task lighting, etc (ibid, p.89).

Finally, based on the perception principles and the new objectives, Lam (1977) derives some rules and recommendations as follows (p.97-100):

1. A clear design intent should be evident in all elements of the visual field
2. Structure should be illuminated directly emphasising the modules, the shape, and the material.
3. Generally one should illuminate continuous planar elements such as walls evenly to appear continuous.
4. To conform to expectations, use low levels of illumination for low colour temperature sources etc.
5. The shape and placement of exterior windows should be derived from the nature of the view.
6. Avoid creating a focus in the luminous environment on unpleasant or distracting elements.

The above recommendations are useful design guidelines based on perception principles and are mostly concerned with artificial lighting. The first guideline applies to all aspects of designing visual elements in general including lighting, colour, material, details and so on. The second rule addresses lighting and more specifically artificial lighting. It highlights the importance of the harmony delivered by the lighting among different element in the visual field. It may also be related to the first rule of a clear design intent. The third rule also addresses lighting and particularly electric lighting in providing continuity and harmony to the visual lit field. The same applies to the forth and sixth rule while the fifth rule addresses daylighting, the view

and windows. The role of windows is not merely to provide daylight or natural ventilation; the nature of the view is perceptually a significant factor in designing exterior windows and should be incorporated in daylighting design.
Research on perception may enable an understanding of some of the properties of light (Lam 1977) as well as offering some general guidelines (above), but on the aesthetic aspects related to visual appearance, there are very few developments because of the associated subjectivity (Flynn 1992). This, of course, is considered one of the deficiencies of the phenomenological approach.

4.6.4. The inadequacy of the approach

The phenomenological approach offers a qualitative investigation into the experiential aspects of daylighting design, but as it is mainly a subjective assessment it is difficult to provide a tangible basis for designers to apply in their design process. Nonetheless, it gives a good understanding of what issues designers should pay attention in order to create an involving and inspiring daylit ambience. It can be argued that a phenomenological approach is more of an intuitive approach and can hardly establish an all-inclusive basis for a good practise of daylighting design. Maldonado suggests that the area of pure intuition must be based on knowledge of past solutions applied to related problems, and that creation is a process of adapting forms derived either from past needs or from past aesthetic ideologies to the needs of the present (Colquhoun 1981). Therefore, it seems the inadequacy of phenomenological approach can be fulfilled by integrating with previously discussed typological approach.

4.7. The integrative approach

Having studied the quantitative vs. qualitative and, likewise, typological vs. phenomenological approaches, this research proposes an integrative approach which tries to bridge the gaps in each one of them as discussed in previous sections. The typological approach has the benefit of informing the designers of available daylighting component types of which they can choose from or combine to suite their design problem. It also can act as a design palette which enables designers with a range of daylighting component possibilities. However, as already discussed, it restricts the designers' imagination and creativity by encouraging them to choose from a table of ready made choices. Besides, it does not address the experiential aspect of the lived space and, therefore, it might exclude the subtleties of experiencing daylight in an interior space. This is where the phenomenological approach can respond to the above subtleties and complete the typological approach deficiencies.

The phenomenological approach addresses the existential and perceptual aspects of experiencing daylit space and tries to enrich our experience of architectural space by involving our seven senses (Pallasmaa 1994). This approach is not as straightforward as the typological approach as it is rather a subjective and perceptual matter. Therefore, the integrative approach takes the typological approach as a basis for designers and the phenomenological approach as an evaluative method to assess and promote the experiential aspects of daylighting component typologies.

4.8. Summary & Conclusion

This chapter started with historical background and the principles of light and daylighting in architecture. The aim of this chapter was to explore and discuss different approaches to daylighting. It identified two main categories of daylighting approaches: the quantitative and the qualitative. The literature review indicates the lack of research on the qualitative aspect of lighting comparing to considerable research on the quantitative aspect. Survey no. I, namely as the impression of light, highlighted the importance of qualitative aspect of lighting in people's everyday usage of language in order to describe light in interior spaces. It was followed by classifications of light which mainly deal with the qualitative aspect of lighting.

The literature review also identified two main approaches of daylighting: the typological and the phenomenological approach which corresponds with the above quantitative vs. qualitative approaches. The typological approach was explored and examples of its application to daylighting design were introduced. It was, then, followed by Survey no. II which was an exploration into a typology of daylighting components with a 'generative approach'. The critique of typological approach and its deficiencies led to the phenomenological approach. Phenomenology and experiential aspects of lighting were discussed and as a necessity perception issues and daylighting design were briefly investigated. Finally, this chapter proposed an integration of the typological and phenomenological approach in order to bridge their individual deficiencies.

CHAPTER 5: REFLECTED DAYLIGHTING AND THE INFLUENCING FACTORS

5.1. Introduction

Chapter 2 discussed daylighting issues of the warm-dry climate of Iran because of the bright sky and harsh direct sunlight. The general trend in the vernacular architecture of the region is to restrict openings or to obstruct direct sunlight from windows. Therefore, it seems the alternative way of natural lighting in such a climate is to use reflected lighting. This chapter investigates the use of reflected light in contributing to daylighting design particularly in warm-dry climates.

There is also another important reason by which reflected lighting is a preferred way of admitting sunlight to interior spaces in such climates: the uniformity of daylighting. Direct harsh sunlight brings an excessive amount of light to the windows and brightens the immediate space inside the room around the window. This, in effect, leaves the rest of the room, in particular the depth of the room, in much less levels of luminance which, in turn, causes glare and discomfort. The lack of uniformity of sunlight in the room does not provide a visually comfortable space or an efficient learning space, and so will form the focus of this thesis. Therefore, the enhancement of the uniformity of daylight and a better distribution of light across the room is another feature of appropriate application of daylight in schools and classrooms especially in this climate.

5.2. Reflected lighting

In a warm-dry climate it is more usual to use reflected light as a source of natural illumination in buildings due to the bright sunlight and overheating problems. Solar control has a major role in the design of buildings in such climates and windows are often designed to exclude direct sunlight. The necessity to keep direct sun off the windows to avoid discomfort suggests the importance of applying shading devices in this climate. In such circumstances, reflected light from external surfaces, the ground and opposite buildings, and other reflecting elements can be a major source of diffused light. Shading devices can also become a secondary source of reflected light. The amount of light reflected by the ground surface can be significant and ground-reflected light has been highlighted in sunny climates.

Hopkinson and Petherbridge (1953) and Griffith et al. (1953) identified the influence of the ground as an important source of natural lighting for buildings located in regions where sun is often unobstructed. Lam (1986) also emphasises the importance of the use of the ground to reflect sunlight into buildings in sunny climates. In a more detailed study, Tregenza (1995) suggests a method for the assessment of the ground reflected component in the mean illuminance on the working plane in a given room.

More recently, Cabús (2002) found that the influence of reflected sunlight on interior illuminance is significant in tropical climates, and even in the cloudy regions of the tropics, the influence of reflected light on interior illuminance can be very large. He argues that there is a key zone of ground outside window that provides the majority of the reflected light (ibid, p. 9-2). He suggests, as a rule of thumb, the boundaries of the ground peak region, where the most amount of light is reflected into the room, for a one storey building (from point A to point B) can be found by the angles GSA=45° and GHB=70°, where G if the base of the façade, S is the sill and H is the head of the window (ibid, p.8-12). The ground reflecting effect for daylighting is independent of the building type and can be considered for different buildings. However, depending on the function of the building and its illuminance requirement, the material and colour of the ground have considerable influence on the amount of reflected light. This issue will be discussed in the surface features section 5.4.4.

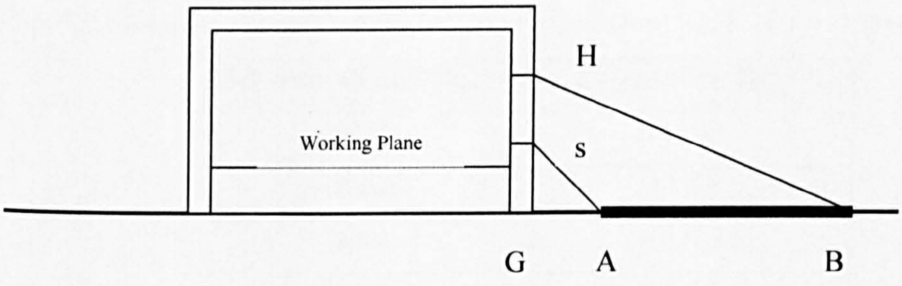


Fig 5.1. Ground peak reflecting region (AB), after (Cabús 2002)

5.3. General physical factors

There are also other general physical factors which have significant influence on the amount of reflected light into a room. The building orientation, the proportion of the street or courtyard and the building configuration are the main factors influencing reflected daylighting.

The main objective in considering a given orientation in warm-dry climates is to minimize the impact of the sun on the building in summer. This means keeping direct sunlight off the windows to prevent visual discomfort and overheating, specifically in summer. Most of the world's hot-dry regions are located in subtropical latitudes, where the highest intensities of impinging solar radiation in summer occur on the eastern and western walls (Givoni 1998, p.346). In winter solar radiation is more dominant on the southern wall. Therefore, this pattern of solar irradiation on different walls results in a clear preference for north-south orientations of the main façade (ibid). In the Northern Hemisphere, for instance, it is easy and economic to provide shading for the southern windows and walls in summer by horizontal overhangs. Southern overhangs can effectively block the sun rays in summer as the sun altitude is quite high (70 to 80 degrees) while allowing the low angle sun to warm up the walls in winter (ibid, p.347).

Building orientation is an important factor even with overcast sky conditions. Table 5.1 shows the variation of illuminance with four general building orientations. It indicates South facing windows still have the highest value of illuminance under overcast sky. The orientation factor is a value used in daylight quantity calculation from the following formula (DfEE 1999, p.17):

Interior Illuminance (lux) = Exterior illuminance (lux) × DF/100 × Orientation factor

Orientation of window	Orientation factor
North	0.97
East	1.15
West	1.21
South	1.55

Table 5.1. Window orientation factors (DfEE 1999, p.17

The profile proportion of the space in front of a window (the height of the wall opposite the window over the horizontal distance between the window and the opposite wall) could also influence on blocking direct sunlight from windows as well as the amount of reflected light which a window receives for natural illumination. Such space is either the street canyon (the space enclosed by the walls at both sides of the street) for rooms which overlook a public space, or the courtyard or patio canyon (the space enclosed by the walls surrounding the courtyard) in case of introvert buildings in which rooms overlook a semi-private space. Therefore, the relationship between the amount of reflected light and street canyon proportion or courtyard canyon proportion needs to be investigated. Street, courtyard or patio canyon proportion will be referred to as street canyon proportion in this research in order to simplify the terms. Besides, the relationship between the amount of reflected light and building orientations needs addressing. The next section investigates the effect of building orientation and street canyon proportion on the amount of reflected light onto the window through a series of experiments.

However, before moving on to the physical model experiments, it is important to address the configuration of a building as another factor influencing reflected lighting. Building configuration is a key decision in the early stages of design which affects the daylighting performance of the building significantly. For example, a single storey building has the advantage of sidelighting as well as top lighting, while a multi-storey building can clearly not offer top lighting to lower floors. Another example is a linear plan building which can have windows on both sides while a deep plan building cannot offer bilateral daylighting.

Double shell buildings are also an appropriate configuration for warm-dry climates as they infiltrate the sunlight through a complicated building envelope (Baker and Steemers 2002). In such buildings there is a transitory space between the external envelope of the building and the internal envelope on which the windows or openings admitting daylight to the rooms are located. A good example of a double shell building is the National Assembly Building in Dhaka by Louis I Kahn (Fig 5.2). In this building, harsh direct sunlight is controlled and filtered through the transitory space between the external and the internal envelopes of the building. Atria, courtyards, porches, galleries, etc. are among important elements of building configuration which can affect reflected lighting performance. Tab 5.2 illustrates building configuration types and summarises their benefits for reflected daylighting.

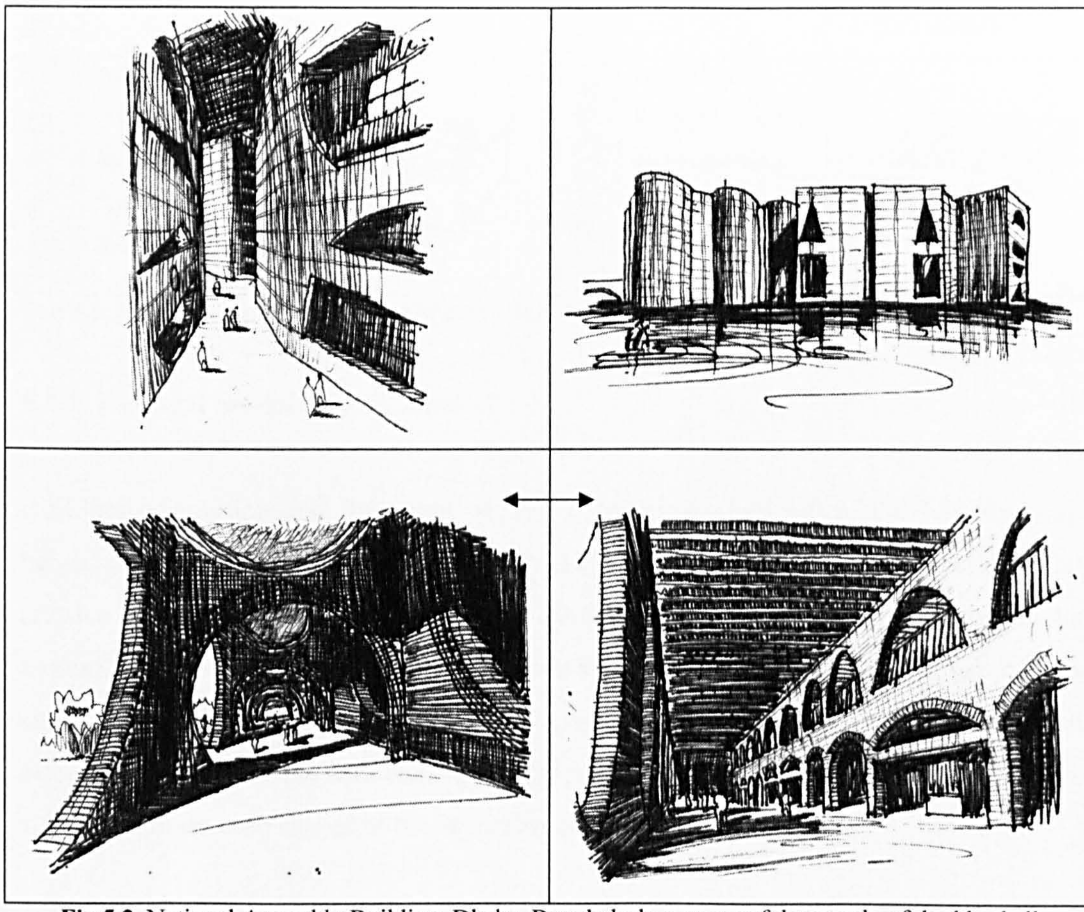
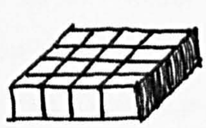
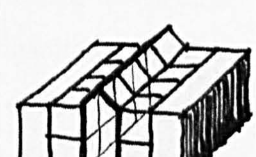
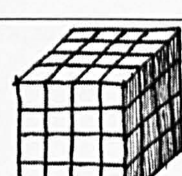
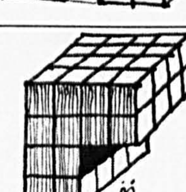
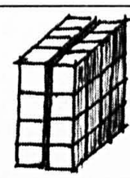
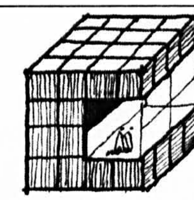
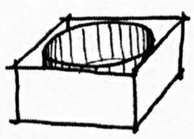
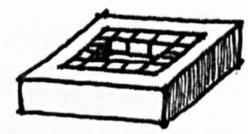


Fig 5.2. National Assembly Building, Dhaka, Bangladesh; a successful example of double shell configuration in hot and humid climate; the two lower drawings show adjacent porches which block the harsh direct sunlight and provide pleasant shade and shadows, the porch surfaces reflect the light deep inside the building

BUILDING CONFIGURATION					
SINGLE-ST.	Advantage of top-lighting, diffusing or redirecting elements needed		ATRIUM	Less contrasting light for interior spaces, solar control needed	
MULTI-ST.	Lack of top-lighting for lower floors, Deep plan issues		PORCH	Provides shade & less glare, enhances reflecting lighting	

BILATERAL	Advantage of side-lighting from both sides /needs diffusing		**GALLERY**	Less contrasting light, enhances reflected lighting	
DOUBLESHELL	Advantages for reflected lighting by two exterior layers and transitory spaces		**COURTYARD**	Reducing daylight levels and improving reflection by inner surfaces	

Tab 5.2. Building configuration types affecting reflected daylighting, after (Baker and Steemers 2002)

5.3.1. Physical model experiments

Building orientation and the street canyon proportion (the ratio of the window wall height over the depth of the space enclosed by the window wall and opposite walls) are two main factors affecting preventing direct sunlight on the window as well as the amount of light being reflected on the windows. There are, of course, other factors such as solar shading devices, lightshelves, window reveal depth, etc. which all also affect the amount of the reflected light. Therefore, there are two main questions to be addressed in the two stages of this experiment.

Firstly, at which orientation and canyon proportion a window is under the shade without any shading devices. Secondly, at which orientation and canyon proportion there is most amount of reflected light on the surface of the window. In the second stage a minimum overhang is introduced where necessary to study the whole range of orientation and canyon proportion. These experiments are in relation to school design and typical conditions whereas classroom windows overlook either the street or the courtyard. Therefore, the canyon proportion (P) in these experiments refers to the height of the wall opposite classroom window wall over the depth of the space between the classroom window wall and the opposite wall across the public street or the courtyard. In these experiments, the height of the classroom window wall and the opposite wall are assumed equal.

5.3.2. Sunlight Exclusion Experiment (SEE)

As discussed earlier, protecting the openings and windows from direct sunlight is one of the main strategies of daylighting in warm-dry climates and the evidence to this rule is seen extensively in the vernacular architecture of the region. Shading devices are usual solutions to protect the windows. Horizontal shading devices are mainly needed for south facing windows (in the Northern Hemisphere) and vertical shading devices for east and west facing windows, while north facing windows do not require any shading devices. However, if the building is in an urban environment where it is surrounded by other buildings, which is sometimes the case in Iranian schools, the surrounding buildings might offer shading to the classroom windows instead of using shading devices. The inside envelope of a courtyard configuration building can also offer shading depending on the proportion of the courtyard space. Therefore, this experiment tries to find out the specifics of such classroom windows where they are not exposed to direct sunlight without any shading devices.

Stage 1

Purpose: This experiment aims to explore the range of orientation in correlation with the canyon proportion in which a window is not exposed to direct sunlight without any shading devices.

Equipments:

The main equipment at this stage is the Heliodon at the Sheffield School of Architecture laboratory. It is a device which creates the appropriate geometrical relationship between an architectural scale model and a representation of the sun. By adjusting the solar declination (season), the earth's rotation (time of day), and site location (latitude) a heliodon can simulate sunlight penetration and shading for any combination of site location and time (PEC 2004). Fig 5.3 illustrates the heliodon consisting of a vertical quarter circular ring with a number of bulbs, a central table for the model and the computer for the control of the system.

Fig 5.3. The Heliodon

Procedure:

The canyon proportion is defined as the ratio of the building height over the width of the street or the courtyard in front of it. The simulated school wall is a multi-storey linear configuration alongside a street. The reason a street is simulated in this experiment is related to Iranian urban condition where multi-storey buildings across the street can offer shading to classroom windows. Nevertheless, the results will also apply to courtyard configuration schools where the courtyard span is not too wide. This experiment could have been simulated with the assistance of computer software such as Ecotect, but the reason cardboard modelling was chosen was to achieve a better understanding of how the sun works throughout the year in relation with different building orientation and canyon proportions. The different street canyon proportions studied at this experiment are P = 0.5, 1, 1.5, 2, 2.5 and 3. A cardboard model was made with six points on one of the walls each representing the bottom of a window placed at each of the above canyon proportions. A large piece of cardboard was attached to the opposite wall to stop any side-light penetrating the canyon since the model is supposed to be a part of a long street and the focus of the study is only the sunlight coming down over the opposite obstruction. The following photo shows the model during the study.

Fig 5.4. The first stage model

The model was studied in two extreme climates of school year months, June and December, and a middle month, March, at three times of the day: 8:00, 12:00, and 16:00. The investigation was undertaken at latitude 30 degrees which includes Shiraz, one of the biggest cities in the warm-dry climate of Iran. One can interpolate the results for the intervening months. Finally, the measurement photocell was mounted vertically onto the window wall as can be seen in thetop street section of Fig 5.5.

5.3.3. SEE Results and Discussion

Results:

The following chart illustrates the results of the first stage without any shading devices.

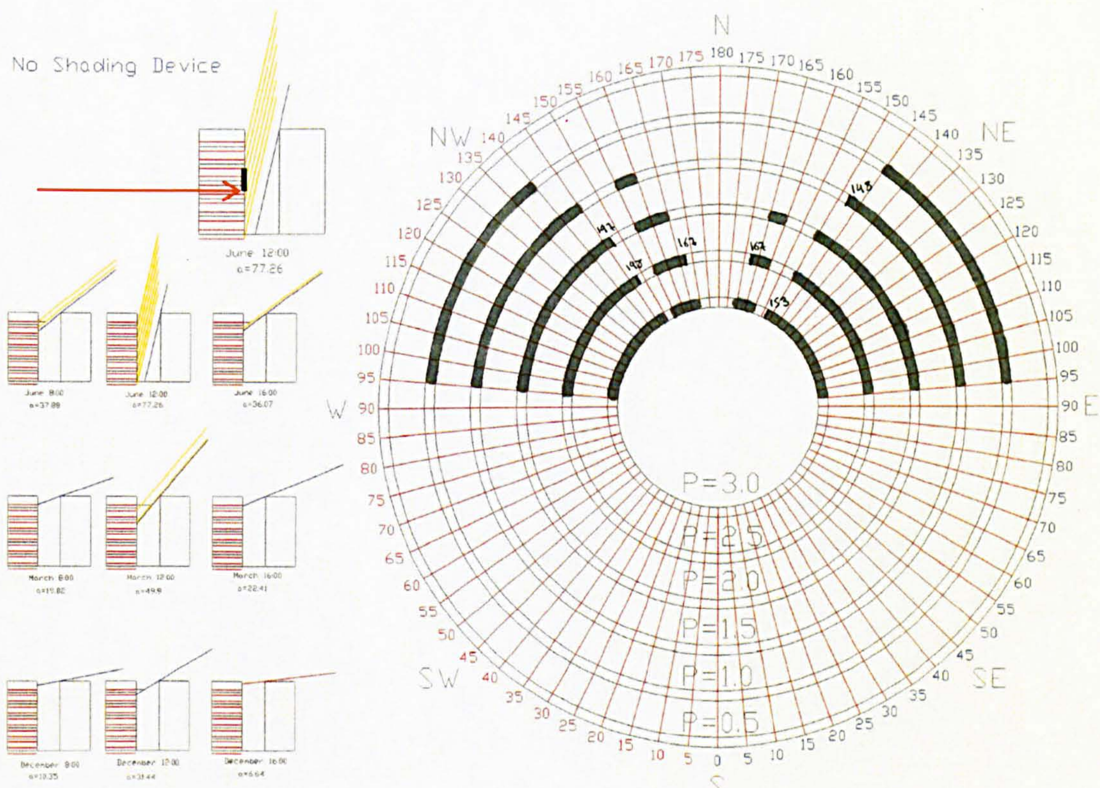


Fig 5.5. The range of window orientation in the shade in correlation with the canyon proportion

The inner ring represents the deepest canyon whose height is three times bigger than its width (P=3) and the outer ring represents the shallowest canyon whose height is half its width (P=0.5). The black marks on the ring demonstrate the range of building orientation by which the windows are in the shade. As can be seen in the left hand side diagrams, due to the nearly vertical altitude of the sun in June at midday all the windows representing different canyon proportions are exposed to direct sunlight. Therefore, all cases are not protected from direct sunlight from orientation -95 degree west to 95 degree east anti-clockwise. Besides, the chart also shows that the deeper the canyon, the more it is protected from sunlight on the northern range of orientation.

However, by using a small overhang on the top of the window most of the orientation ranges are protected from the sun. Assuming the height of the windows is 1.5 meters, a 35 cm overhang would protect it from the sun in June. However a 1m width overhang was studied to ensure the protection of the windows from the sun in other months to study the effect of the obstruction and orientation. The following chart illustrates the results.

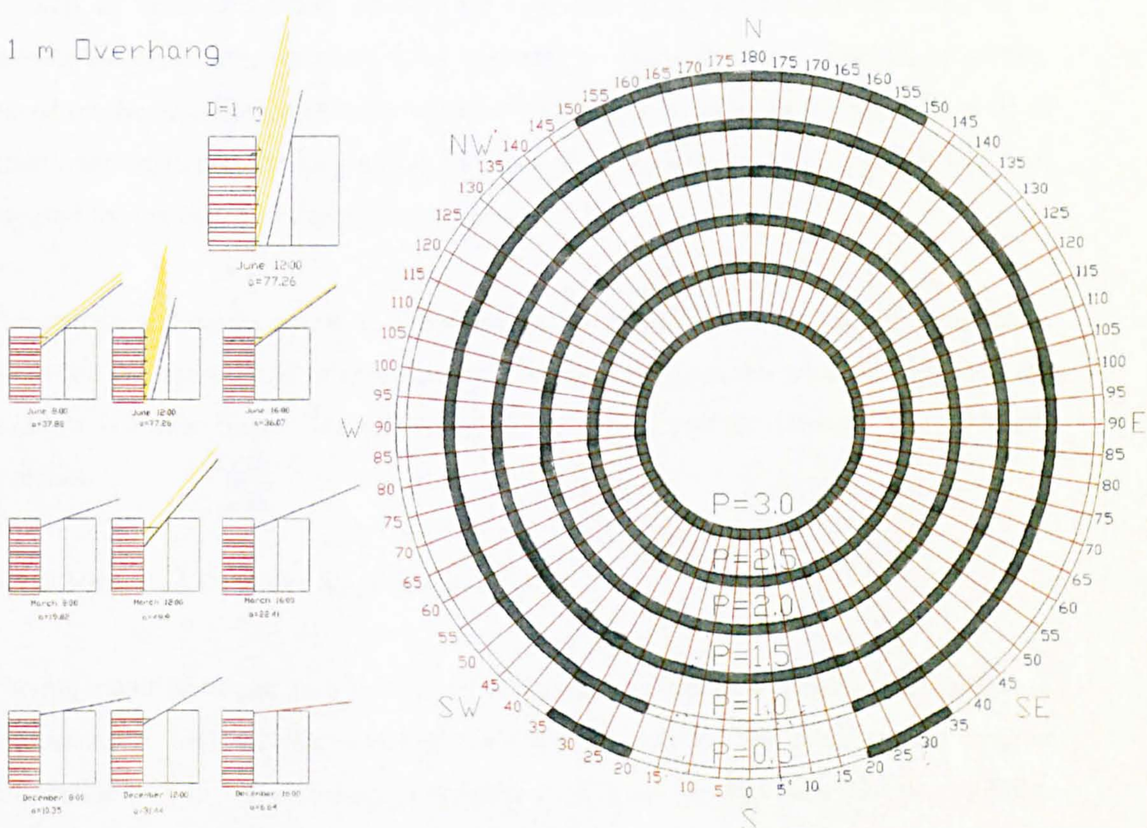


Fig 5.6. The range of window orientation in the shade with a 1m overhang

Discussion:

Although it was expected the windows in a deep canyon are protected from direct sunlight, it was not the case due to the high altitude of the sun in June. However, by providing a minimum overhang all the windows in the canyons with the proportion of

1.5 or higher are protected from direct sunlight. The wider the canyon, the more likely the window is to be exposed to sunlight. This is especially more obvious when the canyon proportion is widened from P=1 to P=0.5. With the height of the window wall half the street or courtyard depth, in most of window orientation the window is partly exposed to direct sunlight even with a 1m overhang. Only the orientation range between 35 to 20 degrees south-west to south and 20 to 35 south to south-east, the window is protected against sunlight with the given overhang. The lesson from this part of the experiment is if the height of the window wall of the school is the same or more than the street or courtyard depth in front of it ($P \geq 1$), then a small overhang will guarantee the protection of windows from exposure to direct sunlight. However, when it is less than the street or courtyard in front of it ($P < 1$), then deeper overhangs as well as vertical shading devices for east and west orientations are required to protect the classroom windows from exposure to direct sunlight. This is, of course, based on the assumption that the window wall height is equal to the opposite wall as mentioned earlier. If the heights are different, then the height of the opposite wall will be used for the canyon proportion calculation.

Nevertheless, the next question is at which range of orientation and canyon proportion there is a greater amount of reflected light on the surface of the window assuming the window is in the shade. The next stage of the experiment is aimed to deal with this question.

5.3.4. Reflected Daylight Experiment (RDE)

Having established the significance of reflected lighting in warm-dry climates, it is important to find out the optimum window orientation as well as the canyon proportion by which the classroom window receive the most amount of reflected light. This part of the experiment only investigates the window orientation and the canyon proportion when the window is in the shade. However, there are other factors such as shading devices, redirecting systems, window reveal depth, surface finish and colour etc. which also contribute to reflected daylighting. They will be investigated in the next chapters.

Stage 2

Purpose: This experiment aims to find the canyon proportion and the orientation of a building which allows the maximum amount of reflected light on the window while it is not receiving direct sunlight.

Equipments:

Apart from using the heliodon in this stage, photocells are used to measure the quantity of light in terms of lux. Fig 5.7 shows the photometry equipments and the photocells which have been used at the experiment.

Fig 5.7. Photometry devices and the photocell

Procedure:

A cardboard model of a long street was made and a photocell was inserted in a wall representing the surface of a window. The street walls are made of cardboard of a higher reflectance than the street floor, representing the lighter surface of the walls and the darker streets in real life in this climate. Typical materials used in building schools in this climate of Iran are mellow brick and light coloured stones where the street is grey asphalt and pavements concrete slabs or grey stones. The classroom window wall is fixed while the opposite wall (of the same height) can be moved to create different profile proportions. Particular latitudes, specific months and the time of the day are not considered at this stage to make the results more generic and applicable to other places. As the altitude (a) of the sun is a determining factor, a range of altitudes such as 10, 30, 50, 70 and 90 degrees are studied in this experiment to cover a possible whole range of sunlight angles in different places. Therefore, to use the results at a particular place one should find out the altitude of the sun rays according to the specific time and location details and apply them to the diagrams. The measurement photocell was mounted vertically onto the window wall as can be seen in the following diagram.

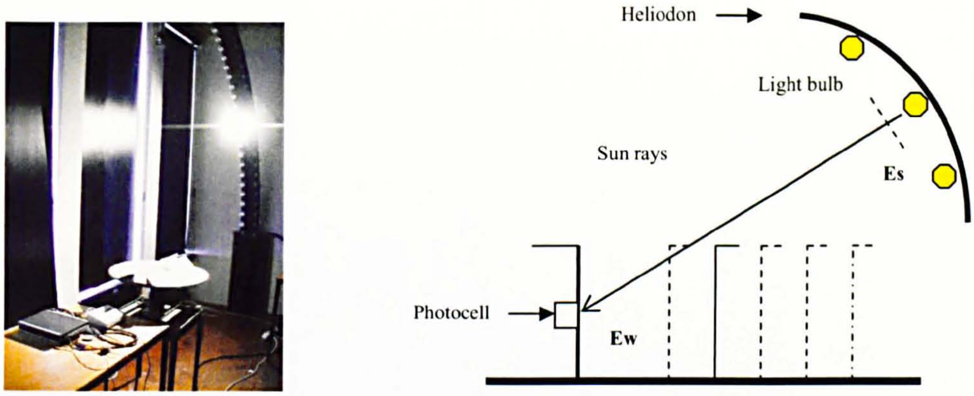


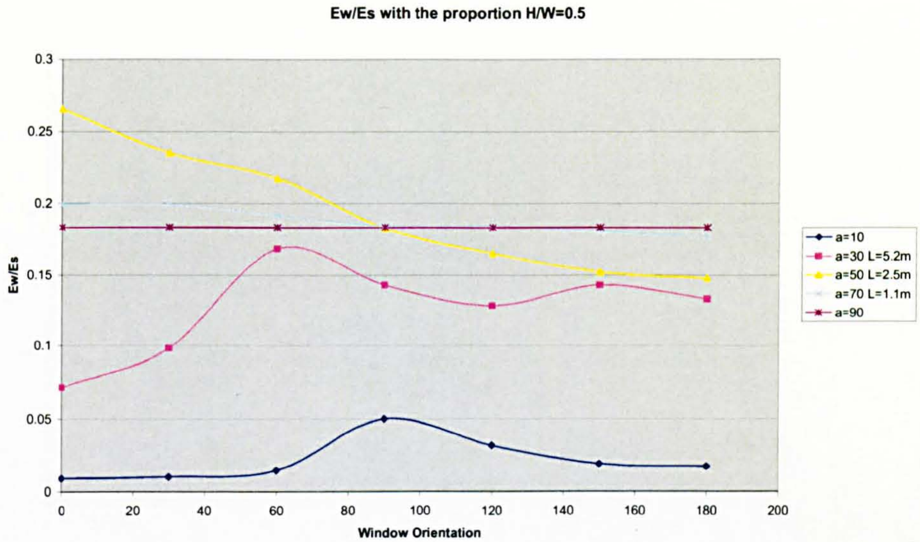
Fig 5.8. The model under photometry and a diagram of the street section with P=1.5 to P=0.5

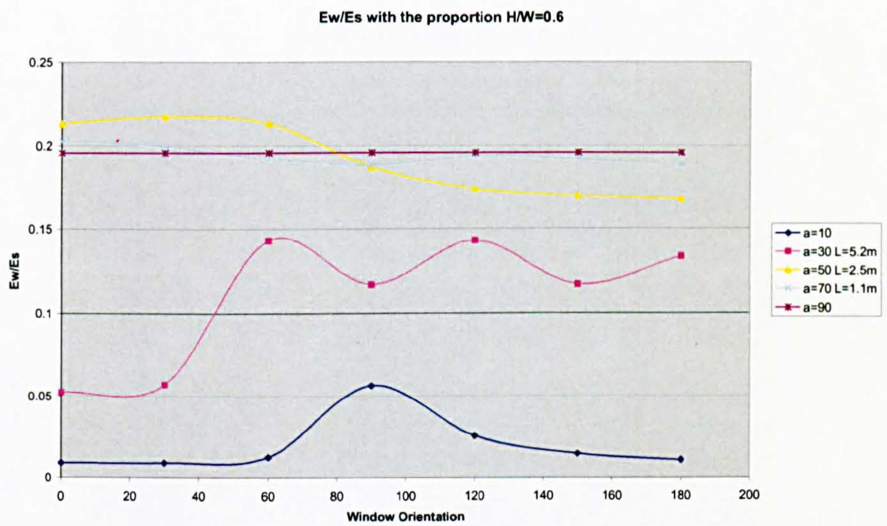
As deeper streets or courtyard canyons are less likely to happen with school buildings in Iran, a new range of canyon proportions are studied at this stage which are P= H/W = 0.5, 06, 0.75, 1.0 and 1.5. Besides, a ratio of **Ew** (the amount of light in lux measured with a photocell on the surface of the window) over **Es** (the amount of light in lux emitted from the light source measured with a photocell on a normal plane as illustrated in Fig 5.8) is considered to be unaffected by the intensity of the emitted light because if the Es of the sun is presumably 50 times larger than the heliodon light bulb, then the Ew on the window will also be 50 times larger than the Ew under heliodon lighting condition. Therefore, Ew/Es ratio is a reliable figure to predict real life situations and is a good indication of the amount of reflected light onto the classroom windows.

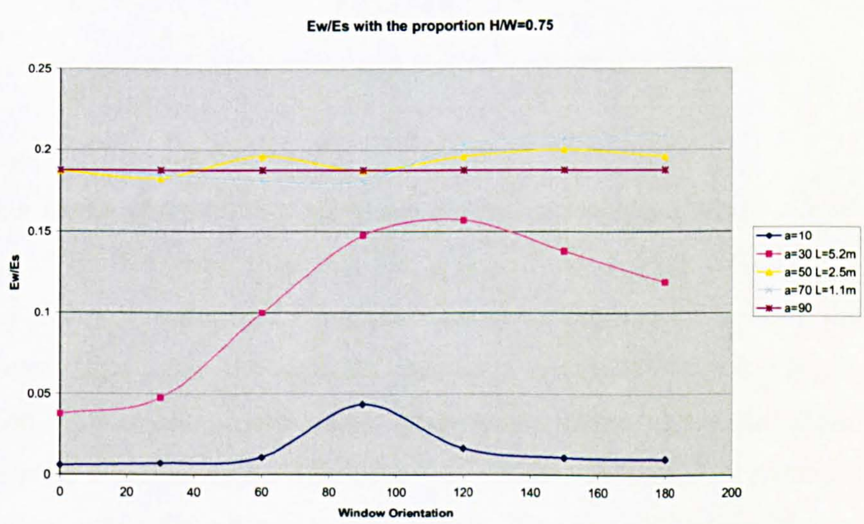
5.3.5. RDE Results and Discussion

Results:

As it is assumed windows are not exposed to direct sunlight in this experiment to study the amount of light reflected off the surfaces onto the window, a minimum overhang is used when required. Therefore, when the sun altitude (a) is 70°, a 1.1 m width overhang is provided to prevent exposure across the range of orientations. With the altitude of 50°and 30°, 2.5 m and 5m width overhang are provided respectively. A 5m overhang is architecturally unreasonable, but it was considered for experimental completeness. The following charts illustrate the results of the experiment. Different colours of the diagrams represent different sun altitudes varying from a=10 up to a=90 degrees. Each diagram represents a specific canyon proportion. The first chart illustrates the results of a wide canyon (P =0.5) when the last chart represents a narrow profile (P =1.5). A discussion of the results will follow after the diagrams.


Ew/Es with the proportion H/W=0.5
Ew/Es
Window Orientation
a=10
a=30 L=5.2m
a=50 L=2.5m
a=70 L=1.1m
a=90


Ew/Es with the proportion H/W=0.6
Ew/Es
Window Orientation
a=10
a=30 L=5.2m
a=50 L=2.5m
a=70 L=1.1m
a=90


Ew/Es with the proportion H/W=0.75
Ew/Es
Window Orientation
a=10
a=30 L=5.2m
a=50 L=2.5m
a=70 L=1.1m
a=90

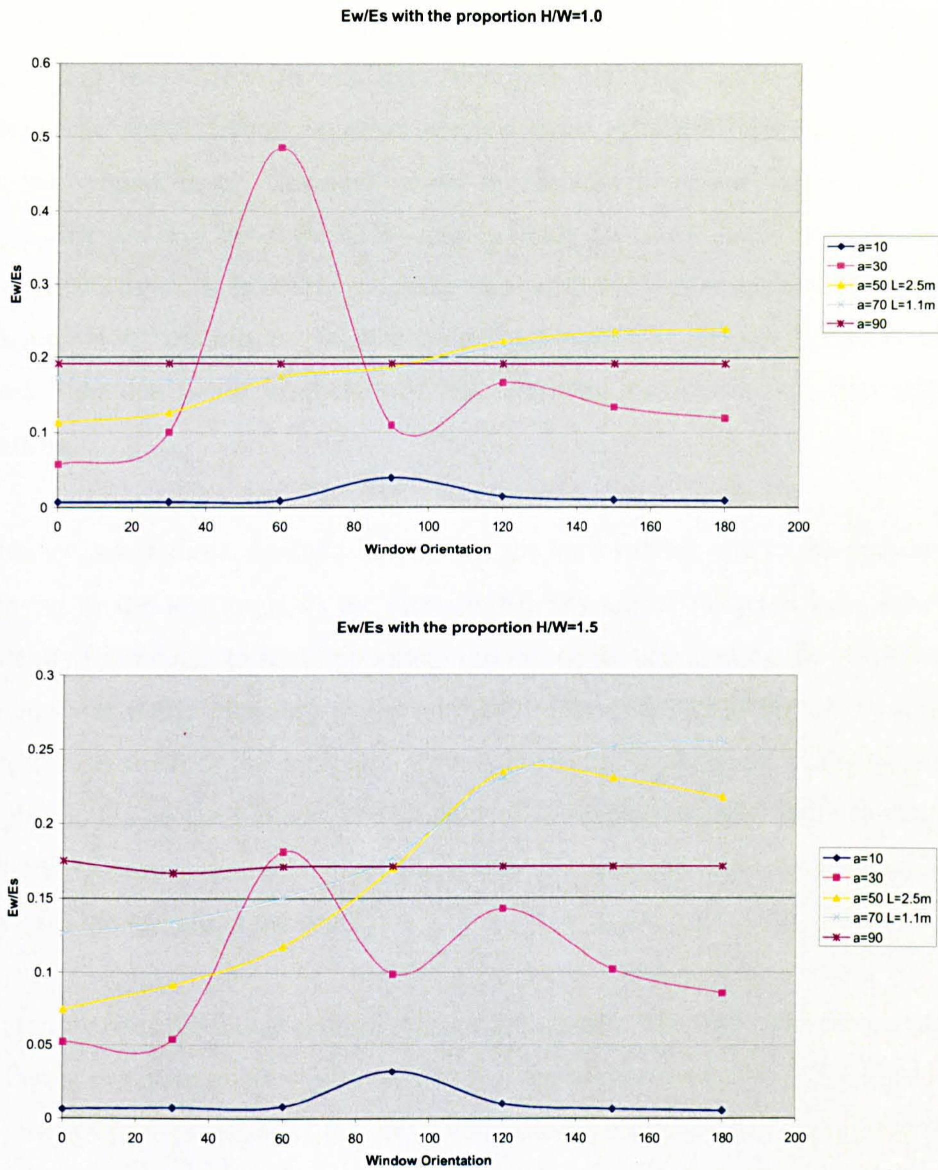


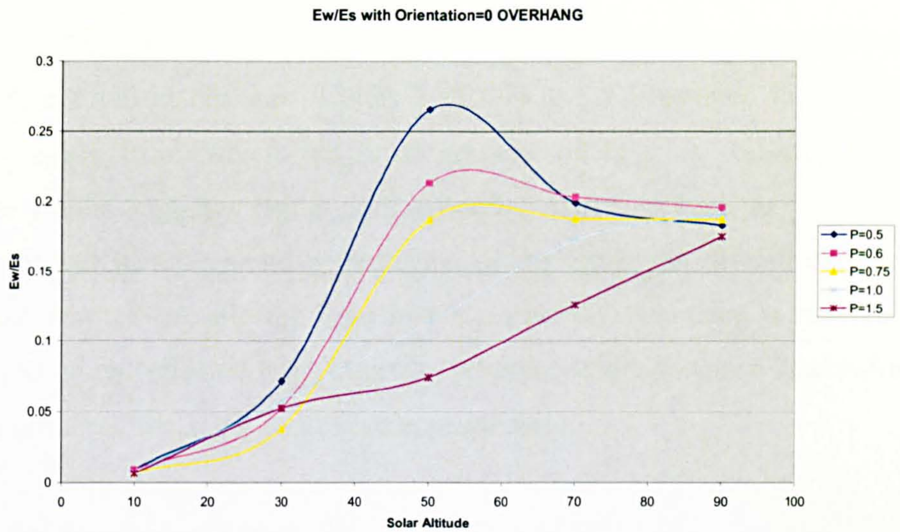
Fig 5.9. Generic charts of Ew/Es to window orientation in terms of sunlight altitude

Discussion:

According to the charts in Fig 5.9, when the sun altitude is quite low at a=10°, the variation of Ew/Es when changing the canyon from a wide H/W=0.5 to a deep H/W=1.5 is almost negligible. However, when the altitude is 30° it seems the amount of reflected light onto the window increases consistently with the change of orientation from south toward north. The reason seems to be the impact of the opposite walls in reflecting the light onto the window due to the low angle of the rays. Nevertheless, when the altitude is even higher 50° (the yellow line), the amount of reflected light decreases in the first two charts (p=0.5 and p=0.6) from south to north orientation. The explanation could be the impact of the street surface in reflecting light since in the wider canyons light first hits the floor rather than the walls. Therefore, the south facing windows receive more reflected light when the light strikes the ground first. However, when the canyon becomes deeper (p=0.75 to p=1.5), as the sun rays strike the wall surfaces firstly the north facing window receive more reflected light. It is nearly the same case with the higher altitude of 70° (cyan line) though at 90° the canyon proportion does not make a significant difference to the reflected light due to the similarity of the reflecting surfaces across the range of orientations.

In summary, when direct sunlight first strikes the wall surface due to the deepness of the canyon or the low angle of the altitude, the amount of reflected light increases consistently from south to north orientation of the window assuming the windows are protected from direct exposure to the sunlight. However, when the direct sunlight first strikes the street or the courtyard ground due to the shallowness of the canyon or the higher angle of the altitude, the amount of the reflected light tends to decrease from south to north orientation since the window is exposed to the first reflection of the light off the ground in the south.

Fig 5.10 illustrates the above ground effect more clearly. The first chart represents the south facing orientation and it generally shows the deeper the canyon, (from p=0.5 to p=1.5) the lower the amount of Ew/Es This could be because when the ground is not the first reflecting surface; the south facing window does not receive the first set of reflected light rays. However, it is nearly the opposite case in the north facing windows as illustrated in the second chart. This means when the window faces the north, the deeper the canyon gets the higher the amount of Ew/Es. This is apparently because when the ground is not the first reflecting surface the north facing window is exposed to the first set of reflected light off the opposite south wall.



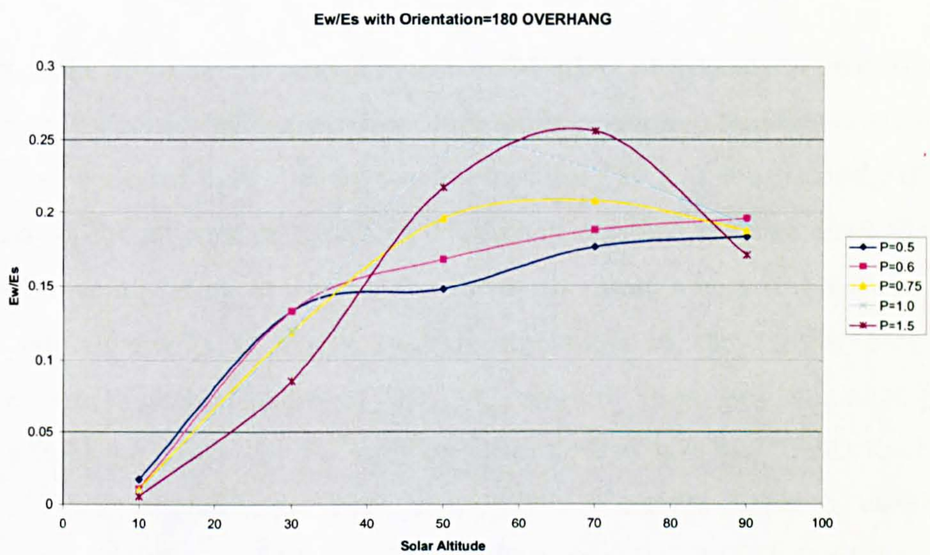


Fig 5.10. A comparison between the south and north orientation in terms of the effect of the canyon proportion on the amount of the reflected light on the window

It can also be concluded that street or the courtyard floor surfaces contribute more to the reflected light than the vertical reflecting surfaces. Therefore, the horizontal surfaces could be considered as a main source of illumination in reflected lighting whereas the vertical surfaces have a secondary significance in terms of light reflection. It is important to note that the reflectance and the finishes of the materials have a substantial effect on the amount of reflected light produced for internal daylighting but they are not quantified in this experiment.

The importance of the ground influence in the internal daylighting, especially the closer part of the ground to the window, in tropical climates is also addressed and established in a recent research (Cabús 2002). Fig 5.1 illustrated the ground peak reflecting region from which the most amount of light is reflected inside the classroom. Cabús suggests using light coloured materials such as beach sand or gravels in Brazil in the ground peak region of the pavement around classrooms to increase the amount of reflected light into classrooms. However, it is important to note that too much reflected light from the ground could also cause discomfort glare in hot-dry climates if it is not controlled appropriately.

5.3.6. Profile Proportion Effect

This part of the discussion is more focused on the effect of the canyon proportion and the optimum proportion of a street or a courtyard in relation to building orientation to provide more reflected light onto the window surface. Fig 5.11 illustrates the effect of proportion on the amount of Ew/Es in 7 different orientations (one chart for each) from the full south facing to the east and the north. With a very low sun altitude at 10° the rate of Ew/Es is nearly constant regardless of the canyon proportion. However, with higher altitudes of 30°, 50°, and 70° there is a common pattern emerging from the charts. In the south orientation (O=0°), in most cases the highest amount of Ew/Es belongs to the widest canyon (P=0.5) and the deeper the canyon, the lower the amount of reflected light. This could be because of the lack of the ground effect in the deeper canyons as discussed before. This pattern is also repeated in the south to the east orientations (O=30°, O=60°, and O=90°) when the canyon is narrowed down, the less and less the variation is in the amount of Ew/Es respectively. However, there is an exception with a sun altitude of 30° where the amount of Ew/Es culminates at the canyon proportion of P=1. One possible explanation is in most orientations when P=1 and the sun altitude is as low as 30°, reflected light from all exterior surfaces reaches its maximum especially in the south/east orientation O=60°.

The interesting point is how the decreasing pattern of Ew/Es with the narrowing down of the canyon is inverted when the orientation is changed from the east to the north (O=120°, O=150°, and O=180°). It means at the northern orientations, in most cases, the narrower the canyon; the more reflected light is received on the window. Besides, the more the building is orientated towards the North the more the variation of Ew/Es is observed in the last three charts. However, the sun altitude of 30° is still an exception in this new pattern. It even follows the first pattern in the last two charts. Finally, the effect of the canyon proportion with the normal sun altitude (a=90°) is also negligible due to the similarity of the sun position in different orientations.

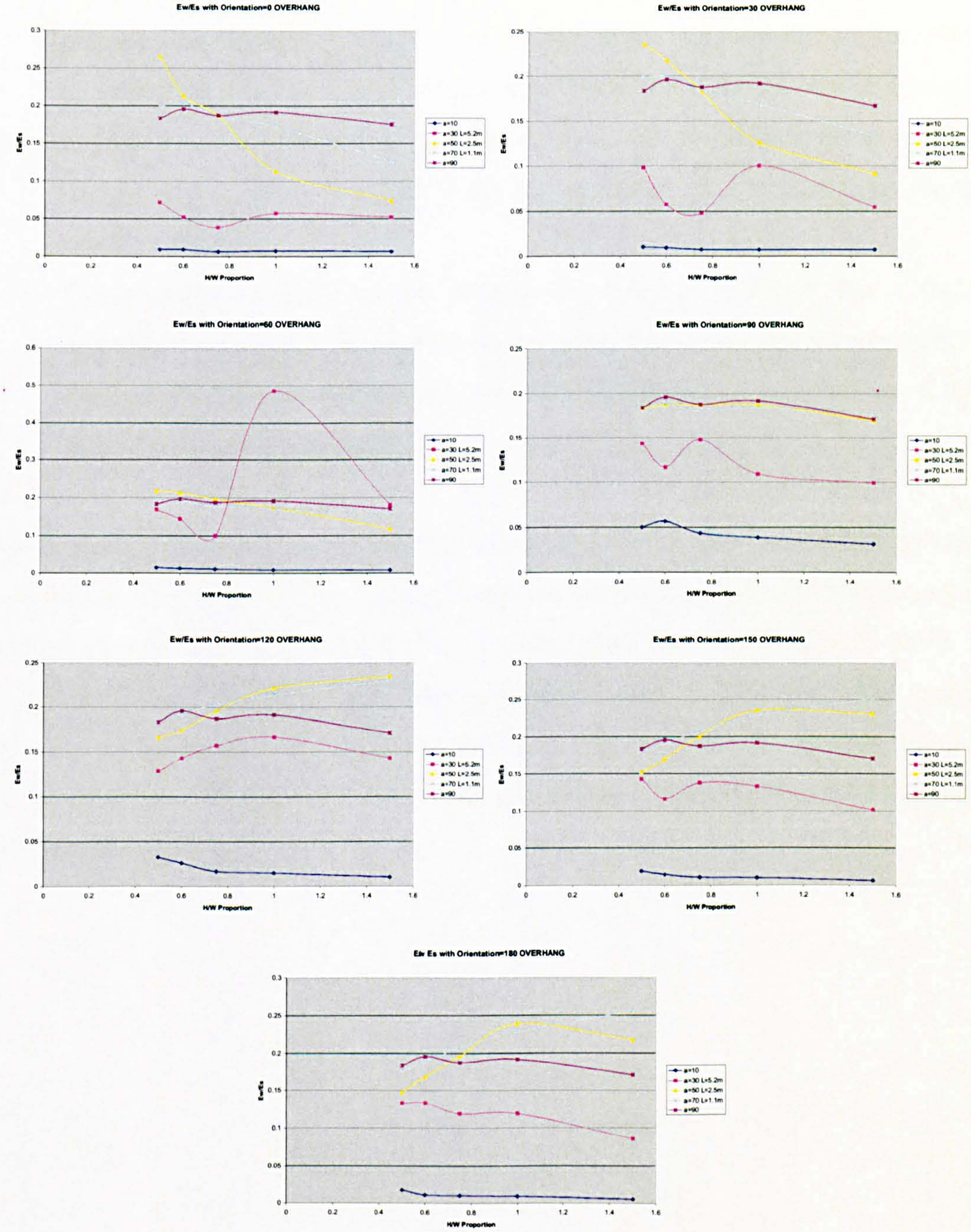


Fig 5.11. The effect of the canyon proportion on the amount of Ew/Es in relation with the building orientation

5.3.7. Conclusion and recommendations

1. The orientation of a building, the street or courtyard canyon proportion, and the altitude of the sun (depending on the time and place) are three main factors affecting the amount of reflected light being used for interior daylighting.
2. The ground reflecting effect is more important in southern orientations since it provides the first set of reflection rays whereas the wall reflecting effect plays an important role in northern orientations. Therefore, a shallow canyon is more appropriate for southern orientation in terms of reflected lighting, while a deeper canyon is more efficient for the provision of reflected light for the northern windows.
3. Consequently, a wide canyon proportion of P=0.5 to P=0.6 has a higher amount of reflected light (Ew/Es) in the south to the east orientation; while a deep canyon proportion of P=1 to P=1.5 has a higher amount of reflected light for the east to north orientation.

This means in an Iranian urban context, where the school site is occupied by other multi-storey buildings and also where classrooms are usually placed at both sides of a corridor in a linear configuration, it is recommended that the classroom block be located at the north part of the site. This will make the southern canyon wider and the northern canyon deeper which will, according to the above results, provide the most amount of reflected lighting for south and north facing classrooms. Fig 5.12 illustrates this recommendation.

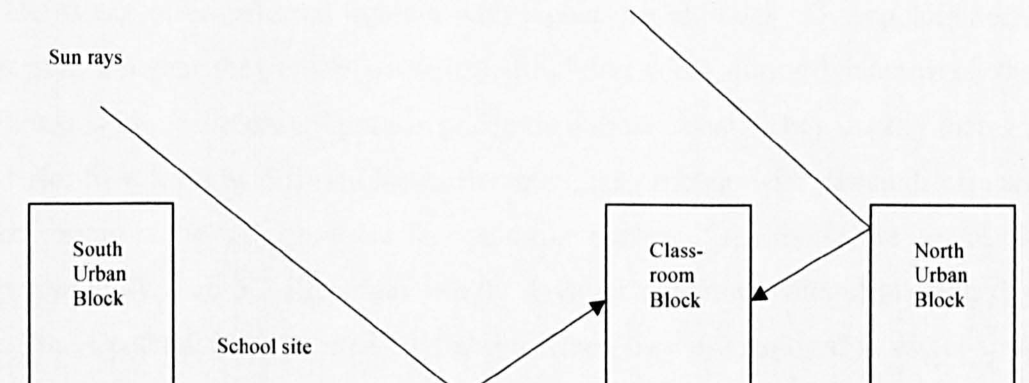


Fig 5.12. A recommendation for the location of a linear classroom block on the school site

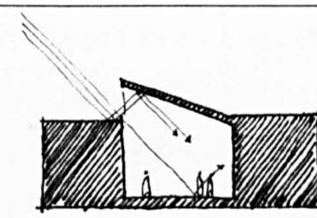
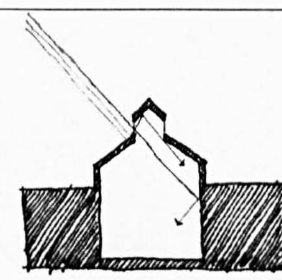
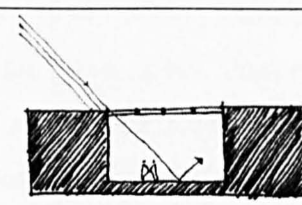
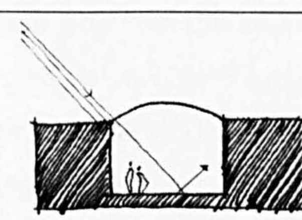
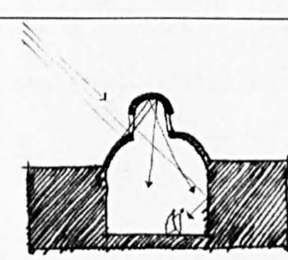
5.4. Specific physical factors

Having discussed general physical factors influencing reflected lighting of a building, there are some specific physical factors which need to be addressed. These factors vary from window and shading devices to the features of surfaces inside and outside a classroom. The rest of this chapter is focused on how these factors can affect reflected lighting and which type of daylight apertures and shading devices are more appropriate for such a purpose.

5.4.1. Daylight apertures

Daylight apertures are the admitting element of daylighting components which was discussed in chapter 4 (section 4.5.2.1). Admitting daylighting components can be divided into three major categories: Lateral, Zenithal, and Global or membrane (Baker and Steemers 2002). Having assumed they are all exposed to direct sunlight, most of them can not offer reflected lighting and allow direct sunlight to enter the interior space especially the classroom. Therefore, most of them would need shading devices to protect the rooms, and especially classrooms as the main part of schools, from direct exposure to sunlight. The type of shading device would, then, have an effect on the aperture reflected lighting performance which will be discussed in section 5.4.2 concerning the influence of shading devices on reflected lighting.

On the other hand, there are a few zenithal daylight apertures which could still offer reflected lighting to some extent without shading devices to classrooms. For instance, lanterns can offer reflected lighting with higher sun altitudes. During summer when the sun is higher they can offer reflected lighting while during winter when the sun altitude is lower direct sunlight can penetrate into the room. They usually increase the interior light level by diffused light. However, the problem with partial direct sunlight penetration is the 'greenhouse effect' and overheating if the rooms are not ventilated appropriately. Tab 5.3 illustrates briefly daylight apertures without shading devices and their potential to reflected daylighting when they are exposed to direct sunlight. The '×' sign on the right side of the table means the given daylight aperture is not appropriate without any shading devices in such a climate as it allows direct sunlight penetration, while the '√' sign means the daylight aperture is protected from direct sunlight. A mixture of both signs means the daylight aperture allows partial direct sunlight penetration into the room. Therefore, only few of the apertures are partially acceptable and in most cases shading devices are required for full sunlight protection.

Daylight apertures	Lateral	Window	Deep reveals could help reflection but windows need sun control	×
		Translucent wall	Shading devices are needed	×
		Curtain wall	Shading devices are needed	×
	Zenithal	Clerestory Partial reflected lighting but low sun angles penetrate		√ ×
		Monitor roof Partial reflected or redirected lighting but low sun angles penetrate		√ ×
		Translucent ceiling Needs solar control or diffusers		×
		Skylight/ Dome Need either diffusers or shading devices to redirect		×
		Lantern Partial reflected lighting but low sun angles penetrate, shading devices		√ ×
	Global	Membrane Needs sun control		×

Tab 5.3. Daylight apertures & reflected lighting potentials without shading devices, after (Baker, 2002)

It goes without saying that window size is another factor which has a considerable effect on reflected lighting. Sunlight in warm-dry or hot-dry climates is intense and large windows may cause discomfort glare which, in effect, reinforces the notion that small windows are more suitable in such climates (Givoni 1998, p.352). This is why most windows in the vernacular architecture of the region are restricted in size. However, small windows reduce the admittance of reflected light from exterior surfaces as a source of illumination. They also reduce the rate of natural ventilation which is another comfort factor in such climate. With proper shading devices, it is possible to provide acceptable indoor comfort conditions and more daylit interiors by using larger windows while avoiding overheating (ibid). Therefore, with the advantage of having a variety of shading devices, restricted openings and small windows is not considered a lesson from the vernacular architecture of the region to be transferred to new school buildings.

5.4.2. Shading devices

In warm-dry climate, shading devices are very important to prevent direct penetration of sunlight inside and avoid overheating. Givoni (1998, p.354) divides shading devices into fixed and operable and argues operable devices are inherently more efficient than fixed shading. Fixed devices are for example horizontal overhangs for south facing windows and vertical fins for west or east facing windows or egg crate which are a mixture of overhangs and fins (ibid). Shading devices can also be divided into external and internal devices. Internal shading devices such as Venetian blinds, roller blinds, etc. are not generally appropriate for such climates. The problem is that the solar radiation absorbed in the room can be dispersed as glass prevents long wave radiation from escaping (Gorji-Mahlabani 2002, p.124). Therefore, they are not appropriate from a thermal point of view as they cause overheating. This points to external shading devices as the most suitable.

Littlefair (1999) elaborates on external shading devices, as well as glazing types, and represents each of them with a table analysing their main features and suitability. Table 5.4 summarizes the characteristics of the main shading devices and glazing types. It also provides a comparative study among exterior shading devices and glazing types in terms of their potentials to reflect light. Each device is evaluated on a number of issues such as the windows they are recommended for, relative total solar transmittance levels in summer and winter, overheating test, glare control, privacy, view out, relative daylight transmittance, daylight at the back of the room, adjustability, and maintenance (ibid, pp 8-26).

Among the above issues three of them are especially relevant to reflected daylighting considerations in classrooms in a warm-dry climate: daylight at the back of the room, glare control, and view out. Daylight at the back of the room is the most important factor as classrooms are usually daylit from one side (assuming south-facing windows) and therefore the first problem is how to illuminate the depth of the room with reflected daylight. Glare control is also of significant importance as classrooms are working areas and any glare discomfort on the studying plane should be avoided. Finally, having a view out is also another important factor in choosing the appropriate shading device, as literature review in chapter 3 highlights the importance of other attributes of window such as view on student performance (Tikkanen 1970; Stewart 1981).

As daylight at the back of the room is of significant importance in daylighting classroom especially in such a climate, the value of daylight at the back of the room (which varies from minimum 0 up to maximum 1) is one of the suitable criteria for choosing appropriate shading devices. Therefore, seven shading devices out of many in tab 5.4 are selected as their daylight value at the back of the room exceeds the average (0.5). Table 5.5 illustrates the selected shading devices (3 from external, 1 from internal and 3 from glazing shading devices) and also compares other two important values of glare control and view out.

The aim of the comparative study in tab 5.4 and tab 5.5 is to address the question about the appropriate choice of shading devices for classrooms in sunny climates and will be tested and discussed in more detail in the next chapter, section 6.2.

		Recommend for	Relative Total Solar Transmittance (South-facing window)		Overheating Test	Glare Control	Privacy	View out	Relative Daylight Transmittance	Daylight at room rear	Adjustability	Maintenance
EXTERNAL SHADING	**Overhang /canopies**	south-facing window	sum: 0.55	win: 0.84	134 hours	good in sum	little benefit	good	diffuse: 0.61	**0.72**	SVIPO	robust But dirt
	Light shelves	south-facing window	sum: 0.51	win: 0.78	111 hours	good in sum	little benefit	good	diffuse: 0.52	**0.90**	SVIPO	robust But dirt
	Fixed/moveable louvres	roof lights	closed: sum:0.04 open: sum:0.26	closed: win:0.04 open: win:0.45	closed: 28 hrs open: 56 hrs	very good dep. design	depends on design	poor	closed: dif:0.03 open: dif:0.32	**closed: 0.03 open: 0.50**	Fixed: SVIPO Move: good	robust But dirt
	Other external shading devices	shutters fins deep-reveals baffles blinds trees	- - - - - -	- - - - - -	- - - - - -	- little little good good good	high little little good good good	none fair fair fair poor excel	none - - - - -	**none low low fair low low**	none SVIPO SVIPO SVIPO none none	low low none robust /dirt low low
GLAZING	**Tinted glazing: reflected & absorbing**	excessive daylit windows	sum: 0.71	win: 0.68	271 hours	fair	good at daytime only	good	diffuse: 0.49	**0.49**	none	low
	Heat mirror: low emissivity glazing	excessive heat gain windows	sum: 0.66	win: 0.63	304 hours	little	good at daytime only	excel	diffuse: 0.79	**0.79**	none	low
	Window films	excessive heat gain windows	sum: 0.51	win: 0.49	155 hours	fair	good at daytime only	good	diffuse: 0.33	**0.33**	none	low
	Other glazing types	diffusing prismatic smart	- - -	- - -	- - -	poor poor low	good good good	low low good	- - -	**fair 0.70 low**	none none good	low low low
	Reducing window area	excessive heat gain windows	sum: 0.50	win: 0.50	198 hours	little	fair	less	diffuse: 0.50	**0.50**	none	low
	Mid-pane Venetian blinds	Glare control rooms	sum: 0.43	win: 0.43	159 hours	excel for opaqu	good	poor	closed: dif:0.03 open: dif:0.32	**closed: 0.03 open: 0.50**	Very good	fair
	Mid-pane fixed reflective louvres	excessive heat gain windows	sum: 0.37	win: 0.90	113 hours	some	good	poor	diffuse: 0.60	**0.68**	SVIPO	low
INTERNAL SHADING	**Curtains**	glare control rooms	sum: 0.50	win: 0.49	241 hours	excel	good	none when closed	diffuse: 0.06	**0.06**	good	low
	Venetian blinds	glare control rooms	sum: 0.57	win: 0.58	289hours	excel	good when lowered	none when closed	closed: dif:0.03 open: dif:0.32	**closed: 0.32 open: 0.50**	very good	dirt
	Fabric blinds	glare control rooms	sum: 0.43	win: 0.43	183 hours	good	good when lowered	none when closed	diffuse: 0.06	**0.06**	good	low
	Reflective roller blinds	excessive solar gain windows	sum: 0.33	win: 0.34	140 hours	good	good when lowered	none when closed	diffuse: 0.06	**0.06**	good	low
	Internal light shelves	south facing rooms	-	-	-	good	low	good	-	**0.90**	low	clean top dirt

Tab 5.4. A summary of shading devices' performance based on (Littlefair 1999, pp 8-26), SVIPO stands for seasonal variation in performance only

Performance values / Shading devices	Daylight at the back of the room	Glare control	View out	
Lightshelves	0.90	Good in summer	Good	√
Internal light shelves	0.90	Good in summer	Good	√
Heat mirror glazing	0.79	Little	Excellent	×
Overhang	0.72	Good in summer	Good	√
Prismatic glazing	0.70	Poor	Very poor	×
Mid-pane fixed reflective louvres	0.68	Some control	Poor	×
Fixed/moveable louvres	Closed: 0.03 Open: 0.50	Very good depending on the design	poor	×

Tab 5.5. Appropriate shading devices for classrooms in sunny climate, based on (Littlefair 1999, 8-26)

The selected shading devices in table 5.5 are sorted according to their performance in terms of providing light at the back of the room which is a crucial issue in deep sidelit classrooms. They redirect more than 50 percent of the admitted light to the back of the room. There are 4 devices in table 5.4 which provide only 50 percent and only one of them (fixed/moveable louvers) appears in table 5.5. The reason for the omission of other three (reduction of window area, mid-pane Venetian blinds, and Venetian blinds) is their poor or no view out as well as poor glare control.

Although all shading devices in tab 5.5 have high value of daylight at the back of the room, it is only the external and internal lightshelves as well as overhangs that have relatively good glare control in summer and good views out. Moreover, lightshelves seem to be more appropriate as the daylight value at the depth of classrooms is higher than overhangs. However, when the main source of illumination is reflected sunlight from the ground, Cabús (2002) suggests that overhangs are preferable to lightshelves in tropical and sunny climates as they reflect more daylight into the rooms.

Cabús (2002, p.8-3) has studied three different shading devices (overhang, lightshelf and louvre) to investigate their impact on the amount of ground reflected light into a room. The assumption is the type of shading device can alter the influence of ground in interior daylighting performance. Cabús (ibid, p.8-8) suggests that of the three shading devices, the overhang can increase the ground reflected component in comparison to a plain window. Overhangs can take advantage of the ground-reflected light as a result of its better performance in conducting the reflected light inside the room. It is suggested that the lightshelf and louvre caused a slight reduction in the ground reflected component (ibid). However, as mentioned earlier, this suggestion is valid only if the main source of reflected light is considered to be the ground-reflected one. When the reflected light from the top surface of the lightshelf is also taken into account, a lightshelf will have higher value of daylight at the back of the room comparing to an overhang, as illustrated in table 5.5.

Furthermore, Cabús results are not fully applicable to schools and classrooms. It is important to highlight the fact that illuminance levels are not the only factor in terms of school daylighting. An even distribution of daylight across the classroom is another important factor to consider while assessing shading devices. The distribution of reflected daylight is more even with lightshelves as they bounce the light deeper into the room while overhangs can not provide a satisfactory level of distribution in the classrooms. Computer simulations in the next chapter, section 6.2, will address this issue more objectively.

In contrast to Littlefair's (1999) approach to shading devices classification (tab 5.4), Baker et al. (2002) have an alternative approach to classifying solar control elements. Tab 5.6 summarises Baker's classification of shading devices and their potential for reflected daylighting. It is important to note that tab 5.6 only values each device on the mere basis of daylight reflection and redirection. Solar obstructers such as shutters or blinds do not obviously contribute to reflected lighting. Flexible screens such as awnings or curtains are also eliminated for the same reasons. Among solar filters, louvres and Brise-soleil can control sunlight and redirect it into the dark depth of classrooms. Rigid screens offer most appropriate shading devices for reflected lighting in comparison to other solar control elements. Overhangs, lightshelves, baffles, and fins are then considered as shading devices with solar redirecting or reflecting potentials. Sills can also redirect the light into the room but they are not considered appropriate reflecting devices as they could cause discomfort glare if the surface is visible. Finally, among separator surfaces, optical division and prismatic division can control sunlight and redirect it accurately. These two elements are considered as part of the innovative daylighting systems which will be discussed in the next section.

The appropriate solar control elements for schools in sunny or warm-dry climate with the ability to redirect natural light can be referred to as innovative daylighting systems. Littlefair (1996, p.v) suggests innovative daylighting systems are appropriate to use where the space is too deep to give adequate uniformity of lighting with conventional means, as they would give unacceptable gloomy areas within the room and also when there is much sunlight available usually for a south facing window wall in a sunny location. These two requirements are already met in the daylighting conditions of sidelit classrooms in warm-dry climate of Iran especially for the south facing façade. The next section will focus on these systems and attempts to assess them in terms of their suitability for schools in the warm-dry climate.

	Elements		Description	Suitability
Solar Control Elements	Separator Surfaces	Conventional division	A transparent separator allowing view and light and possibly air	×
		Optical division	A control element which can diffuse, redirect & control light	√
		Prismatic division	A prismatic separator which redirects light beams	√
		Active division	An expensive electric component which controls light intensity	–
	Flexible Screens	Awning	To Provide a decreased & less contrasting light levels near it	×
		Curtain	To obstruct or diffuse solar radiation	–
	Rigid Screens	Overhang	To obstruct high angle solar radiation, efficient solar protector	√
		Lightshelf	Solar protection near window & redirection deep into the room	√√
		Sill	Can reflect and redirect light near window but not deep in the room	√
		Fin	Depending on the sun angle, can reflect & redirect the light inside	×
		Baffle	To protect against sunlight & redirect, homogeneous light level	√
	Solar Filters	Jalousie	To control direct sunlight & regulate its entry	×
		Louvre	To control sunlight and redirect it inside by reflection	√

		Brise-soleil	An exterior structure to obstruct direct sunlight & redirect as well	√
	Solar Obstructers	Shutter	To obstruct solar radiation totally, inside or outside window	×
		Blind	To control direct sunlight & regulate its entry	×

Tab 5.6. Solar Control elements of daylight apertures and their reflected lighting potentials, after (Baker, 2002, pp 5.19-20)

5.4.3. Innovative daylighting Systems

Chapter 3 provided research evidence on the importance of a uniform distribution of daylight across the working area of a classroom in order to avoid glare discomfort and improve concentration. This is a particular issue in typical deep classrooms with windows with overhangs facing from south-east to south-west in sunny climates, as daylight is not distributed well across the classroom and also the back of the room is usually not sufficiently daylit. Innovative daylighting systems are designed to address the above problems in deep sidelit spaces. A one-sided daylit room is considered too deep to give sufficient uniformity of lighting when the following criterion does not apply to it:

$$l/w + l/h \leq 2/(1 - R_B)$$

Where l is the depth of the room, w is its width, h is the window head height and R_B is the average reflectance of the surfaces at the back of the room (Littlefair 1996, p. 33). If this condition is not met, and the average daylight factor is reasonably high (over 2% at least), then the room is a possible candidate for the use of innovative daylighting systems (Littlefair 1989). The above formula applies to the CIE overcast sky distributions where windows can be larger in order to admit diffused skylight into classrooms. However, in the sunny and warm-dry climates, windows tend to be smaller in order to avoid excessive exposure to the sun and overheating. Therefore, the above criterion does not apply to clear sky distributions and sunny climates. The following example in the warm-dry climate of Iran clearly shows that the above formula is not applicable in sunny climates.

Jahan-Ara school in Shiraz is a typical primary school in Iran where the classrooms are on average 6.5 meters wide and 5.5 meters deep and the window head height is 2.2 meters. The reflectance at the back of the room is measured 0.93 and daylight factor is considerably high at 4.4% to 9.2% (measurements are recorded in the second section of chapter 6). According to the above formula 5.5/6.6 + 5.5/2.2 is less than 2/ (1-0.93) and, therefore, the innovative daylighting systems do not seem to be recommended for such classrooms in a sunny climate. This is obviously an incorrect recommendation because innovative daylighting systems are practically good daylighting solutions as their performance will be proven by ECOTECT simulations in the next chapter. The above limiting depth formula needs adjusting in order to be applicable in clear sky distributions which is beyond the scope of this research.

Innovative daylighting systems are recommended for Jahan-Ara school in Shiraz and further computer simulations in chapter 6 will show that a simple lightshelf can contribute significantly to the uniformity of daylight in such classrooms. Because of the importance and efficiency of such daylighting systems in sunny climates the rest of this section will focus on different systems and their applicability for Iranian schools.

Innovative daylighting systems work by redirecting incoming sunlight or skylight to parts of the building where it is required (Littlefair 1996). They have two main aims: the first aim, and the more important for daylighting design of sidelit classrooms, is to improve distribution of daylight in a space (Littlefair 1989). The second aim is to control direct sunlight so that it can be used as an effective working element- this is termed as beam daylighting or sunlight-tracking systems (ibid). Daylighting systems such as lightshelves, mirrored louvres etc. redirect diffuse skylight as well as direct sunlight while sunlight-tracking systems such as light pipes are equipped with mirrors and are dependant on direct sunlight for long periods to be effective and cannot be efficient systems in cloudy climates (Littlefair 1996, p.iv). Therefore, both systems seem to be appropriate for sunny climates and clear sky most of the time; however, sunlight tracking systems are generally technologically advanced and expensive to use.

Tab 5.7 summarises different types of innovative daylighting systems which could be used for daylighting design in primary schools in warm-dry climate of Iran. These systems redirect sunlight rays or diffuse skylight (in some cases) to dark parts of deep rooms, or anywhere in the building where needs daylighting, through reflecting, refracting or diffracting the light (Littlefair 1996). The first group of these systems is daylighting systems which includes lightshelves, prismatic glazing and holographic diffracting systems. The second group is sunlight-tracking systems which include light pipes and mirrored systems. As most of these systems are potential solutions for the research design problem of daylighting issues in warm-dry climate schools, they are going to be discussed in the following sections.

<table>
<tr><td rowspan="5">INNOVATIVE DAYLIGHTING SYSTEMS</td><td rowspan="3">DAYLIGHTING SYSTEMS (CORE DAYLIGHTING)</td><td>1. Light shelves</td><td>Internal, External or a mixture</td><td>Works by Reflection of sunlight</td></tr>
<tr><td>2. Prismatic glazing</td><td>2.1. Sunlight directing triangular prisms
2.2. Sunlight excluding triangular prisms
2.3. Lens systems (Clerestory only)
2.4. Other prism geometries</td><td>Works by Refraction of sunlight</td></tr>
<tr><td>3. Holographic diffracting systems</td><td>Developing stage</td><td>Works by Diffraction of sunlight</td></tr>
<tr><td rowspan="2">SUNLIGHT-TRACKING SYSTEMS (BEAM D.)</td><td>4. Light pipes</td><td>Reliance on direct sunlight</td><td>Sunny climate</td></tr>
<tr><td>5. Mirrored systems</td><td>5.1. Fixed louvre system
5.2. Moveable louvres
5.3. Reflective sills & scoops (glare)
5.4. Rooflight systems (esp. north rooms)
5.5. Greenhouses</td><td>Works by Refraction and Refraction of sunlight
Maintenance issues
Glare issues</td></tr>
</table>

Tab 5.7. A summary of innovative daylighting systems, after (Littlefair 1996, pp 2-30)

5.4.3.1. Lightshelves

Lightshelves provide shade to occupants near windows, while allowing daylight deep into the room through reflecting it up to the ceiling (Littlefair 1989). A lightshelf divides the glazing into a view window below the shelf and a clerestory window above it where light is reflected off the top of the lightshelf onto the ceiling and consequently inside the room. They are suggested as a suitable solution to reflected daylighting in deep sidelit classrooms and also they have been recommended in tab

5.5 and 5.6 for their potential to improve the distribution and uniformity of light in classrooms in sunny climates (Littlefair 1999; Baker and Steemers 2002).

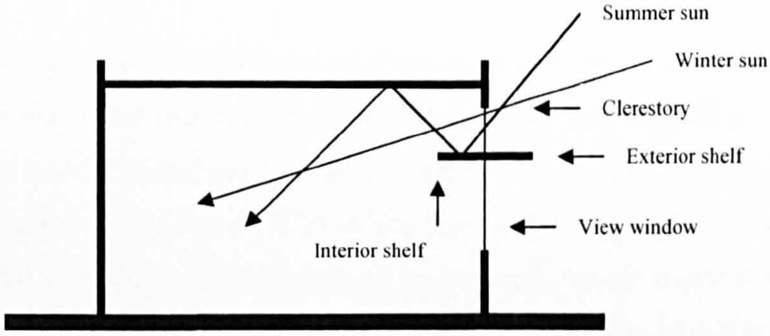


Fig 5.13. A lightshelf and its application in summer & winter

Lightshelves can be exterior, interior or both as illustrated in Fig 5.13. An exterior lightshelf casts shadow on the exterior of the window which will result in reducing solar gain to the room (Lam 1986). An external lightshelf improves daylight uniformity by reducing the contrast between the back of the room and the brightly lit areas near the window (Littlefair 1996, p.19). This contrast is a typical issue in south facing classrooms (northern hemisphere) without any light redirecting systems, but lightshelves reflect sunlight or daylight deep into the darker zone of a classroom and therefore, improve its uniformity across the room. This will usually improve the appearance of the back of the room by reducing the gloom which was there with a conventional window without a lightshelf (Lynes 1979). This will be tested in the next chapter, section 6.3. On the other hand, an interior shelf provides better visual protection from sun glare near the window as it is illuminated by reflected light. It also prevents part of the direct sunlight penetration in winter while an exterior shelf admits more direct sunlight inside the room in winter when the sun altitude is low.

According to the above pros and cons of the two type of lightshelves, it seems a combination of interior and exterior lightshelves as illustrated in fig 5.13 has a better performance for classrooms in warm-dry climate (Baker, Steemers et al. 1993), though some additional moveable shading devices are still required. A recent study addresses the problem of sun protection of lightshelves in tropical climates and suggests semi-transparent fins on the view windows are appropriate shading supplements (Laar 2001). Laar's computer simulations support his suggestion and it seems in sunny climates semi-transparent fins protect areas near the window from disturbing direct sunlight and in consequence reduce glare discomfort.

Lightshelves have recently become of interest, though the history of them goes back to early 1950s when Building Research Station (or present BRE) was involved in lightshelf research, using deep wards in Larkfield hospital in Greenock (Hopkinson 1952; Longmore 1952; Petty 1952) as the context. The problem was how to light a deep hospital ward by daylight alone and yet retaining visual comfort for patients near the window. The lightshelf or *'window baffle'* was the solution found, where additional light was reflected off the top of the lightshelf deep into the ward. Measurements on a scale model revealed that the daylight factor throughout the ward were less than for the same window without a lightshelf. However, the daylight was more uniformly spread across the ward and the visual conditions were improved.

Lightshelves have been tested inside the BRE mock-up facility comparing the daylighting performance of two identical deep rooms, one with and one without a lightshelf (Aizlewood 1993). The results show that, under overcast skies the lightshelf reduces illuminance by 5-30%, with the least reduction at the back of the room (ibid). This issue is not of great concern for the warm-dry climate of Iran as overcast skies only occasionally happen during winter; otherwise the sunshine is fairly consistent. On the other hand, during the BRE test, on sunny days the front of the room is shaded from direct sunlight and hence has larger reductions in illuminance, while illuminance in the rest of the room is reduced by 0-20% (ibid). Littlefair (1995) confirmed these findings through computer modelling for conventionally shaped rooms. However, the reduction of illumination near the front is not really an issue in Iran. The real benefit is the increase of illumination at the rear and more uniform profiles across the room.

However, ECOTECT computer simulation results in chapter 6 show that under direct sunlight and clear sky distributions, lightshelves in south-facing rooms (in the Northern Hemisphere) can slightly increase the illuminance at the back of the room. Chapter 6 results confirm the findings of Robbins (1986) and Selkowitz et al (1983), as they also indicate south facing lightshelves can give higher illuminance near the back of the room compared to the equivalent bare window under direct sunlight.

Lightshelves do not have to be horizontal as tilting the lightshelf outwards will improve shading but reduces internal reflected illuminance; while tilting it inwards may increase daylight penetration but provides poor shading (Littlefair 1996, p.20). Figure 5.14 illustrates a simple classroom with a flat ceiling but with two different lightshelf angles. When the lightshelf is tilted outwards (left) the amount of reflected light at the back of the room is reduced, but it provides better shading for the view window especially in summer with high altitude solar rays. On the other hand, the right diagram in Fig 5.14 shows when the lightshelf is tilted inwards light is reflected deeper in the room which improves the uniformity of light across the room. However, the lower part of the view window is exposed to direct sunlight which can cause discomfort glare and overheating if it is not equipped with other forms of shading devices. Having discussed different angles of lightshelves, Lam (1986) suggests that a horizontal lightshelf is often the best compromise.

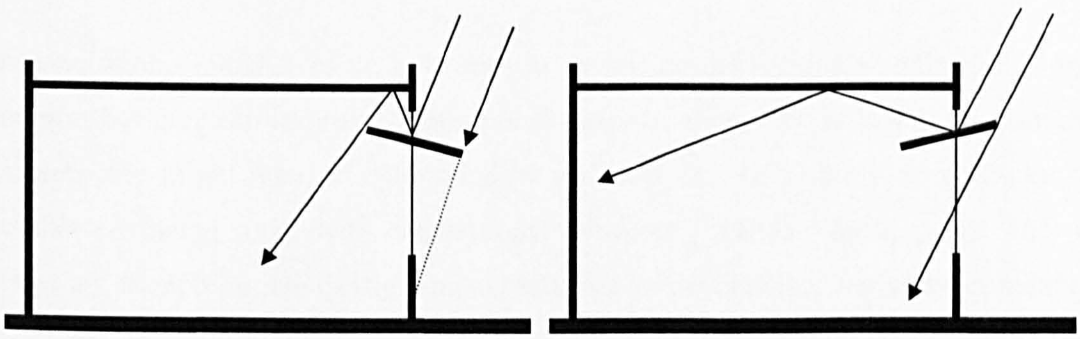


Fig 5.14. Two types of tilted lightshelves (inwards & outwards) and their advantages & disadvantages

The shape and the geometry of the room also affect the daylighting performance of the lightshelves. Ellinwood (1983) suggests that a sloping ceiling has little effect on internal daylight availability if the window head height remains the same. The results of ECOTECT simulations in chapter 6 confirms Ellinwood finding. Of more importance in the room shape in terms of its effect on its reflected lighting is the height of ceiling. Littlefair (1996, p.20) suggests lightshelves require a high ceiling, ideally 3 meters or above, to be most effective. The computer simulation results in chapter 6 will confirm this important fact, but the drawback of high ceiling is construction costs which need to be taken into account.

Another important design factor of daylighting performance is the finish of lightshelves. It goes without saying that both internal and external lightshelves should have as reflective a finish as possible in order to have the best daylighting performance. Computer simulations show that a light-coloured external shelf can increase the incoming reflected daylight by 10% comparing to a dark shelf. This is also affected by the specular reflectivity of the top surface.

BRE mock-up model tests show that a specular surface will result in improved daylight penetration as the majority of the light from outside is projected inside, while with a diffuse surface on the top of the shelf almost half the reflected light is lost (Littlefair 1996, p.21). However, the maintenance of specular shelves is more difficult. Lam (1986) warns that a specular surface will reflect an image of any dirt on the shelf onto the ceiling. Therefore, a semi-specular finish may be a compromise for the top of the lightshelves. Nevertheless, maintenance of lightshelves must be considered at the design stage.

In conclusion, lightshelves do not result in enhancing daylighting illuminance of the interior, but they can improve lighting uniformity of a room by reducing the contrast between the bright area near the window and dark end of a south or south-east to south-west facing room with conventional windows (Littlefair 1996, p.21). That is why they are appropriate daylighting systems for classrooms in a warm-dry climate of Iran, as the main lighting problem is the contrastive lighting conditions inside classrooms and the lack of uniformity arising out of conventional south facing windows.

5.4.3.2. Prismatic Glazing

The direction of incoming sunlight or skylight into a room can be changed by reflection of refraction. Reflection was the principle behind lightshelves, while refraction is what happens to light going through prismatic glazing. Prismatic glazing blocks have been used over 50 years mainly to redirect diffuse skylight entering a room (Hopkinson 1966; Ruck 1985). There is a variety of prismatic glazing such as *sunlight-directing* and *sunlight-excluding triangular prisms*, *lens systems* and other prism geometries (Littlefair 1996, pp 22-29). The prismatic panel is usually inside a double-glazed unit. Such glazing is not limited to sidelighting applications but can also be used to redirect sunlight deeper into an atrium or a light shaft (ibid, p. 23).

The aim of sunlight-excluding triangular prisms is to reject sunlight but to admit skylight from near the zenith (ibid, p.26). In such prismatic glazing the tilted sheet has one face of each prism silvered so that direct sunlight is reflected back out (Sweitzer 1992). These are suitable glazing systems to block direct sunlight in sunny climate schools while admitting diffuse skylight in. However, as they distort the view out they are being used in high windows or clerestories where view is not needed.

Lens systems have the ability to make the diffracted sunrays converge or diverge in the required direction. Prismatic sidelighting systems usually rely on a white ceiling to reflect the light back onto the working plane. They cannot perform well in a flat rooflight unless a lens system is used where the concentrated beam of sunlight can be spread over a wider area (Littlefair 1996, p.28).

One of general problems with prismatic glazing in sidelit rooms is the potential glare discomfort because of its glowing effect. Shading is a possible solution to avoid glare but it reduces illuminance levels in a room. An alternative is to form the prismatic panels into louvres which can be tilted to redirect sunlight (Edmonds 1993).

In conclusion, prismatic glazing can reduce glare by redirecting daylight and sunlight but they inevitably obscure the view out and are not recommended for classrooms' view windows. However, they are a suitable choice for high-level glazing where view does not matter. These systems, especially the moveable ones which have better daylighting performance, are expensive and require extra maintenance (Littlefair 1996, p.29). Therefore, they can be used in limited high areas of school glazing in sunny climates where conventional windows with shading devices or lightshelves do not perform so well.

5.4.3.3. Holographic diffracting systems

The above two systems involve reflecting or refracting sunlight or daylight to alter the direction of light in required places. Light can also be bent by diffraction which is the principle behind holographic glazing (Baker, Steemers et al. 1993). These systems are in the development stage, but when developed might provide a cheap and flexible way to redirect incoming daylight and sunlight (Littlefair 1996, p.30).

The above three systems are part of 'core daylighting systems' which redirect both daylight and sunlight. As discussed, lightshelves are an appropriate daylighting system for sidelit classrooms in warm dry climate of Iran, which could be accompanied with other shading devices such as fins. The following two innovative daylighting systems are sunlight-tracking systems and, as mentioned earlier, are most suitable for sunny climates. Because of the fairly constant sunlight in the warm-dry climate the following two systems can be considered in the daylighting design of schools; however, the cost of their construction and their maintenance is fairly demanding, and need to be taken into account during the selection of such daylighting systems.

5.4.3.4. Light Pipes

The light pipe is perhaps the most exciting innovative daylighting system because of the long distances it can operate (Littlefair 1986). The principle behind them is to channel sunlight into any part of a building. Some of them require a heliostat which is an apparatus containing a moveable mirror to track, collect and concentrate sunlight into light pipes (Robbins 1986), while short light pipes with wide shafts do not require a heliostat (Littlefair 1996). They are generally a sensible system for Iranian sunny climate especially in deep plan offices. However, addressing the specific research design question, light pipes might not be recommended as most classrooms can benefit from sidelighting with appropriate shading devices and daylighting systems such as lightshelves. Besides, as mentioned earlier the cost of their construction, their complexity, and their maintenance is another concern which does not necessarily make them a priority in daylighting system selection.

5.4.3.5. Mirrored Systems

Mirrored systems are more applicable and less complex compared with light pipes (Littlefair 1996, p.8). The simple principle behind them is light reflection by small mirrors installed for each window. Instead of a complicated distribution system with pipes and emitters, the surfaces of the room spread and diffuse the light. There are a variety of mirrored systems: fixed louvre systems, moveable louvres, reflective sills and scoops, and rooflight systems (ibid, pp 8-15). Mirrors may be replaced by shiny or bright glossy surfaces, but the amount of reflected light will be reduced.

Reflective louvres stop direct sunlight falling on the occupants and, instead, redirect it onto the ceiling towards the back of the room (Rodgers, Ballinger et al. 1979; Smart and Ballinger 1983). They usually form a large diffuse light source on the ceiling as the reflected light mostly hits the ceiling first and then is reflected back in the interior (Fig 5.15). The aim is to improve penetration of light deep into a space, which satisfies the research design question, but there are some problems to address. First of all maintenance of louvres can be difficult especially if they have upper silvered surfaces (Lam 1986). Secondly, they restrict the view out which is an important factor in school design. Finally, because of their fixed positions they could cause glare discomfort (Littlefair 1996, p.8). Therefore, moveable louvres have better performance as unwanted reflected sunrays downwards can be easily redirected away from the working area by altering the angle of louvres. Their maintenance is also easier as the louvre surfaces are more accessible.

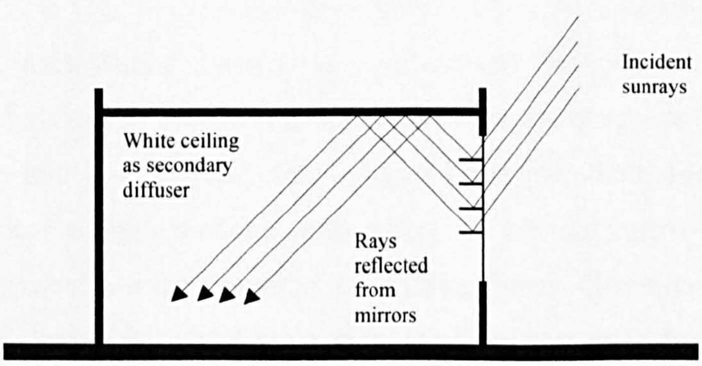


Fig 5.15. Redirecting sunlight and daylight by reflective louvres

Reflective sills and scoops are another mirrored system to redirect light inside a room. However glare is a potential difficulty with sills if the surface of it is visible to the occupants or students in a classroom. Therefore, tilting the reflective window sill outwards can reduce glare as, generally, any horizontal reflector placed beneath occupant's normal eye level causes glare discomfort (Littlefair 1996, p.13). On the other hand, light scoops near the top of the window under the ceiling, if properly designed, can increase illuminance levels inside the room and also redirect the light deeper into the room (Fig 5.16). They can be used either with sunlight or daylight. Light scoops can be considered in daylighting design of classrooms in sunny climates as they contribute to the deep penetration of light.

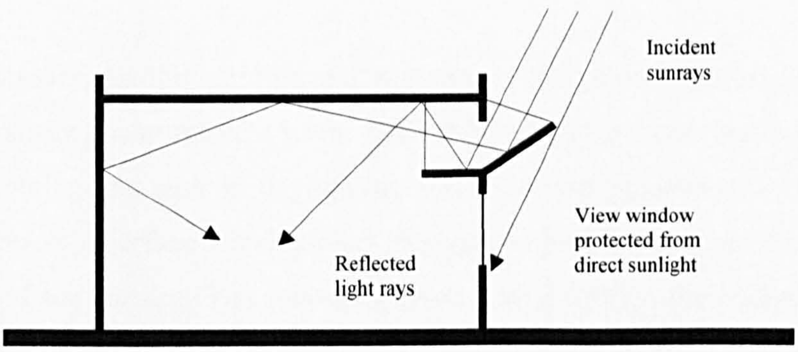


Fig 5.16. Redirecting sunlight and daylight by a reflective scoop over the view window

Finally, redirecting systems can also be used in roof-lit spaces where there is a need for a better distribution of daylight or sunlight if required. One of their applications is for north-facing rooms which have usually poor illuminance levels (in the northern hemisphere) (ibid, p.14). In the warm-dry climate of Iran where sunlight is consistent and directional, north-facing classrooms with conventional windows have usually poor daylight levels and as observed in Jahan-Ara case study school (chapter 6) even during the sunny hours of day most electric lights are switched on. Fig 5.17 illustrates a Rooflight system solution toward north where the sloping mirror reflects diffuse skylight into the room and increases the room illuminance. However this system can only be used in single-storey classrooms or the top level of a multi-storey school.

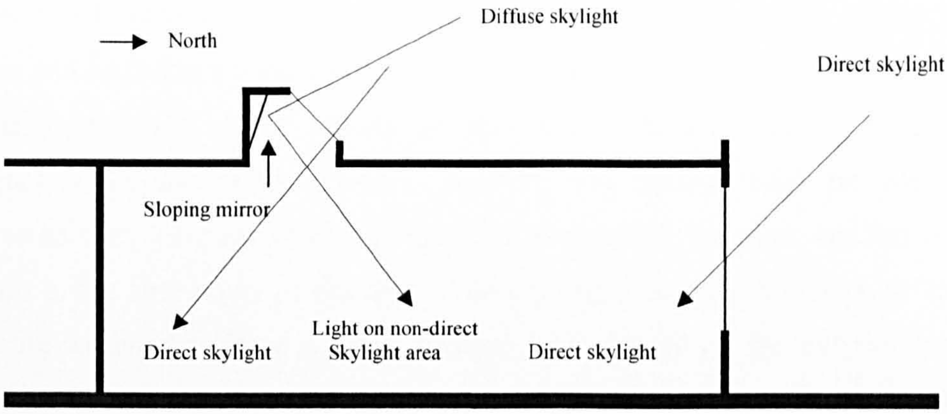


Fig 5.17. A mirrored Rooflight solution for north-facing classrooms

5.4.4. Surface features

Having discussed shading devices and innovative daylighting systems, it is important to address surface features of a room since this is another important factor affecting reflected lighting and general daylighting and solar performance of a building. The main features of a surface which affects daylighting performance are the material and the colour of the surface. The following section will address their importance in the vernacular as well as their influence on the reflected lighting performance of a building in the warm-dry climate.

5.4.4.1. Material, Colour and texture

Traditional buildings in hot dry climates are built of high-mass with heavy materials such as bricks, adobe and mud (Givoni 1998, p.358). The traditional schools in the warm dry climate of Iran (next chapter) are examples of high thermal mass buildings with very thick walls and small windows protected from the sun by the thickness of the wall. The thick and heavy structure of the walls and the roof restrain the swing of the external temperature and maintains the internal temperature at a fairly comfortable level. It is necessary to use high thermal resistance material in such climate in the exterior envelope to minimize the conductive heat flow into the building's mass during daytime hours (ibid, p.360).

The colour of walls and roofs has a tremendous effect on the solar impact on the building and its indoors conditions (Givoni 1998, p.355). The exterior colour of walls and the roof has a direct impact on the surface temperature, heat gain, and subsequently the indoor temperature. Southern and eastern walls are specifically sensitive to their external colour as they are exposed to the most amount of solar radiation in the first hours of the day. Although light colours with high reflectance values are assumed to have a better thermal performance on the exterior surfaces, especially south and east, they can cause glare in external regions (ibid, p.356). The lack of vegetation and light colours of terrain in such areas as well as the light colours of buildings, for better thermal performance, together can cause a glaring effect. Givoni suggests that darker colours could also be used without causing excessive heat load and medium-light colours can be used for north and southern walls to create a less glaring environment (ibid).

The amount of daylight reflected from external or internal surfaces depends on the reflectance value of the material of the reflecting surface. Table 5.8 illustrates typical reflectance values of building materials. Reflectance value varies between 0 and 1. A surface which ideally reflects all the light it receives has the highest reflectance value of one while a dark surface which presumably does not reflect any of the receiving light has the lowest reflectance value of zero.

The texture of the external and internal surfaces can also have an impact on the daylight reflected into the learning space. It is obvious that smooth surfaces reflect daylight more efficiently than ragged or unsmooth surfaces. However, it is important to note that variation in surface texture can help to minimise the sense of large institution in schools (DfES 2002, p.42). Therefore, learning spaces can have smoother textures to have greater amount of reflected daylight, whereas spaces which do not require as much illumination such as circulation can have different patterns of texture.

Reflecting Surface	Building Material	Reflectance Value	Reflecting Surface	Building Material	Reflectance Value
				White glazed tile	0.7
Ground	Snow	0.8	**External Material**	Portland stone	0.6
	Sand	0.3		Medium limestone	0.4
	Pavement	0.2		Concrete	0.4
	Earth (dry)	0.2		Brickwork (buff)	0.3
	Earth (moist)	0.1		Brickwork (red)	0.2
	Green vegetation	0.1		Granite	0.2
				Window glass	0.1
				Tree foliage	0.1
				White paper	0.8
Paint Colours	White	0.85	**Internal Material**	Stainless steel	0.4
	Pale cream	0.81		Cement screed	0.4
	Light grey	0.68		Carpet (cream)	0.4
	Strong yellow	0.64		Wood (light veneers)	0.4
	Mid-grey	0.45			
	Strong green	0.22		Wood (medium colours)	0.2
	Strong red	0.18			
	Strong blue	0.15		Wood (dark)	0.1
	Dark grey	0.14		Quarry tiles	0.1
	Dark brown	0.10		Window glass	0.1
	Deep red-purple	0.10		Carpet (deep colours)	0.1
	Black	0.05			

Tab 5.8. Approximate values of reflectance under diffuse daylight (British-Standards 1992)

5.4.5. Microclimate effect

The microclimate of buildings is influenced to a large scale by trees, plants and water features around the building openings. Olgay (1963) maintains that trees contribute to the immediate physical environment. They can reduce air borne sounds and if densely planted the surface of leaves catches dust and filters the air. Givoni (1998, p.357) also emphasizes the importance of plants and vegetation on the microclimate of buildings. He argues different types of plants can contribute to the following objectives: shading of the roof, walls, and windows; shading of play and rest areas outside the building; reducing and filtering the dust; elevating humidity levels in hot and dry climates; reducing the temperature around the building and finally concentrating and increasing airspeed for natural ventilation purposes (ibid). Water features also improve the humidity levels and quality of air for natural ventilation of the building considerably.

Trees and vegetation also secure visual privacy and also contribute to the reduction of heat loss during winter and the absorption of radiation in summer (Gorji-Mahlabani 2002, p.127). In fact, they can contribute to the shading performance of the building considerably depending on the type of the tree and its density. Trees not only can obstruct the exposure of windows to direct intense sunlight in warm dry climate, they can also filter sunlight through their dense leaves and deliver more gentle and non-glaring light for illumination. Apart from the many microclimatic benefits of trees and plants mentioned above, they can contribute to diffused daylighting of schools if properly chosen and located.

5.5. Summary

Reflected lighting is an appropriate solution to daylighting design in warm-dry climate of Iran to avoid discomfort glare and overheating. There are two major physical factors which can influence reflected daylighting of school buildings or classrooms: general and specific. General physical factors such as building orientation and configuration as well as the street or courtyard canyon proportion has been investigated through two tests and the results were discussed in the first part of this chapter. The importance of the ground reflected sunlight for classroom illumination in the warm dry climate was highlighted and some design recommendations have been suggested.

The second part of this chapter investigated specific physical factors which can influence daylighting performance of schools in the warm-dry climate of Iran. These specific factors include daylight apertures, shading devices, innovative daylighting systems and surface features. Most daylight apertures need shading devices to control direct sunlight but there are few zenithal apertures such as roof monitors or lanterns which can control direct sunlight to some extent without shading devices (tab 5.3). Table 5.4 compares and contrasts different shading devices on the basis of their performance such as glare control, light redirecting capability, allowing a view to outside, etc. Therefore, a few shading devices are selected to be suitable for classrooms in the warm-dry climate of Iran on the basis of the aforementioned comparative study (tab. 5.5).

Innovative daylighting systems are also recommended for reflected daylighting in school in the warm dry climate of Iran. They are divided as core daylighting systems, which are based on redirecting sunlight or daylight, and beam daylighting systems which reflect and conduct the sunlight. Core daylighting systems such as lightshelves, prismatic glazing and holographic systems are briefly introduced and their applicability in schools in the warm-dry climate of Iran are assessed. Beam daylighting systems such as light pipes and mirrored systems are also possible solutions for reflected lighting in schools in such a climate and their applicability is discussed.

Finally, surface features of a building such as material and colour and their effect on reflected lighting is discussed. Microclimate of buildings including plants and ponds around a building in such a climate also has an effect on the daylighting performance of schools which was addressed at the end of this chapter.

Having discussed reflected daylighting and the influencing factors, next chapter explores the above influencing factors in the vernacular architecture of the region and historic schools in the warm-dry climate of Iran in terms of their reflected daylighting performance. It will, then, examine a typical contemporary classroom in terms of its daylighting performance and also evaluate some of the influencing factors using ECOTET simulations.

CHAPTER 6: HISTORIC AND CONTEMPORARY CASE STUDIES IN IRAN

6.1. Historic Schools in the warm-dry climate of Iran

The main characteristic of warm-dry regions which affects human comfort as well as urban and building design is the combination of low humidity and high summer daytime temperature (Givoni 1998). One of the main problems faced by the designers of modern schools in this climate is the prevention of overheating (DFES 2003). It seems that appropriate use of shading devices and good façade design, together with the use of thermal mass, helps to limit summertime overheating (ibid p.7). It can also be observed in the traditional architecture of the region that keeping the direct sunlight off the windows and cooling the spaces with the help of the microclimate around the building are important in dealing with the overheating problem. In other words, reflected lighting, using indirect light, seems to have been a suitable daylighting strategy in this climate in the past. This issue has been addressed in the vernacular architecture of this climate as the result of embedded experience of local architects in the handling of practical problems (Rudofsky 1964).

Vernacular architecture is now the term most widely used to denote indigenous, tribal, folk, peasant and traditional architecture and it is worth finding a definition for it to give a clearer picture (Oliver 1997). "*Vernacular architecture comprises the dwellings and all other buildings of the people. Related to their environmental contexts and available resources, they are customarily owner- or community built, utilizing traditional technologies. All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies and ways of living of the cultures that produce them*" (ibid p.xxiii). In considering the appropriate design in a hot-dry or warm-dry climate, from the human comfort point of view, lessons can be drawn from the vernacular architecture and town planning. The vernacular has been developed over many centuries in response to many factors, of which an important one is the climate (Givoni 1998). Therefore, it can be seen as a rich source of knowledge for designers, especially in extreme climates. However, lessons should be discovered and identified since it is not a written body of knowledge. The vernacular is an evolved knowledge based on people's needs and the adaptability of the buildings to the environment and the climate. An exploratory study of some vernacular buildings could shed light on their relevancy to passive design issues and daylighting. As the main focus of the research is daylighting in schools, 15 appropriate historic schools have been chosen in three main cities of the warm-dry climate of Iran: Esfahan, Shiraz and Kashan. Schools which are successful examples of design in terms of daylighting will be examined in this chapter. Against this, the last part of this chapter will look into a typical modern school in Shiraz which fails to provide comfortable daylighting conditions. Most traditional and vernacular buildings of the warm-dry climate of Iran are naturally ventilated and provide a comfortable and pleasant ambiance for the people, whereas, some new buildings are uncomfortable and unpleasant without mechanical ventilation. Therefore, the first part of this chapter aims to find the principles of environmental design, specifically natural lighting, behind the vernacular in order to help inform designers to build better places to live and to learn.

Although some of these case studies are not ordinary pieces of vernacular architecture, because of the importance and the authoritative role of religious schools at the time, the principles of environmental design may be seen behind the strict geometry and decorations. The main limit to this case study is the nature of the analogy between the old schools and the present, or future schools, which have apparently different systems of education and curriculum. In the old schools students used to sit on the floor in a circle around the lecturer, while in typical contemporary primary schools in Iran students sit in rows on chairs facing the blackboard which is, of course, based on an outdated educational paradigm as discussed in chapter 3.

Nevertheless, apart from these differences there are some similarities between them which make this investigation worthwhile. The first thing in common is they are both places for reading and learning. Although some physical features such as size of the classrooms have changed, they are still spaces to provide privacy and concentration for students to learn. The type of light used for the act of reading is another feature in common. Reading and writing which are typical school activities require a minimum level of illuminance with relatively high illuminance uniformity over the task area (DFEE 1999). Direct sunlight is also avoided in reading areas since it causes glare and visual discomfort. This investigation aims to find the common features in the historic examples of defeating the overheating problem as well as providing natural lighting and ventilation.

This study first explores the daylighting components in a single study-bedroom (Hojra) as the most important element of historic schools which has a significant effect on the configuration of historic school buildings (Soltanzadeh 1985). It explores these elements in different schools comparatively. It also investigates the sources of light in the study-bedrooms (Hojras) in relation to the daylighting components (i.e. windows and other apertures). Secondly, it looks at daylighting components in teaching places (Madrass) which are usually large semi-closed spaces covered with a high dome used for lecturing and teaching theology students. Thirdly, reflected daylighting and two important factors affecting the amount of reflected light onto the windows of Hojras will be examined. The effect of colour will, then, be addressed as it has a direct impact on the amount of reflected light in classrooms. The next section will involve the field study photometric measurements.

A photometric study was carried out in some schools to find out the levels of illumination in the interior and exterior spaces of schools which will be discussed in section 6.1.5. The quantitative study will help understand the level of light available in the Hojras in comparison with the high amount of sunlight in courtyards. However, it is important to consider other comfort issues such as natural ventilation affecting daylighting in order to have a comprehensive understanding of the subject. It is also clear that the proportion of classrooms has a significant impact on its daylighting which is discussed in section 6.1.7. Therefore, this study looks into different schools in order to explore common proportional features as well as their effect on the distribution of its daylighting. Finally, it will sum up the common features and generic principles and rules in the historic buildings in terms of daylighting and environmental design and also discuss the applicability of these rules to future schools.

6.1.1. Daylighting components in a single study-bedroom (Hojra)

Hojras (study-bedroom) are fairly long rooms arranged around the courtyard and are used for studying as well as accommodating students. Each one is usually connected to the courtyard through a small semi-open space which could also be considered as a shading device or a portico (Fig 6.1). To make a clearer analysis of daylighting components, it is necessary to make a distinction between two groups: admitting (pass-through) and conduction components as discussed in chapter 4 (section 4.5.1). Admitting components are devices to admit light to a room by allowing it to pass from one side to another; for example, windows are the most common device. Conduction components direct and conduct light inside the building and are usually a spatial medium between admitting components and the interior lit space (Baker 1993).

The admitting components in the Hojras are side windows. The main daylighting component is a high small window (clerestory) over the entrance which is usually covered by a latticed screen. Clerestory windows admit light from the brighter part of the sky and, as it is more likely to cause glare, latticed screens help reduce the glare. An important feature of clerestory windows is as we have seen that they can provide daylight deep into the room (DFEE 1999). Windows in the entrance door are the second component to provide natural light into the room. However, in some cases such as Nimavard School (C.No.2: case study no. 2 of Appendix A) there are no windows in entrance doors in ground floor Hojras, which could possibly be for the provision of privacy for living students. In Qavam School in Shiraz (C.No.13, Appendix A) there are also two small windows at both sides of the entrance door to provide more natural light in the Hojras (Fig 6.2). *The shape and position of windows affects the way in which daylight is distributed, wide shallow windows giving a broad distribution and tall narrow windows a deep but narrow distribution for instance* (ibid p.9,10). The side windows are generally the tall narrow type since a wider window will cause overheating in this climate.

There are two conduction components in the Hojras: the portico and the deep window reveal. The portico which, will be discussed in detail, is an external component which conducts daylight from the courtyard onto the admitting components; whereas the window opening conducts light from admitting components into the room. The surfaces of the window reveal around the high window and the entrance act as deep reflecting surfaces and helps produce a uniform distribution of light.

Fig 6.1. A typical Hojra at Chaharbagh School in Esfahan

Fig 6.2. Qavam School

Latticed screens are mostly located at the exterior surface of the opening and help filtered light bounce off the surfaces of the window reveal into the room. Moreover, they make the surfaces of the reveal a radiant reflecting surface for the people inside.

Porticoes

Porticoes have been observed in most case studies to act as a shading device as well as a semi-open space for studying and relaxing. They are usually 3 meters wide, the same width as the Hojras, and averagely 1.5 meters deep in the case studies. The depth of the portico means that it acts as both a horizontal sun shade for south light as well as a vertical shading device (as a fin) which obstructs the low angle east and west sunlight. The geometrical facetted surface of the portico's ceiling helps in reflecting light onto the windows of the Hojra. The following diagrams show how the multi-facetted surface creates more reflected light onto the windows compared to the ordinary overhangs and fins.

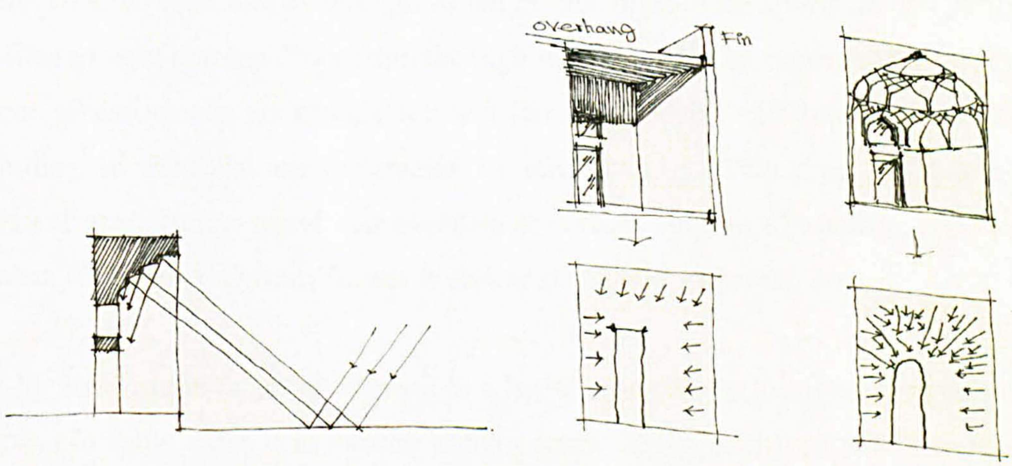


Fig 6.3. The conduction of reflected light onto the windows in the traditional Porticoes in comparison with ordinary overhangs and fins

Although porticoes are an essential part of Hojras in traditional schools, there is an exception to this rule at Agha-bozorg School in Kashan (C.No.15, Appendix A). There are no porticoes in front of Hojras at this school, which makes climatic control more difficult. However, this problem is dealt with in another way in this case. The entrances of the Hojras are usually through the porticoes facing the courtyard since it is protected against sunlight by the shading devices. But in this case where there are no shading devices; the entrances to the rooms are through narrow corridors next to the rooms which moderate the temperature (Fig 6.4). In addition, dense latticed screens soften the harsh sunlight and reduce the glare.

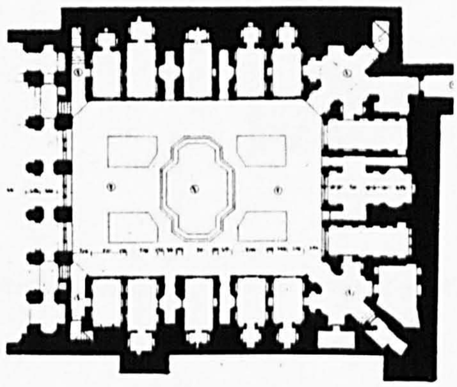


Fig 6.4. Entrance corridors between Hojras

6.1.2. Daylighting components in the teaching places (Madrass)

A Madrass is usually a large semi-closed space covered with a high dome used for lecturing and teaching theology students. The Madrass is illuminated thoroughly by indirect natural light mostly through its tall portico open to the courtyard and partly by the filtered light coming down from the high windows and the clerestories beneath the dome. These spaces are usually tall and have high levels of illumination (Fig 6.6) according to the photometric studies in section 6.1.5. This type of Madrass is observed at the more grand and established schools such as Chaharbagh School in Esfahan (C.No.1) or Qavam School in Shiraz (C.No.15, Appendix A).

The Madrass in the majority of cases is a larger space for lecturing in comparison to Hojras. In some cases it is located in the corners of the courtyard with less natural light; whereas, in other cases such as Jadeh-bozorg School (C.No.3) it is located in the middle of Hojras' wings with higher levels of illumination. Large windows at two-storey level facing the courtyard admit sunlight and filter it though the latticed screens (Fig 6.6). In this specific case, the length of the room runs alongside the courtyard and is consequently more exposed to the sunlight. It can also be seen that the high ceiling improves the uniformity of the distribution of light in the room which will be proved in the third stage of the experiment in section 6.2.

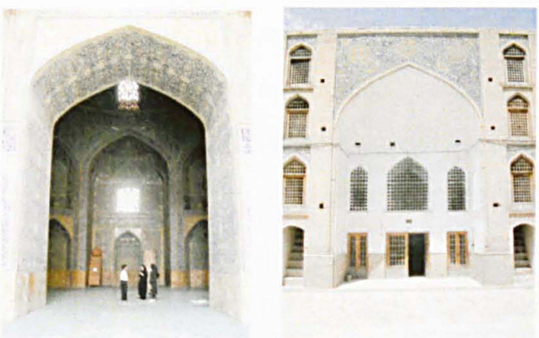


Fig 6.5. Chaharbagh Madrass

Fig 6.6. Jadeh-bozorg Madrass

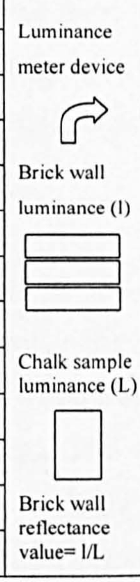
6.1.3. Reflected daylighting and the effect of building orientation and courtyard canyon proportion

As direct sunlight in this climate has high intensity and can cause visual discomfort and overheating, light reflected off the surfaces into the room is more acceptable, as discussed in chapter 5. The main reflecting surface is the courtyard floor together with the overall surfaces of the portico. In the physical model experiment in chapter 5 (section 5.3.4), it was found that the ground reflecting effect is more important in southern orientations since it provides the first set of reflection rays whereas the wall reflecting effect plays an important role in northern orientations. Therefore, a shallow canyon or profile is more appropriate for southern orientation in terms of reflected lighting, while a deeper canyon/profile is more efficient for the provision of reflected light for the northern windows.

It was found that a wide canyon proportion of P= height/width of the courtyard =0.5 to P=0.6 has a higher amount of reflected light (Ew/Es) in the south to the east orientation; while a deep canyon proportion of P=1 to P=1.5 has a higher amount of reflected light for the east to north orientation. The shallowest courtyard is in Nimavard School (C.No.2, Appendix A) where P<0.5, therefore, the amount of reflected light is higher in the south and east façades.

6.1.4. The effect of surface colour and reflectance

Givoni (1998, p.356) underlines the significant impact of colour of the walls and the roof of the building on its indoor environment where the solar intensity is high. He suggests that eastern and southern walls are very sensitive to their external colour, while the northern wall is the least sensitive. Table 6.1 illustrates different surface materials in schools and their reflectance value. The method of calculating materials' reflectance value was by using a luminance meter device and a white chalk sample. The chalk sample is a perfect diffuser, presumably reflects all the light it receives and its reflectance value is approximately 1.0. For calculating the reflectance value of each surface, the chalk sample was placed next to the surface and then the luminance value of the surface and of the sample was measured by the luminance meter. The reflectance value of the surface is the ratio of the surface luminance value over the sample luminance value as illustrated in Table 6.1. White plaster has the highest reflectance value among the materials used in schools. Most of the interior surfaces of the rooms in the case studies are light in colour which helps reflect light and increase the amount of illumination inside. In addition, the surface of walls and cornices of porticoes are light in colour to help reflect light inside the rooms.

	Materials	Materials I (cd/m2)	Sample L(cd/m2)	Reflectance value	Diagram
Interior	light plaster wall	20	25	0.8	
	Grey plaster wall	17	26	0.654	
	Floor carpet	2	60	0.033	
	Door wood	85	435	0.195	
Exterior	white plaster wall	309	436	0.709	
	Marble wall	123	448	0.274	
	wall Brickwork	253	910	0.278	
	Enamelled mosaic	243	842	0.288	
	Turquoise tile	58	292	0.199	
	White enamelled tile	149	292	0.51	
	Jagged grey stone	190	927	0.205	
	Jagged white stone	327	876	0.373	
	Floor brick mosaic	65	261	0.249	

Tab 6.1. The reflectance value of different surfaces

However, because of the intensity of direct sunlight in this climate, all-white buildings, while being better from the thermal viewpoint, may intensify the environmental glare (Givoni 1998). Therefore, lower reflectance materials as a design solution for the courtyard floor and walls will have the effect of reducing the glare and improving environmental comfort in this climate.

6.1.5. The photometric study and the levels of interior and exterior illumination

This photometric study aims to discover whether the illuminance levels in the historic schools meet the minimum requirements and also if light is distributed evenly across learning spaces. It also measures exterior illumination levels to find out the intensity of sunlight on the school exterior surfaces as potential sources of reflected lighting.

The photometric study was undertaken using a luminance meter device which can measure the brightness of any surface in terms of cd/m2. This device only measures the luminance value of material surfaces and in order to measure the illuminance factor, the reflectance value of the material is required according to the following formula:

E (illuminance lux) = L (luminance cd/m2) × π / ρ (reflectance value)

Reflectance value is the luminance measured on the surface of the material over the luminance of a white sample whose reflectance is approximately 1.0 (Table 6.1). Therefore, reflectance value is a rate between 0 for black absorbent surfaces and 1.0 for perfect diffusers.

For the daylight illuminance to be adequate for the task in a classroom, it will be necessary to achieve a level of not less than 300 lux, and for particularly demanding tasks not less than 500 lux on the working plane (DFES 2003). When this cannot be achieved, the daylight will need to be supplemented by electric light. This seems to be the case in most Hojras observations, since electric light is still necessary for basic acts of reading and writing on a bright sky day. Figure 6.7 shows the illuminance levels calculated on the interior surfaces of some Hojras in bright sky conditions. Luminance values of the target points in the photos were measured by the luminance meter in the real room and then the illuminance values were calculated with the above equation. It is important to mention that the luminance values which were measured in the field study by the luminance meter were a more realistic figure as luminance or brightness is what we see from illuminated objects. However, as the author intended to compare the field study measurements with the available illuminance standards for learning spaces, all the luminance levels were converted into illuminance levels in lux and are presented in red colour onto the photos of the real spaces where the measurements were made.

Fig 6.7. Illuminance levels in a Hojra in Chaharbagh school (C.No.1)

It should be noted that most of the calculated illuminance levels are for vertical surfaces and can not be compared with the standard horizontal illuminance levels recommended by DfES (2003). They are only an approximate guidance of the lighting conditions in the Hojra's internal surfaces. The only horizontal illuminance level in the above Hojra (C.No.1) is measured at 75 lux on the floor where the students do their reading without electric lighting which seems inadequate comparing to the standards. With electric lights switched on in the above Hojra, the horizontal illuminance on the floor was measured 395 lux which is adequate for reading.

Light-coloured surfaces inside Hojras as well as portico surfaces can sometimes be used as a good design solution to reflect the available light off the surfaces in the room to increase reflected light. That is the case in most case studies as walls and ceilings in Hojras either have white plaster finish or are painted white. However, in some parts of the schools the internal surfaces reflectance value is low and hence they do not contribute to illuminance levels on the horizontal plane. An example of fairly low illuminance levels is the library in Agha-bozorg school C.No.15, Appendix A. The lux levels on the following photo show that the illuminance level on the working plane (94 lux) is below the standard, even with the supplementary electric lighting. In addition, the figures show the distribution of light is not uniform for a reading area.

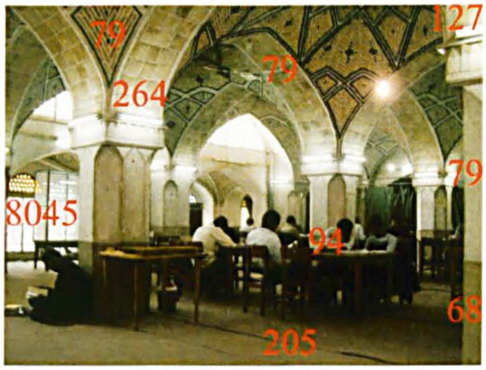


Fig 6.8. Illuminance levels in the library C.No.15

On the other hand, the photometric study shows high levels of illumination in the courtyard horizontal plane as well as the surrounding vertical surfaces which were calculated by using the measured luminance levels and the aforementioned equation (Fig 6.9). The outside is so bright that it can cause discomfort glare if light is admitted directly into the rooms. This explains the small Hojra openings and latticed screens which have sacrificed sufficient natural illumination for the reduction of glare and heat gain. High illuminance levels in the Chaharbagh or Agha-bozorg School courtyard (over 68000 lux on the courtyard floor) indicates the high intensity of light available in such a climate and it can be used for natural lighting if admitted indirectly and conducted into the classrooms appropriately. Courtyard floor and walls can also contribute considerably to the amount of light reflected onto Hojra windows, but they are covered with fairly low reflectance materials in case studies to help reduce the glare. Therefore, with the help of light redirecting systems such as lightshelves, rooms in such a climate can have larger openings as well as sufficient natural illumination while discomfort glare is also avoided.

Fig 6.9. C.No.1 and C.No.15 vertical and horizontal illuminance levels in the courtyard

6.1.6. Other comfort issues affecting daylighting

It seems that in this particular case study, and in others in the same climate, cooling and comfort conditions are more important than the illumination levels in the study-bedrooms. This can be understood in the context of the emphasis on the main vernacular strategies of energy conservation and human comfort in hot-dry and warm-dry regions: lowering the indoor temperature in day time, natural ventilation and minimizing heat gain and loss (Givoni 1998). The presence of the high window over the entrance door also helps the natural ventilation of the room, since warm air rises up and the opening at high level allows a better circulation of air. Besides, although the courtyard floor is a significant source of reflected light, it is covered mostly with grass to exploit the natural cooling effect. Therefore, it can be seen to be necessary to strike a balance between the climatic elements such as daylight, ventilation and heating in order to create a sustainable place for living and learning, in which various factors are in equilibrium.

6.1.7. The impact of the proportion of a room on its daylighting

The study-bedrooms are narrow, about 3 meters wide, with the short side adjacent to the courtyard. The building should preferably be compact and less exposed to the sunlight to lower the temperature elevation of the interior during the daytime hours (Givoni 1998). In other words, the surface area of its external envelope should be as small as possible to minimize the heat flow in the building (ibid, p.340). This compact configuration also allows more rooms fit in and built around the courtyard. On the other hand, the depth of the room causes the lack of illumination at the back of the room (Fig 6.5 & 6.10). The illuminance level is less than 100 lux on the horizontal plane at the back of the Hojras without electric lighting. This level was calculated by the conversion equation $E=L\pi/\rho$ where L is the measured luminance level on the working plane which is the floor in Hojras. However, the height of the room, about 4 meters at the axis, lets light bounce off the surfaces easily in order to improve the illumination at the back of the room. It also allows a better circulation of air for natural ventilation. Therefore, the height of rooms has a significant effect on the amount of natural lighting as well as natural ventilation.

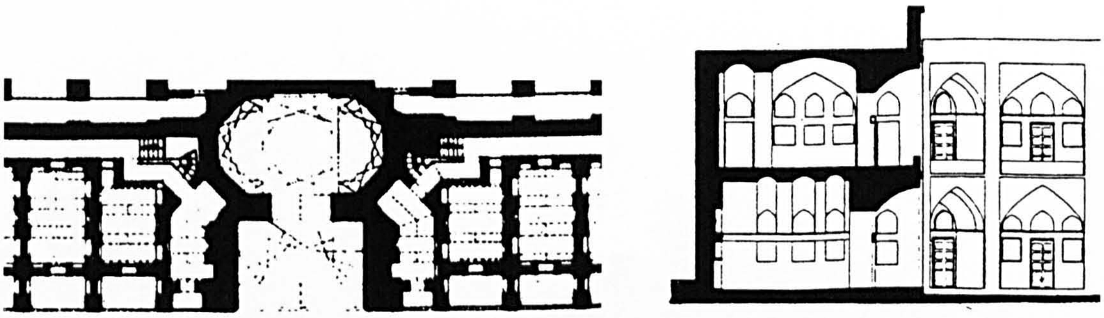


Fig 6.10. Kasegaran School (C.No.7)

The following comparative study (Fig 6.11) illustrates the proportion of Hojras in all 15 case studies (C.No.1 to C.No.15), which makes it easier to study and compare their physical features. Each cube represents a single Hojra in each case study with its dimensions (height, width and length) noted next to them in Fig 6.11. It should be noted that the Hojra in case study no. 5 is represented by two attached cubes as the height of the Hojra drops at the back of the room. The width of the rooms is about 3 meters and is nearly the same in every school. The length of rooms varies from 3 meters in smaller schools to 6 meters in larger schools. The height of the Hojras is an average of 4 meters, which is fairly tall for a small room.

High windows over the entrance help improve the illumination at the back of the room, as well as giving better distribution of light in the room. However, Hojras with the height of only 3 meters do not have this high window (C.No.4, C.No.10) and according to measurements the illumination levels are lower than for those higher ceilings. Therefore, taller rooms with clerestories have higher natural illumination levels comparing to shorter rooms without high windows according to illumination measurements in all Hojras.

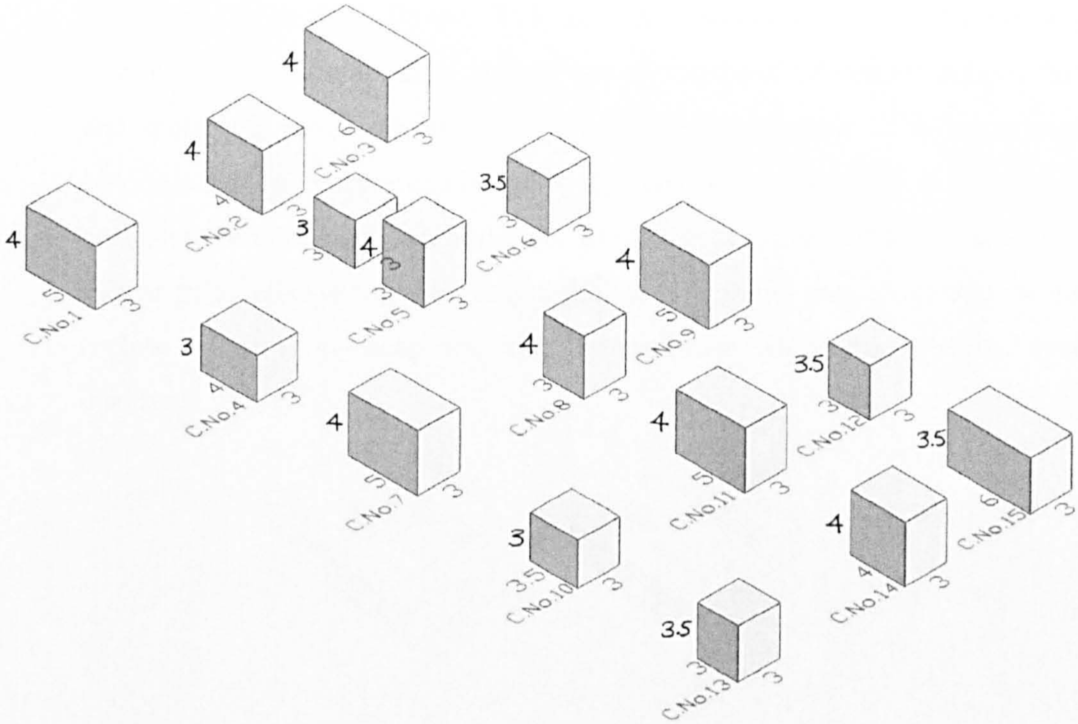


Fig 6.11. A comparative study of Hojra proportions in each of 15 case studies

6.1.8. Common features and Generic principles of daylighting in historic schools

In conclusion, the generic principles of daylighting in historic schools in the warm-dry climate of Iran can be summarized as follows:

- The compact configuration and the low ratio of building surface/ building volume seems to be a general rule of environmental design at this climate (Shojaie 2004). Therefore, a cubic and fairly solid building like the drawing below left is preferred to a wide-spread plan building on the right. However, this rule should be considered alongside the courtyard rule.

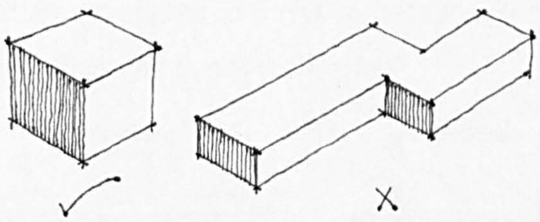


Fig 6.12. General building configuration preference

- A configuration that has a special role in warm-dry regions is an internal courtyard or patio (Givoni 1998). Courtyards seem to be an appropriate configuration in this climate. Tall trees and plants act as natural shading devices and climatic controls, and the use of water cools down the temperature and make the inner climate more pleasant and tolerable. The introverted configuration of courtyards also gives the inner space more privacy, which is consistent with cultural and religious issues. Finally, one of the reasons that Hojras fit together along their length (below left) rather than along their width (below right) is to keep the compactness rule which has already been discussed above.

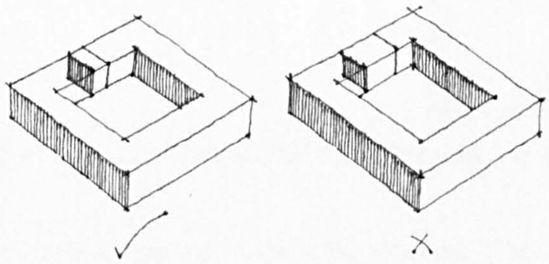


Fig 6.13. Courtyard configuration & Hojras

- In most case studies, the windows of Hojras are located facing the courtyard in order to prevent an unpleasant air draft during the warm season, which can be caused by opposite windows (below right). This seems to be in contradiction with the common notion of cross ventilation as a good solution but the dry air outside the building reduces the quality of the draft passing through two opposite windows with higher speed. However, a larger opening at the courtyard side and a small controlled opening at the top part of the back of the room might improve the circulation of the air which is explained in the next principle. There are usually two windows facing the courtyard (the entrance window and the clerestory or the high window above the entrance) which allow a pleasant air circulation in direct contact with the controlled climate of the courtyard with trees and ponds (below left).

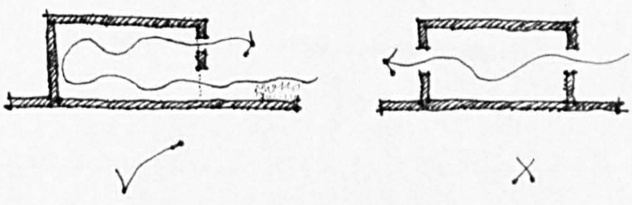


Fig 6.14. Fenestration & ventilation

- In some exceptional cases such as Khan School in Shiraz (C.No.11) in which there are windows on opposite walls in some of the Hojras, latticed screens slow the speed of air. In addition, the different height of the windows helps a better circulation of wind flow.

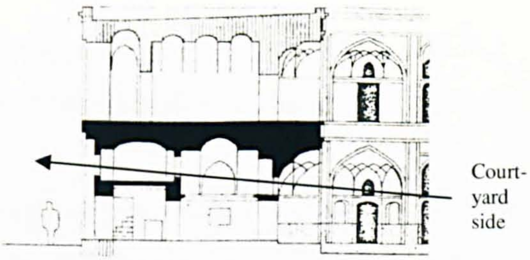


Fig 6.15. 3 Opposite windows in a Khan school Hojra **Fig 6.16.** 3 opposite latticed screens

- Porticoes are a common feature in the case studies. They perform as shading devices as well as transitory spaces between the private study-bedroom and the courtyard, and could be used for small group discussion when in the shade. The light coloured surfaces of the porticoes also help reflect the light inside the room. These porticoes are not specific to the historic schools, but are an important generic element in the vernacular architecture of this climate.

  In Jadeh-bozorg school (C.No.4) porticoes at first floor level are interconnected through small gateways and they are also used as semi-open corridors which are preferable to dark corridors at the back of Hojras (e.g. C.No.3).

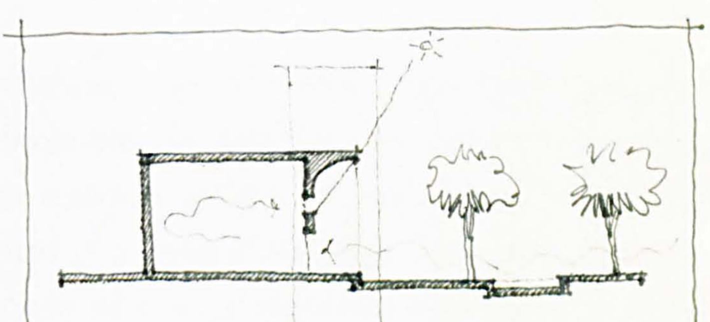


Fig 6.17. Portico as a shading device and a transitory space

- The minimum surface of window to minimize heat gain and loss as well as their high position (clerestories) is another common feature. These high windows conduct light to the back of the room and are also protected from direct exposure to sunlight by the porticoes.

- At some positions in which clerestories are exposed to direct sunlight due to the low angle of the sun, latticed screens filter the light and also reduce glare.

- The tall height of the rooms (average 4 meters) is another common feature which allows the light bounce off the surfaces and provides an even distribution of light as well as better air circulation inside the room.

- High reflectance materials such as plaster reflect most of the light received and increase illumination inside Hojras.

- Low reflectance materials such as brickwork or enamelled mosaics or other materials with rough texture such as jagged stone covering the courtyard floors reduce reflected light and the glare.

- There is a balance between visual and thermal comfort in the vernacular schools.

6.1.9. Discussion

Most of the above lessons from the historic schools can be applied to the design of contemporary schools, although there are some limitations in using some of them. Thus, porticoes are a distinct feature in case studies and could be introduced into the future design instead of the normal overhangs which are common in contemporary Iranian schools. As we have seen porticoes not only perform as shading devices, but also can be used as temperature moderators, transitory spaces between the private and the public and even corridors at higher ground levels. The vertical walls of porticoes could also protect windows from east or west low angle sunlight (acting as vertical shading devices) and also reflect the light onto the window and increase the reflected illumination inside classrooms. Courtyard configuration is another consideration for the design of contemporary schools as they have been a successful feature of the vernacular architecture of the region. A recent study in the tropical climate of Brazil shows that the light reflecting off the courtyard may produce an increment of up to 55% in the average illuminance of the rooms (Bittencourt and Melo 2001, p.1349). Despite the benefits to reflected daylighting and natural illumination of schools, the limitation in using courtyards is mainly due to the shortage of land in fairly crowded areas of town which may make it difficult to incorporate them.

The tall height of Hojras is another issue to address in the next section of this chapter, since they increase the amount of reflected daylight as well as contribute to a uniform distribution of light. One might argue it is not economical to build high ceiling schools; however, if this is a crucial element in maximizing the amount of reflected daylight, it could be considered with other design solutions such as mezzanine classroom areas to make the most of a tall room.

The clerestory (the high window) is another vernacular design feature that could be transferred to achieve a better daylighting and natural ventilation. It is usually used in tall Hojras and does not perform as efficiently with a lower ceiling. The next section will investigate the clerestory effect, as well as the height and shape of a Hojra, by using the ECOTECT simulation software. It will examine the contribution of above elements to reflected daylighting in Hojras.

6.2. Daylight Analysis of a general Hojra by ECOTECT

This section investigates daylight analysis using ECOTECT in a simplified general Hojra. ECOTECT is a building analysis and conceptual simulation software specifically to study the environmental aspects of a building such as lighting, heating, acoustics etc. This study aims to find out the significance of the clerestory and the high ceiling as well as the portico and the ceiling geometry by studying the amount of reflected light and the distribution of daylight in the room by changing some physical factors of the room.

6.2.1 Methodology & Simulation results

A single Hojra with a simplified portico with the dimensions of Chaharbagh School Hojras (C.No.1) is modelled in ECOTECT. The daylight analysis is undertaken on midday on 15th of April which is the date of field study photometry measurements. There is a limitation in ECOTECT capability which needs addressing. Daylight factors are usually based on uniform or CIE overcast sky distribution. Therefore, there is no choice of clear sky condition in ECOTECT and the light levels do not vary with the building orientation (Marsh 2003). The first stage is to study the effect of clerestory on daylighting performance. The second stage is to find out the significance of the height of Hojra and its contribution to reflected daylighting. The third stage is to study the impact of the portico as a shading device on the daylighting performance of the room. Finally, the last stage studies the sloped form of the ceiling and its effect on the daylight factor and the internally reflected light in the Hojra. The results are discussed separately in each section and the conclusion will follow up in the end.

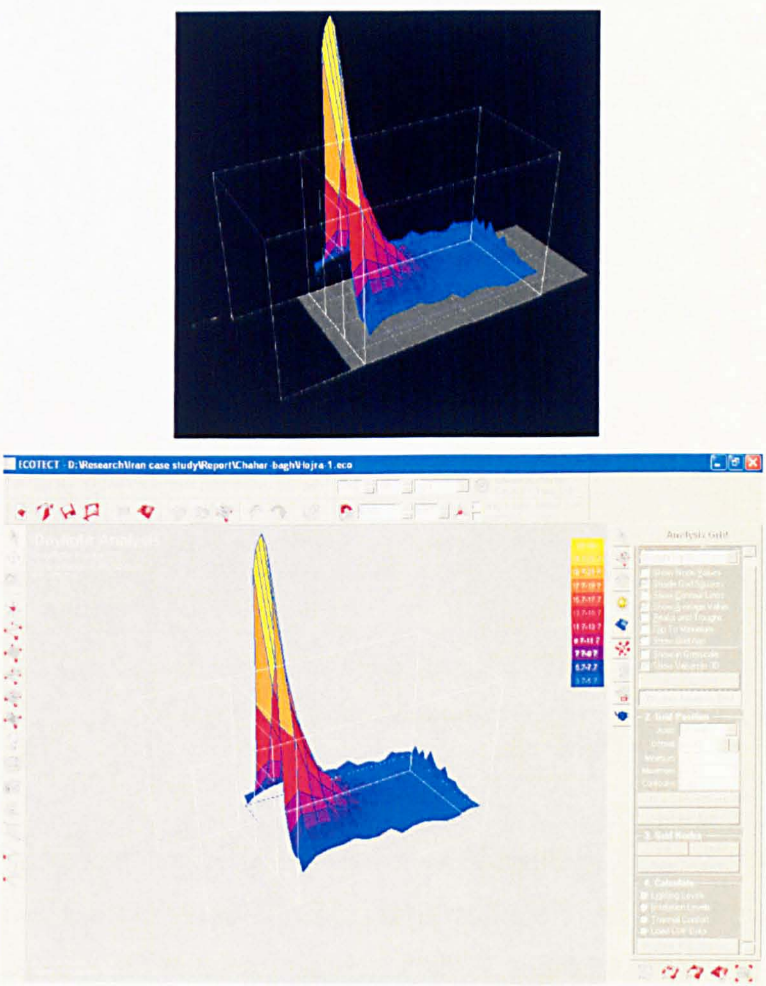


Fig 6.18. 3D visual representation of daylight factor in a south facing Hojra simulated in ECOTECT

Stage I

At this stage the clerestory is eliminated in the simulations in order to study its effect on the daylighting performance in comparison with the original Hojra. Figure 6.19 shows the plan of a Hojra with only the view window and no clerestory (right) with its daylighting factor analysis which is compared with a normal Hojra with the view window and a clerestory (left). The right simulation represents the daylight factor variation across the plan of the room and shows that Daylight factor varies from 3.1% (blue zone) at the back of the room up to 23.1% (yellow zone) in front of the opening. As can be seen, the daylight penetration is not as deep as Hojra with a clerestory in the left image. This shows the effect of clerestory in conducting light deeper inside the room. Moreover, the daylight factor has dropped from the minimum 4.6% in the original Hojra (left) to 3.1% in the Hojra without a clerestory (right).

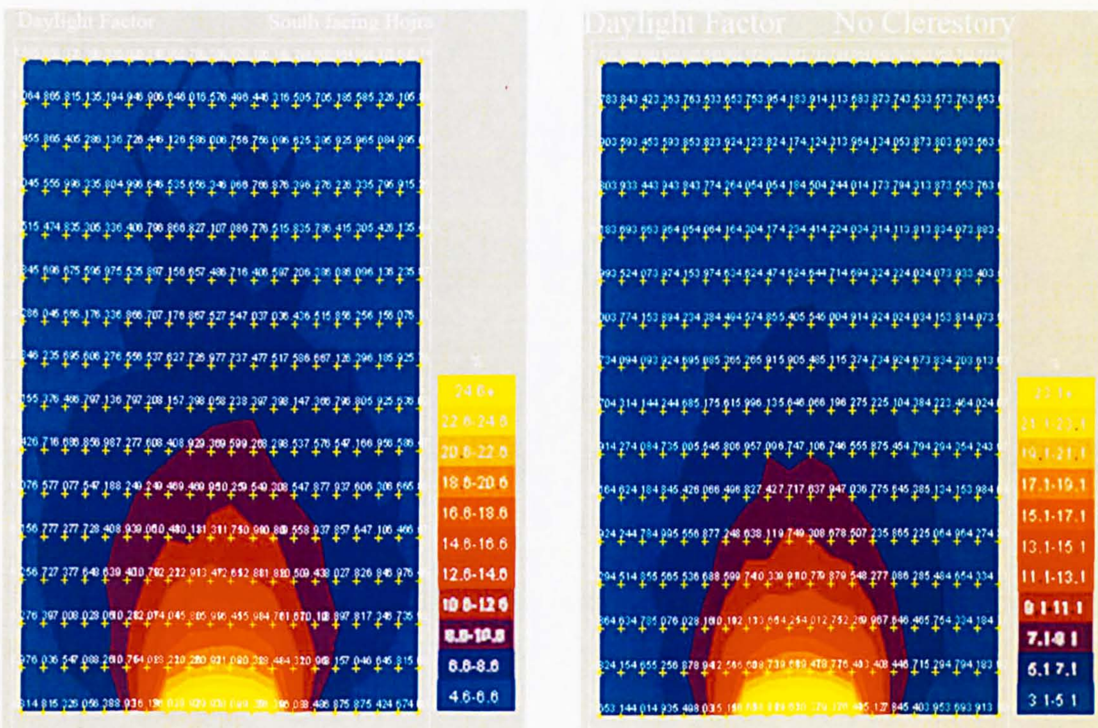


Fig 6.19. Daylight factor analysis in the plan of a single south facing Hojra with a clerestory (left) and without a clerestory (right)

To study the significance of the clerestory in terms of the depth of daylight penetration, another model simulates the condition in which clerestory is the only window in Hojra for daylighting analysis. Fig 6.20 shows the internally reflected lighting component (IRC) diagram in the profile of the Hojra with a view window and a clerestory (left) and only with a clerestory (right). Ecotect calculates the IRC and separates it from other sources of light in the room. The right diagram shows a low amount of internal reflected light. It has dropped to the maximum of 1.05% at the back of the room which is 3 times less than the model with no clerestory and 4 times less than the first model with clerestory and the view window (below left). Nevertheless, the sharp increase of the internally reflected lighting diagram towards the back of the room is a proof to the contribution of clerestory in conducting reflected light deep inside a room.

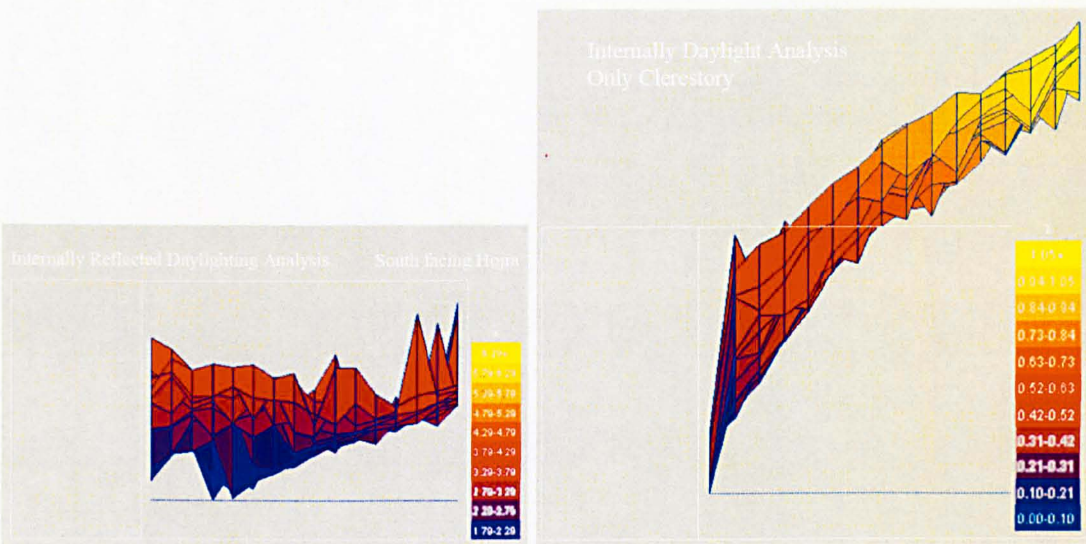
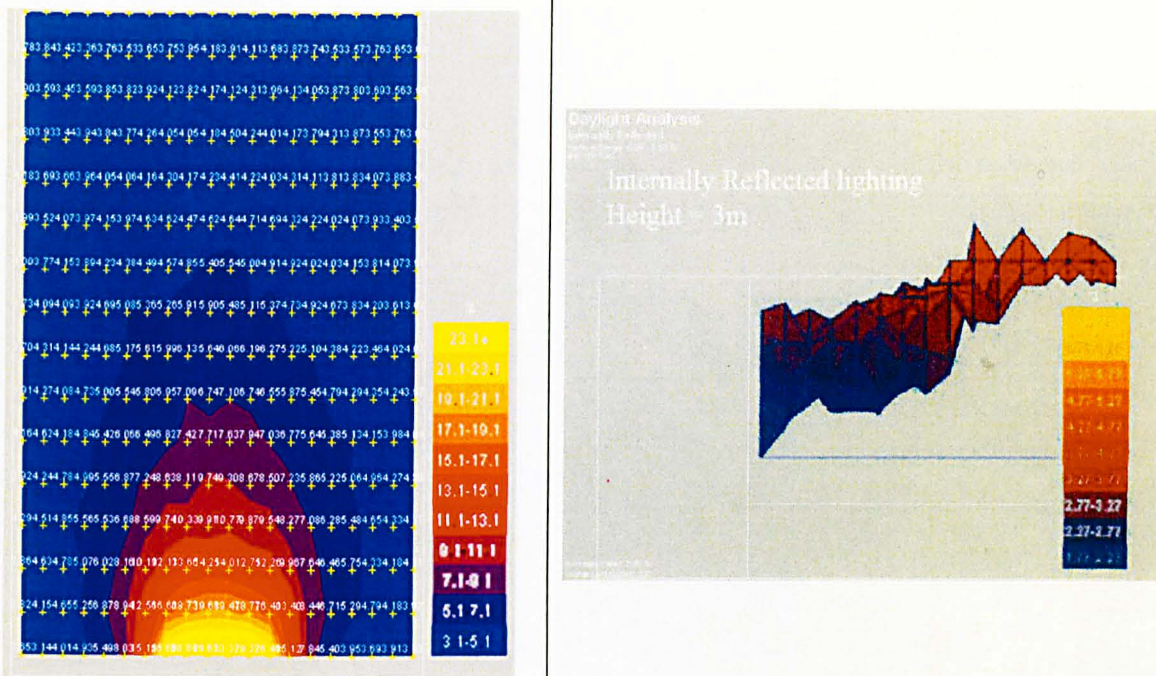


Fig 6.20. Internally reflected daylight component (IRC) analysis in a single south facing Hojra (profile) with a view window and a clerestory (left) and with only a clerestory (right)

Stage II

The height of Hojra model in this stage is reduced from 4m to 3m to study the impact of the room height on the daylighting. This model represents Hojras in the historic school case study number 3 and number 10 where there is no clerestory and the height is 3 meters. According to Fig 6.21 the minimum daylight factor at the back of the room has dropped from 4.6% to 3.7%. Besides, as can be seen by comparing daylight factor diagrams of Fig 6.21 and Fig 6.19, natural light does not penetrate as deep in Fig 6.21 as in Fig 6.19. The internally reflected daylight component diagram also illustrates the distribution of reflected daylight is less uniform than in Fig 6.19. Therefore, it seems the tall height of Hojra in stage I has a considerable effect on the daylighting performance of Hojra.

South facing Hojra Height = 3m



Plan of Hojra

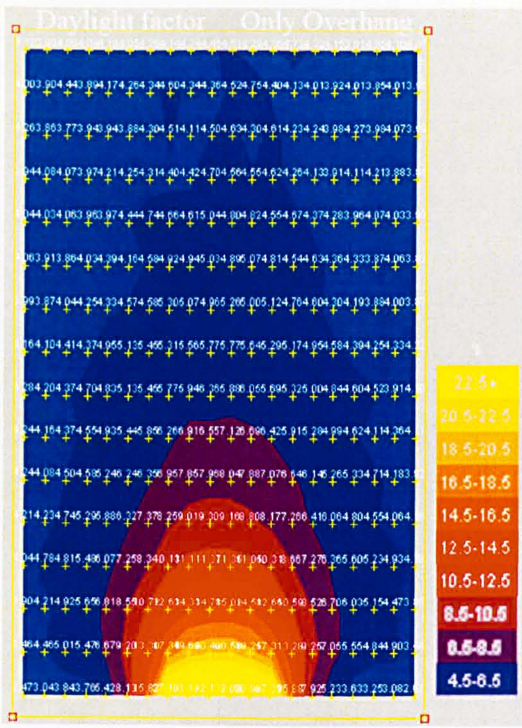
Profile of Hojra & its portico

Fig 6.21. Daylight factor and internally reflected daylight (IRC) analysis in a single south facing Hojra with the height of 3 meters

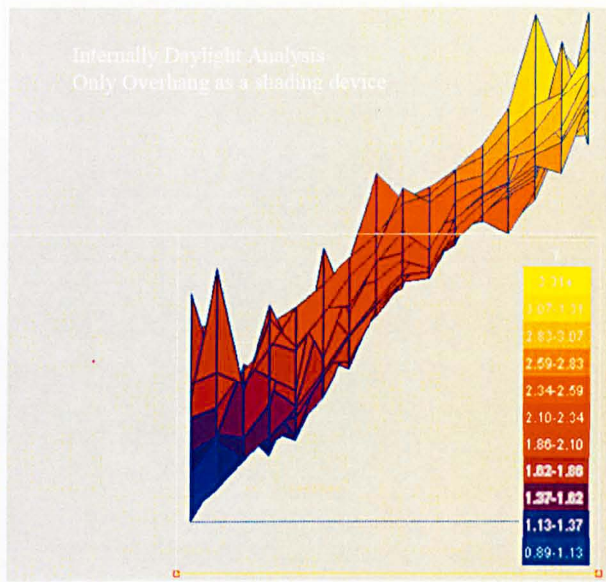
Stage III

At this stage the focus of the study is the effect of the portico acting as a shading device; with a combination of an overhang and fins. There are two scenarios to be studied in this stage. First, when the side walls of the portico are omitted and so only the overhang acts as shading device and secondly when there is no portico at all. Fig 6.22 illustrates the results of simulating the first model with ECOTECT. The daylight factor diagram on the left shows not much difference in the amount of daylight in the first model in the first stage. However the internally reflected daylight (IRC) diagram on the right illustrates a sharp increase towards the back of the room. In addition, the highest amount of reflected light drops from 6.29% in the original Hojra (Fig 6.19 left image), which the portico performed as fins as well as overhang, to 3.31%. This shows the effect of fins in reflecting light into the room as well as contributing to a more even distribution of reflected light across the room.

South facing Hojra



Plan of Hojra

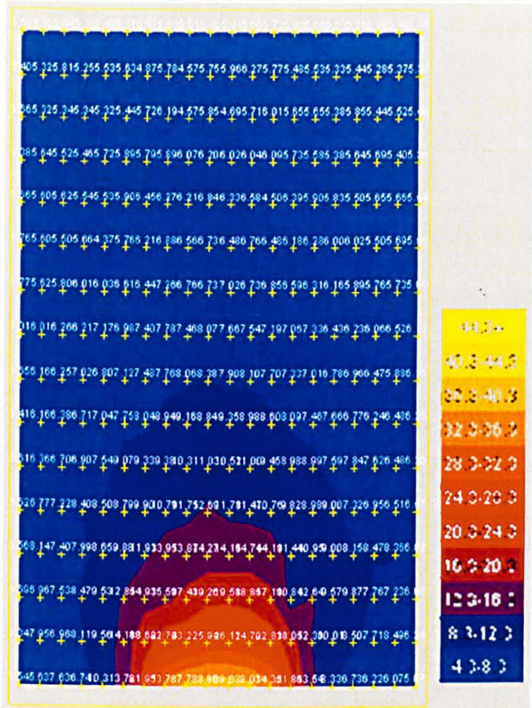


Profile of Hojra & an overhang

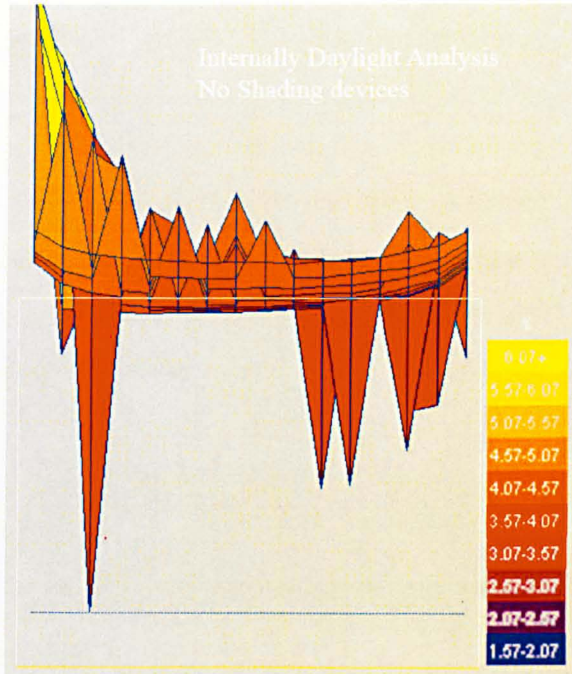
Fig 6.22. Daylight factor and internally reflected daylight analysis in a single south facing Hojra with only an overhang and no vertical shading devices

The second model for simulation is the same Hojra but with no shading devices (without a portico). As sunlight penetrates into the Hojra without any shading devices, the daylight factor near the window is quite high but drops down quickly across the depth of the room. Fig 6.23 illustrates an excessive amount of daylight near the window and fairly low levels of daylight deep inside the room. It shows the importance of portico as a shading device for sun protection, as well as contributing to an even distribution of light across the room. The internally reflected (IRC) graph also shows an uneven distribution of reflected light with high percentage of reflection near the window which can cause discomfort glare in classrooms.

South facing Hojra



Plan of Hojra

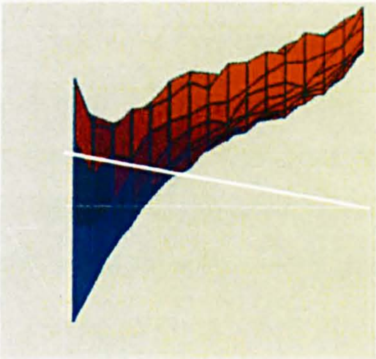
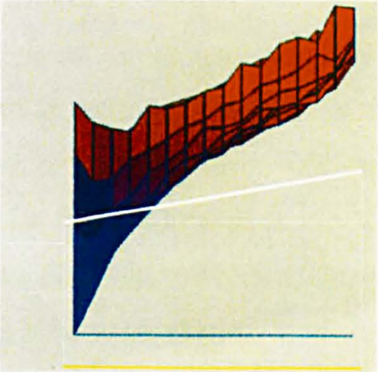


Profile of Hojra without portico

Fig 6.23. Daylight factor and internally reflected daylight analysis in a single south facing Hojra without any shading devices

Stage IV

The last stage is to study the sloped form of the ceiling and its effect on average DF (daylight factor) and IRC (internally reflected component). The average daylight factor is the average interior to exterior illuminance under an overcast sky. It is important to mention the this ratio is different in the field study as the sky was clear but as mentioned before Ecotect can not consider a clear sky illuminance distribution for its calculations. Daylight factor has 3 components: Sky Component (SC) which is directly received from the sky, Externally Reflected Component (ERC) which is received by reflection from external surfaces, and the last component is Internally Reflected Component (IRC) which is received by reflection from interior surfaces (DfEE 1999, p.15). Table 6.2 illustrates a well protected shading device for Hojra which does not allow the penetration of direct sunlight during working hours. Two models are tested to study the impact of sloped ceiling on daylighting performance of the room. In the first model the sloped ceiling lowers toward the back of the room. The DF average is the same with the flat ceiling but the IRC average is slightly reduced. The next model is the same Hojra but with the sloped ceiling lowering toward the façade. It is interesting to see both DF and IRC averages are increased slightly which improves the daylighting condition of the room. An explanation to the slight increase could be the direction of the sloped ceiling. When the slope lowers toward the back of the room, light is mostly reflected towards the area closer to facade and does not make much difference to the back of the room. On the other hand, when it lowers toward the façade, the reflected light is conducted to the back of the room and provides more uniform distribution of light across the room.

	Daylight Factor (DF) **Average Value %**	**Internally Reflected Component (IRC)** **Average Value %**	**ECOTECT Simulation** **In the Hojra profile with shading devices**
Sloped ceiling lowering toward the back of the room	**7.58**	**2.93**	
Sloped ceiling lowering toward the façade	**8.17**	**2.98**	

Tab 6.2. The impact of sloped ceiling on DF & Internally reflected daylight component (IRC)

6.2.2. Conclusion

- Stage I verified the importance of clerestory in conducting light deeply in the room as well as creating a more even distribution of light which is more appropriate for a learning environment.
- It is concluded in stage II that the tall height of Hojra improves daylighting performance of the room in terms of quantity as well as quality (uniform distribution of light in the room).
- Stage III highlights the significance of the portico as a shading device (a combination of horizontal and vertical shading surfaces) not only in terms of sun protection but also for daylight distribution.
- Stage IV shows that a sloped ceiling lowering toward the façade improves both the average daylight factor and the internal reflected light compared to a flat ceiling or a sloped ceiling lowering toward the back of the room

6.3. Contemporary Primary schools in the warm-dry climate of Iran

The previous section was based on a quantifiable approach in order to study daylighting in a historic study-bedroom, Hojra. This section tries to combine the quantitative and qualitative approaches, as suggested in chapter 4, in order to study daylighting in a contemporary school in the warm-dry climate of Iran. Therefore, it will incorporate a brightness study, which is more of a qualitative approach, with quantitative ECOTECT simulations to evaluate daylighting conditions in one of the classrooms.

Jahan-Ara school, a newly built primary school at the northern part of Shiraz, is claimed to be a successful piece of design by the Iranian education authorities in Fars province. It has been chosen as a case study for two main reasons. Firstly, it is a typical design for building new primary schools in Iran and, secondly, its classrooms do not have appropriate daylighting conditions in terms of task lighting as well as visual amenity (DfEE 1999). The students near windows complain about excessive brightness and the glare whereas students far from the window need electric lighting for reading and writing in a sunny day. A recent study (Laar 2001) addresses the major problem in tropical office buildings as the extremely uneven daylighting distribution close to the façade causes glare and creates spots without sufficient daylighting a couple of meters back from the windows.

6.3.1. A typical modern primary school in Shiraz and its daylighting problems

This section introduces Jahan-Ara school and analyses the daylighting conditions in its classrooms. A classroom in this school is the focus of research in the next section on how to improve daylighting conditions by choosing a suitable daylighting component.

Fig 6.24. South-west facing façade, Photo © F. Ai

Fig 6.25. The main façade and classroom windows, Photo © F. Ai

The building is orientated towards the south-west which is consistent with the a range of south-east to south-west facing facade suggested for this climate as it receives most of the natural light during daytime (Shojaie 2004). This school has 18 classrooms, each accommodating 30 students and has an area of approximately 37m^2 (5.5m x 6.7m). Half of the classrooms face south-west and the rest admit daylight from north-east windows. The building external material is local yellow and red brickwork for the classrooms, and light coloured local rugged stone for the entrance block.

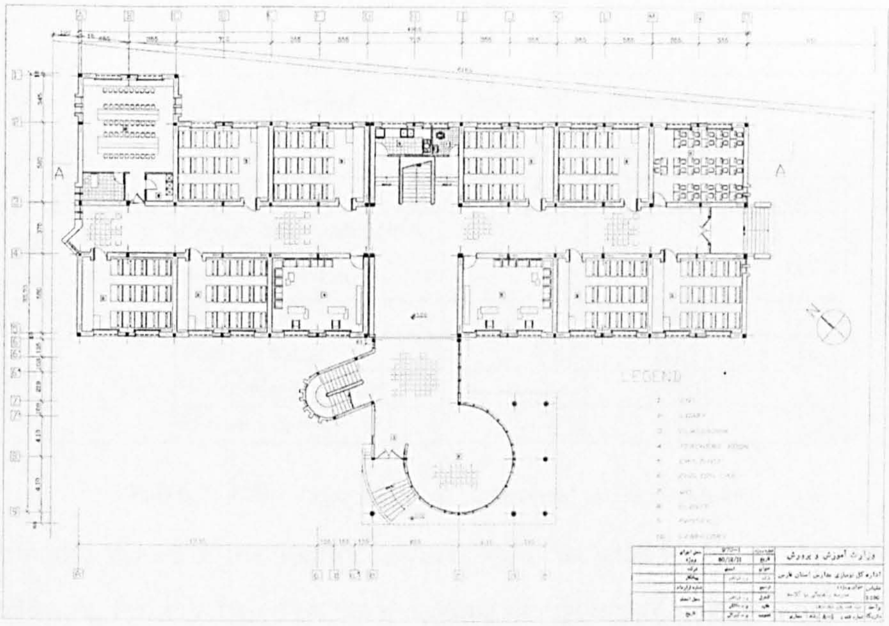


Fig 6.26. Ground floor plan of Jahan-Ara School, courtesy of Iranian Education Department

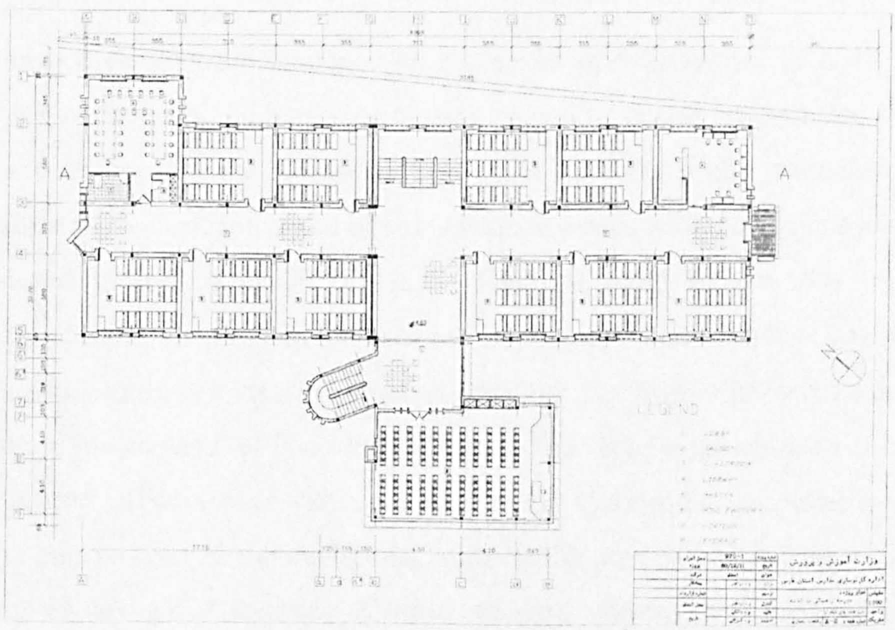


Fig 6.27. Ground floor plan of Jahan-Ara School, courtesy of Iranian Education Department

The following table shows a list of materials used in the classrooms and their reflectance value measured at the school. The method of calculating materials' reflectance value was by using a luminance meter device and a white chalk sample. The chalk sample is a perfect diffuser and its reflectance value is approximately 1.0. For calculating the reflectance value of each surface, the chalk sample was placed next to the surface and then the luminance value of the surface and of the sample was measured by the luminance meter. The reflectance value of the surface is the ratio of the surface luminance value over the sample luminance value as illustrated in Table 6.2.

	Materials	Materials' L(cd/m2)	Sample's L(cd/m2)	Reflectance value
Interior	creamy plaster wall	270	290	0.93
	Glossy stone wall (up to the height of 1m)	171	330	0.52
	blackboard	31	265	0.11
	Floor mosaics	112	245	0.45
	White plaster ceiling	200	200	1.0
	Wooden chairs	65	245	0.26

Tab 6.3. Reflectance values of classrooms interior surfaces

The illuminance values of the interior surfaces are calculated for the daylighting studies via the following formula based on the measured luminance of interior surfaces:

$$E \text{ (illuminance lux)} = L \text{ (luminance cd/m2)} \times \pi \ / \ \rho \text{ (reflectance value)}$$

The luminance values were measured on-site under an overcast sky in April at about midday. Fig 6.28 shows the luminance values in yellow colour on different parts of a vertical surface opposite the blackboard in a south-west facing classroom (left image). These values were, then, converted into illuminance values with the above equation and are presented in red colour in Fig 6.28. The left hand image is a numerical description of lighting pattern in terms of lux (red figures) and cd/m2 (yellow figures). The right hand image is a visual representation of lighting distribution and the brightness using '*posterize command*' of Photoshop software. The visual representation of light as a pattern, instead of numerical values, facilitates the quantitative assessment (Demers 1997). As can be seen in the daylighting distribution pattern image (right) there is a sharp drop of daylight at the back of the classroom, whereas there are high levels of illumination close to the windows.

Fig 6.28. Illuminance values (red) and luminance values (yellow) in a south-west facing classroom (left) and the uneven lighting distribution pattern (right)

6.3.2. The analysis of the lighting pattern

According to Arnheim (1974) brightness is a better way of describing the lighting condition in a room in comparison to illuminance values. Brightness is perhaps the simplest of the visual sensations (Gregory 1972). The term brightness usually refers to the strength of sensation resulting from viewing surfaces of spaces from which light comes to the eye (IES 1984). In fact, the brightness obtained by a given intensity depends on the state of the adaptation of the eye and on various complicated conditions determining the contrast of objects or patches of light (Hopkinson 1970).

The sensation of brightness cannot be measured in the same way as other physical quantities are measured (Moon 1961). However, recent research (Demers 1997) suggests a method of representing brightness with digital images of the illuminated room and the use of a computer imaging software like Photoshop. In her research, posterization is used to generate lighting patterns obtained from a classification of pixels into groups of pixel values defined within certain boundaries (Demers 1997). With such a method, five zones of lighting zones are suggested where white represents 100% brightness, three grey zones representing 75%, 50% and 25% brightness respectively and finally the black zone represents 0% brightness.

Analysis

The lighting condition in one classroom facing south-west and an opposite classroom facing north-east were studied on-site under two different sky conditions: overcast and clear sky. A digital photo was taken from each classroom and the images have been converted to the five zone lighting pattern by using the posterization command in Photoshop in order to study the distribution of daylight in the classrooms.

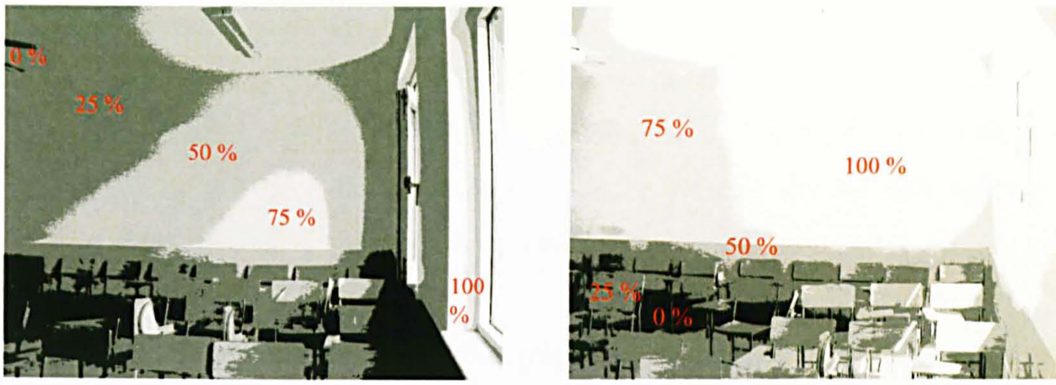


Fig 6.29. Five zone lighting pattern of south-west classrooms under overcast sky (left) and clear sky (right)

As can be seen in the left hand photo of Fig 6.29, under overcast sky condition there is a small patch of high brightness surface close to the window, and it then drops quickly into darker zones. In other words, daylight is not well distributed across the classroom. This problem still exists under clear sky condition (right hand image) where there is a great amount of the surface covered with high brightness which is a potential cause of discomfort glare on the chairs next to the window. However, in terms of lighting levels, according to on-site photometry in Fig 6.28 there is high level of illumination in the south-west facing classroom. On the other hand, the level of illumination drops considerably in the north-east classrooms (Fig 6.30).

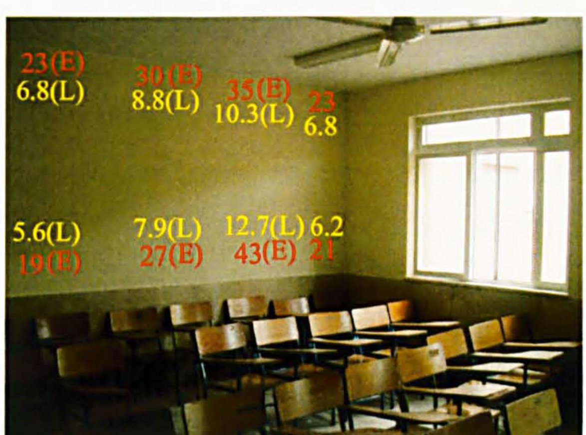


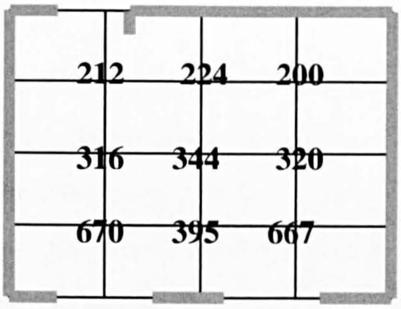
Fig 6.30. Illuminance values (red) and luminance values (yellow) in a north-east facing classroom

The procedure was the same as Fig 6.28, the luminance values of different parts of the vertical wall opposite the blackboard were measured by the luminance meter which are presented in yellow colour in Fig 6.30. These values were, then, converted into illuminance values with the $E=L\pi/\rho$ equation and are presented in red colour in Fig 6.30. Under overcast sky condition the illuminance level in the north-east classrooms is about one quarter that of the opposite classrooms in Fig 6.28. The north facing classrooms do not have sufficient daylight under overcast sky for task lighting and electric lights are used to supplement the low daylight.

However, as can be seen in the lighting pattern zones analysis (right hand image of Fig 6.31) daylight is more evenly distributed in these classrooms under clear sky conditions. The reason is that under these conditions it is the diffused and reflected daylighting which is the main source of north-facing room illumination and it is most under the clear sky.

Fig 6.31. Five-zone lighting pattern of north-east classrooms under overcast sky(left) & clear sky(right)

The above luminance measurements (Fig 6.28 & 6.30) were made on-site on a vertical surface in order to study the distribution of daylight across the classroom. However, in order to evaluate the amount of natural illumination in the classroom, it was necessary to find out the illuminance values on the horizontal working plane. The following diagrams (Fig 6.32 & 6.33) show the amount of illumination in terms of lux at nine points in a south-west and a north-east facing classroom under clear sky conditions. The values were measured on-site by a luminance meter on the working plane and were converted into illuminance values by using the $E=L\pi/\rho$ equation. As was discussed in the chapter 3, for the daylight illuminance to be adequate in a classroom, it is necessary to achieve a level of not less than 300 lux and up to 500 lux (DfES 2003). Figure 6.32 shows there are high levels of natural light on the horizontal plane close to the windows; whereas, the level of illumination at the back of the room is below the standard. In addition, the amount of illumination on the first row close to the window is nearly three times more than the third measured row at the back of classroom. This clearly indicates an uneven distribution of light in the classroom which is not appropriate in a reading and learning environment (ibid).



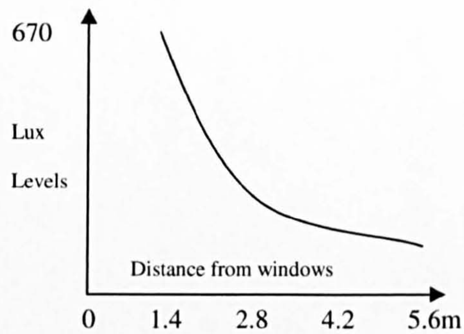
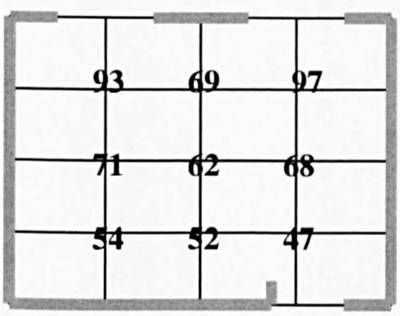


Fig 6.32. Plan a south-west classroom and illuminance values at nine horizontal working plane points under a clear sky (left), Diagram of lux levels in different depths of classroom (right)

On the other hand, in the north-east facing classroom (fig 6.33) the difference between illumination values closer to the windows and far from them is much less than in the opposite classrooms. This shows a fairly even distribution of light in the classroom which is more appropriate for a learning environment (DfEE 1999). However, the levels of illumination are far lower than standard indicating a need for electric lighting even on a bright sunny day.None of the classrooms in this school thus provide an appropriate daylighting condition for the students.



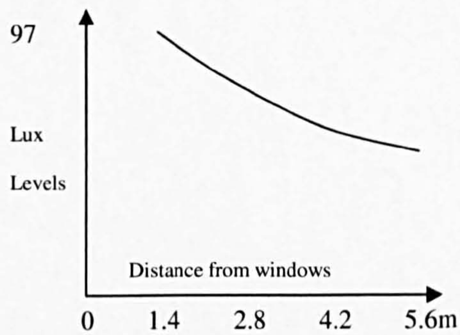


Fig 6.33. Plan a south-east classroom and illuminance values at nine horizontal working plane points under a clear sky (left), Diagram of lux levels in different depths of classroom (right)

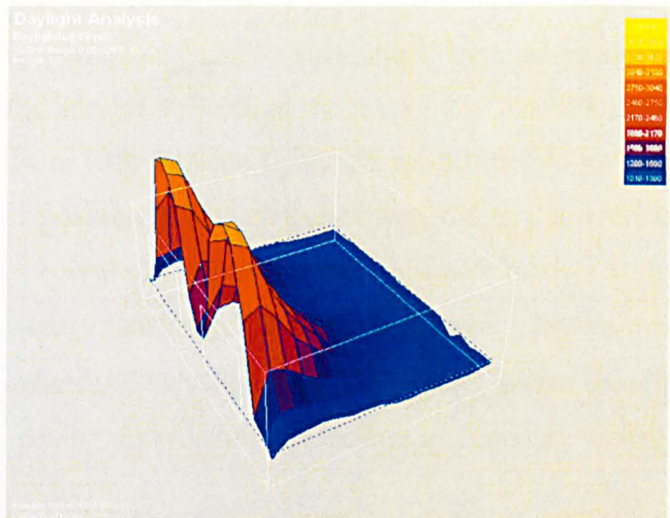
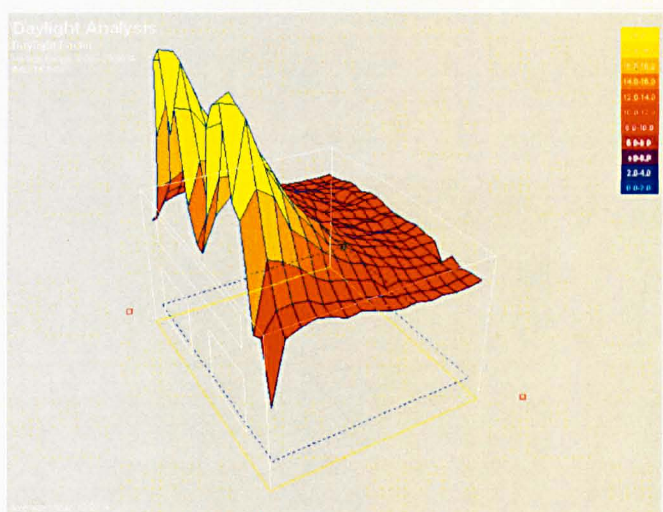
The main problems observed in the classrooms under sunny sky conditions are penetration of direct sunlight into working area of south-facing classrooms as well as direct view to clear sky which causes discomfort glare.

6.3.3. Daylight Analysis of a classroom in Jahan-Ara school by ECOTECT

This section investigates what would happen if a few alterations were made to the façade of the classroom, and studies the daylighting implications in the classrooms using ECOTECT simulations. The models are simulated on 25th of April at midday time when the photometry was done in the actual place.

The first alteration is to the height of classroom. As can be seen in Tab 6.4 the height of the classroom is increased from actual 2.7m to 4m. With the location and size of windows unchanged, the change of height causes a drop of 10% in the average daylight factor from 9.23% to 8.40%. In addition, the internally reflected (IRC) average also reduces by about 20% from 4.47% to 3.64%. It can be concluded at this stage that an increase in the height of a classroom without any change in its window area or window location could lower the daylighting performance of the room. This is because there is less reflected light from the ceiling which is further away from the windows.

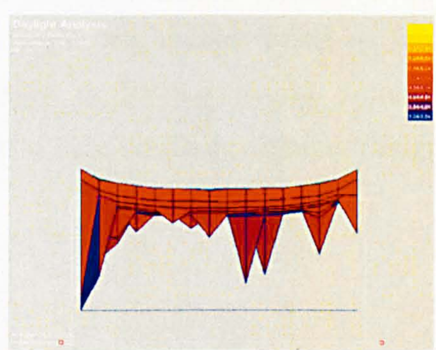
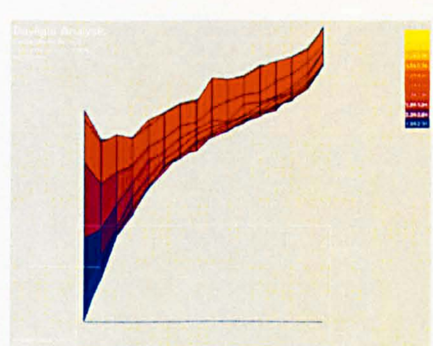
However, adding a clerestory to the new model increases both of the daylighting measures; the daylighting factor (DF) is increased over 30 % and internally reflected (IRC) average by about 40%. Nevertheless, direct sunlight can still penetrate these three first models at some hours of day, due to the lack of any shading devices, which is unacceptable in a learning environment

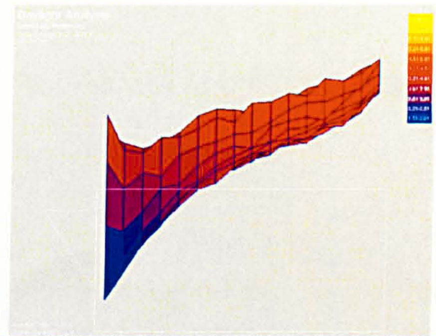
	Daylight Factor (DF) Average Value %	Internally Reflected (IRC) Average Value %	ECOTECT Simulation
Model 1 **Basic model** **L=6.7m** **W= 5.5m** **H= 2.7**	**9.23**	**4.47**	
Model 2 **H=4m**	**8.40**	**3.64**	
Model 3 **H= 4m** **+** **Clerestory** **With h=0.8**	**12.34**	**6.24**	

Tab 6.4. The impact of increasing classroom height (H=4m) & adding a clerestory (h=80cm) in the taller classroom on DF & Internally reflected daylight component (IRC)

Therefore, in the next stage the first attempt is to prevent direct sunlight and to increase the reflected daylight deep inside the room using shading devices and lightshelves. Model 4 represents lightshelves on the windows; the specifications are included in the Table 6.5. It is reasonable to expect the amount of DF and IRC averages reducing about 22% compared to the base model as there is no area of direct sunlight in the room at this stage. However, the internally reflected component diagrams in Tab 6.5 indicate the significance of the lightshelves in conducting reflected light to the back of the classroom.

The last simulation, model 5, is well protected and surrounded by shading devices, which keeps direct sunlight off the interior throughout the school day. The DF average increases slightly by about 7% from 7.06% in the lightshelf model (no. 4) to 7.58%, which could be due to the lower position of lightshelves compared to the overhang. Although the average DF has decreased slightly in the lightshelf model, a slight increase of 2.5% is seen in the average IRC from 3.20% in model 5 to 3.28% in model 4. This finding verifies the performance of lightshelves in illuminating deeper areas of a room by reflecting light on the ceiling and making the ceiling a secondary source of illumination.

	Daylight Factor (DF) Average Value %	Internally Reflected Average Value %	ECOTECT Simulation
Model 1 Basic model L=6.7m W= 5.5m H= 2.7	**9.23**	**4.47**	
Model 4 Lightshelf for each window 0.5m inside 1m outside 0.5m from window top	**7.06**	**3.28**	

Model 5 **Surrounded shading device** **Overhang & triangular fins**	**7.58**	**3.20**	

Tab 6.5. The impact of increasing classroom height (H=4m) & adding a clerestory (h=80cm) in the taller classroom on DF & Internally reflected daylight component (IRC)

6.3.4. Conclusion

The above studies show that it is possible to improve daylighting conditions of classrooms in even quite compromised situations such as Jahan-Ara School. The shading device and redirecting system alterations to the base model classroom in the above studies were not comprehensive and only covered overhangs with fins and lightshelves. It was beyond the scope of this research to test all shading and light redirecting devices on the base model.

However, the next chapter tries to investigate daylighting solutions in schools more comprehensively through a study of different case studies based on the findings of previous chapters. Chapter 7 aims to draw daylighting lessons from a number of contemporary exemplar schools in order to help create daylighting design guidelines in the concluding chapter 8.

CHAPTER 7: EXEMPLARY SCHOOLS AND DAYLIGHTING LESSONS

7.1. Introduction

On the basis of the analyses and findings from previous chapters, a set of components can be identified in order to use in the design of classroom lighting. These components can be divided into four main groups:

Group 1: Deep penetration and even distribution of daylight (from chapter 3, 5 & 6)
Group 2: Daylight redirecting systems, also acting as shading devices (chapter 4 & 5)
Group 3: Shading devices(chapter 2 & 4)
Group 4: General features affecting daylighting (chapter 2, 5 & 6)

The first three groups are design features with direct impact on daylighting of classrooms and schools; while the fourth group is design features which have indirect influence on daylighting and, more specifically, reflected daylighting of classrooms. The first three groups can also be grouped as specific features against the general factors influencing reflected daylighting as was suggested in Chapter 5. The first group includes design features which contribute to deep penetration and even distribution of daylight in classrooms such as Rooflights or borrowed lighting. The second group functions as systems of daylight redirection, some of which could also be considered as shading devices, such as lightshelves or louvres. The third group includes shading devices which obstruct or filter sunlight and daylight in different ways. Finally, in the last group are a few design features such as courtyard configuration or the height of classroom ceilings which have an indirect impact on daylighting performance of the building.

This chapter aims to gather empirical evidence and investigate how often the above features are used in reality, and then to draw conclusions from them. This chapter, therefore, examines 100 exemplar school designs across the world and is focused on their daylighting solutions. These exemplar schools have been chosen out of over 300 exemplar schools on the basis that most of them are representatives of the new education paradigm discussed in chapter 3, addressing the new spatial requirements in school. Exemplar design and its development is one way to help create schools for the future, as it brings about concepts and ideas thatcan be used as the starting point for creating high quality school buildings (DfES 2003, p.4). There are patterns and themes emerging from exemplar designs which can be used for building schools for the future: *inspirational & innovative spaces, engaging children, inclusive community, learning clusters, indoor courtyards, flexibility & adaptability, sustainability*, etc. (ibid, p0. 8-21). However, it is the daylighting solutions of these exemplar designs which are the focus of this chapter.

The exemplars are classified on the basis of their student age group as well as their climate. In terms of the age group, they are classified under five groups: secondary or high school, middle or junior school, primary or elementary school, early childhood learning environment (ECLE) or infant school, and finally alternative learning environment (ALE) or academy schools. ECLE and ALE are the new terms used to comply with the new education paradigm as schools are preferably referred to as Community Learning Centre (CLC), classrooms as Small Learning Community (SLC) and corridors as Learning Streets (Nair and Fielding 2005).

Table 7.1 shows both the age group and climatic classification. Over half of the case study exemplars (51%) are primary or elementary schools which are more relevant to thesis research question. However, there are definitely lessons to be learnt from other age group schools, as they are all learning environments and some of the tasks are similar. Nonetheless, there is more spatial flexibility in primary schools and also daylighting and connection to outdoors is more vital for students' development (DfES 2002). Infant schools have obviously less features in common with other schools, in terms of their limited learning task based spaces, and therefore, the number of exemplars is limited (8%).

Another significant factor distinguishing the exemplars is the climate and the amount of sun available. These 100 school exemplars are not comprehensive and have been chosen from a number of leading references in this area of knowledge (DFE 1994; DfES 2002; DfES 2002; Curtis 2003; DfES 2003; Nair and Fielding 2005; DfES 2006; DfES 2006; Nair and Fielding 2007). They vary from hot tropical to cold and humid, from places with abundant and excessive sunlight to less sunny and overcast climates. Table 7.1 shows that the exemplars are from 10 countries across the world: UK, USA, Mexico, Canada, Israel, India, New Zealand, Australia, Japan and Germany. The climate of the school places in the above countries has been identified by Koppen classification system and can be roughly classified into 7 groups as shown in Table 7.1 (Microsoft-Encarta 2003).

Fig 7.1 illustrates the climatic similarities of different parts of the world. Although there is a significant lack of evidence and research on exemplar schools in warm-dry climates, there is a considerable number of exemplar schools in the western United States (California & Texas), Israel and Australia which begin to fill the gap.

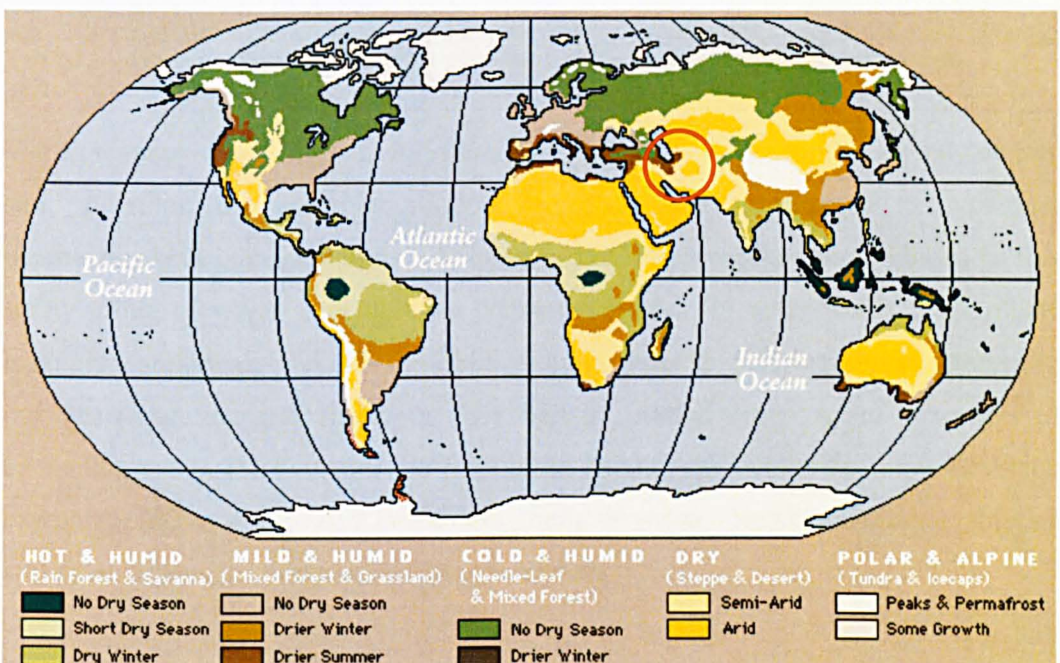


Fig 7.1. World Biomes (Terrestrial Plant Formation) and climatic differences (Microsoft-Encarta 2003)

The focus of this thesis is the warm-dry climate of Iran and, therefore, an indicator or index of '*sunny-ness*' is considered bydividing the 7 climatic groups into 3 broad categories. This is illustrated in Table 7.1. The first colour zone (yellow) groups the mild/dry and sunny climates, while the third colour zone (green) groups mainly overcast cool/cold and humid climates. The middle zone (beige) represents the temperate/hot and humid zone in which natural ventilation plays a significant role in the environmental design of the building.

Sec. High	Mid. Jun.	Pri. Ele.	ECLE Infant	ALE Aca.	CLIMATE	UK	US A	M X.	CA	IS R.	IN D.	NZ	AU S.	JA P.	G R.	Tota l
1	-	3	-	-	Hot & Dry	-	3	-	-	-	1	-	-	-	-	4
2	3	12	1	5	Mediterranean	-	17	-	-	5	-	-	-	-	-	23
-	-	1	-	-	Temperate	-	-	-	-	-	-	-	1	-	-	1
1	-	-	-	-	Temp. & Dry	-	-	1	-	-	-	-	-	-	-	1
-	1	2	1	-	Temp.&Humid	-	4	-	-	-	-	-	-	-	-	4
2	-	2	1	2	Tropical/subT.	-	1	-	-	-	4	-	2	-	-	7
15	2	26	4	2	Mild & Humid	45	1	-	-	-	-	1	-	1	-	49
3	2	5	1	-	Cold & Humid	2	7	-	1	-	-	-	-	1	1	11
24	8	51	8	9	T O T A L	47	33	1	1	5	5	1	3	2	1	100

Tab 7.1. A summary of selected exemplar schools across the world classified by their climate

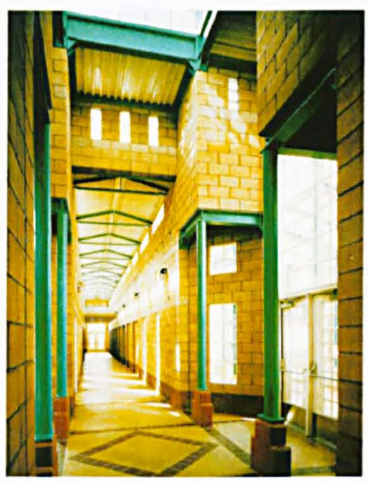
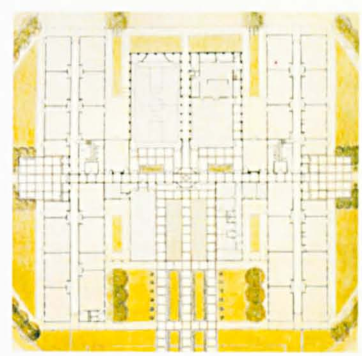
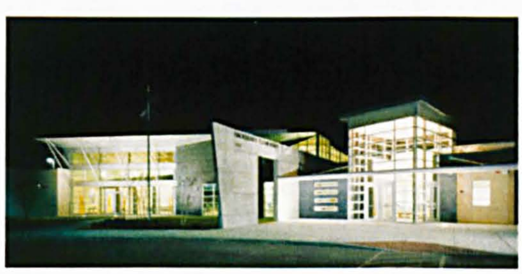
The first sunny climatic group has skies as bright as in the warm-dry climate of Iran and, therefore, the exemplar schools are more relevant due to the common overheating and glare problems. About one third of exemplars are included in this sunny group of which over half are primary schools. In other words, 18% of the exemplars are primary schools in mild/dry sunny climates, which are most relevant to the thesis question and, therefore, they will be studied first. A small number of exemplars are in the temperate to hot humid zone (11%) while the majority of the exemplars (60%) are located in the less sunny climates. However, these exemplars still have lessons for design in the Iranian climate.

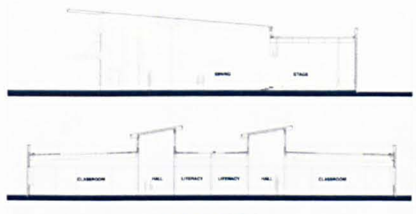
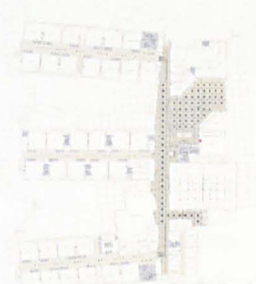
It can also be argued that the term 'climate' is not the only defining feature of daylighting design in schools, as the key aspects of daylighting design are not completely determined by aspects normally associated with climate such as heat or humidity. The defining factors for daylighting design in schools, as discussed in chapter 3, are avoiding discomfort glare, control of brightness, minimum illumination levels, and evenness of the distribution of daylight across the room. These factors are basically common to any climate. However, daylighting lessons and generic principles from other climatic zones will need adaptation on the basis of climatic priorities. For instance, issues of overheating are less pressing in cooler climates than they are in the warm-dry climate of Iran.

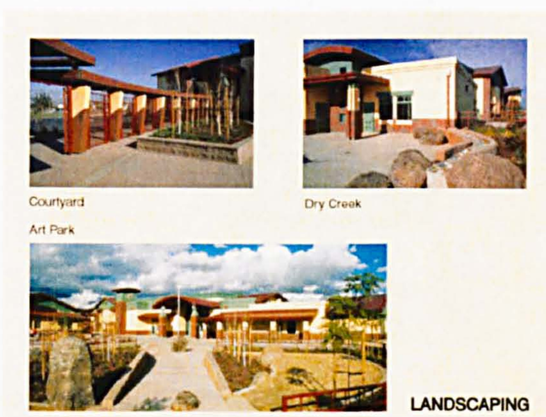
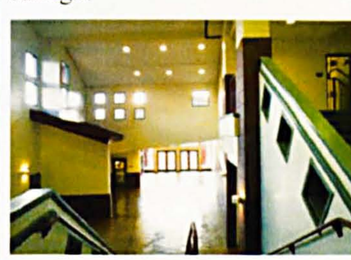
The following Tables in sections 7.2, 7.3 and 7.4 highlight daylighting lessons drawn from these award-winning case studies and exemplars in different climates based on the aforementioned four groups of components. These daylighting lessons have been extracted from Designshare exemplars and other case studies. The lessons will be categorized based on the four groups and the exemplars different climate. They will also be analysed and discussed thoroughly after presenting the exemplars in order to draw conclusions from them. Although most of the selected case studies could be considered as exemplars because of the standard and quality of design, some of them have some drawbacks in terms of the school daylighting, which are identified and mentioned in the lessons with the '—' symbol. All positive lessons are marked with the '+' symbol.

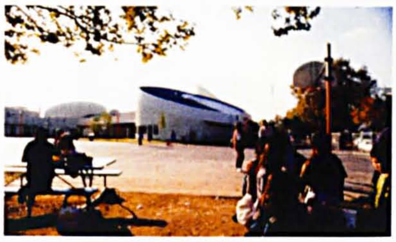
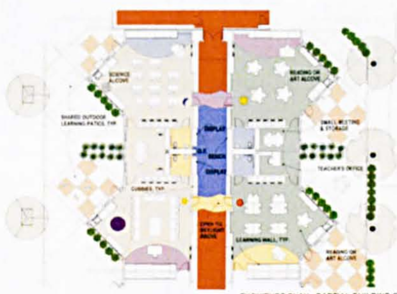
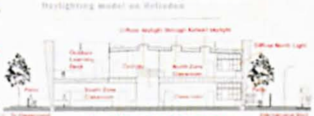
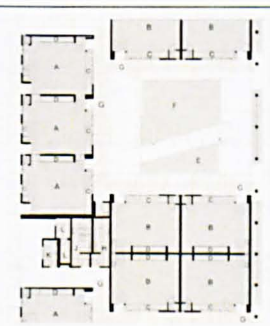
7.2. Exemplary Contemporary schools and daylighting in sunny climates

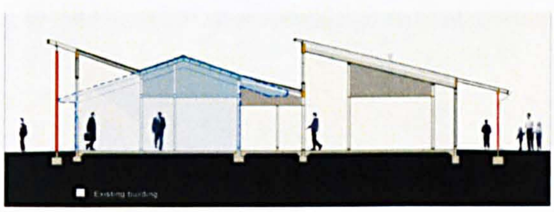
The following tables (Tab 7.2 to Tab 7.6) summarises 29 exemplar school designs in the mild/dry sunny climates. Almost half of the images in this chapter (Tab 7.2 to 7.16) are downloaded from http://designshare.com, and the rest (52%) come from other sources. Designshare is a global community of educational professionals, and provides an invaluable service as a facilitator of ideas and resources about best practices and innovations in schools from early childhood to university level (Nair and Fielding 2007). It includes over 400 award-winning case studies in over 30 countries.

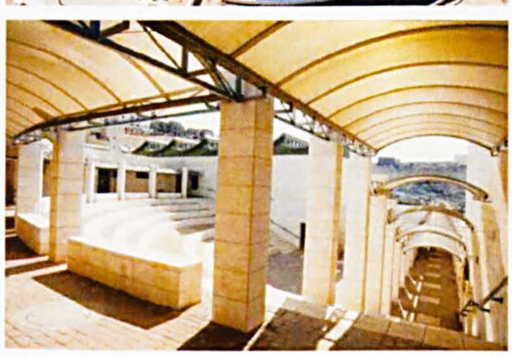
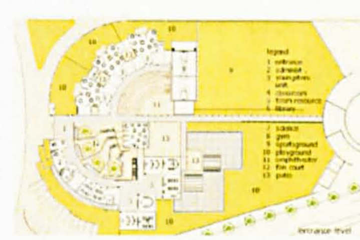
E01	**Desert View Elementary School, New Mexico(H & D)**	**Daylighting lessons**
Exemplar 01	 	+ Courtyard configuration + High windows (clerestories) to admit daylight deeper in the space + Walkways shaded by translucent fibreglass roofs & canvas awnings (budget-conscious project) + Use of glass bricks for tiny clerestories to reduce glare + Restricted fenestration to avoid overheating & thermal reasons – Lack of any sunlight redirecting system for classroom windows (Curtis 2003, pp.148-155) 
E02	**Hackberry Elementary School, Texas (Hot & Dry)**	**Daylighting lessons**
Exemplar 02		+ Incorporating daylighting in all learning spaces + Daylighting corridors and circulation via clerestories and translucent panels + Deep overhang on the south side + Skylights in classrooms create an even distribution of daylight

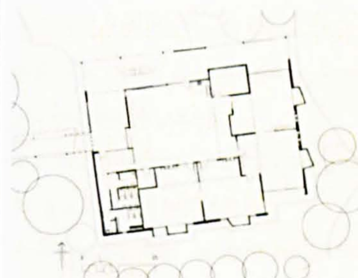
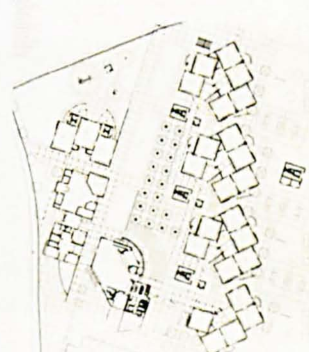
Exemplar 02	 Biulding Sections	– Too much glazing, potential overheating – Lack of shading or redirecting devices on classroom windows
E03	**Roy Lee Walker Elementary, Texas (Hot & Dry)**	**Daylighting lessons**
Exemplar 03	 	+ Skylights with baffles in the classrooms to create an even distribution of light + U courtyard configuration 
E04	**The Riverside School, India (Hot & semi-arid)**	**Daylighting lessons**
Exemplar 04	 	+ Courtyard configuration + Foliage of the trees filtering strong sunlight & provides shade + Canvas canopies providing shade –Lack of shading devices or redirecting systems, hence, glare discomfort in classrooms 
E05	**Almond Elementary School, California (Med. /Temp.)**	**Daylighting lessons**

E x e m p l a r 0 5	 	+ Daylight as the primary lighting source in classrooms & library + pop-up roof monitors or north-facing clerestories to maximize daylight + daylight compensation sensors for sustainability reasons 
E06	**Ernesto Galarza Elementary, California (Med/Temp.)**	**Daylighting lessons**
E x e m p l a r 0 6	 	+ Courtyard configuration + Tree canopies to provide shade + Skylights in the common areas + Overhangs as shading devices + Massive building with low fenestration + Small openings due to harsh sunlight 
E07	**Webster Elementary School, California (Med/Temp)**	**Daylighting lessons**

Exemplar 07	  	+ Skylights as the main source of daylighting to keep children in touch with time of day and changes in weather while avoiding distractions from outside activities + Curved ceilings reflect daylight as well as light from fixtures without glare or shadows + Massive building with minimum fenestrations due to harsh sunlight
E08	**Cesar E. Chavez Education Centre, California**	**Daylighting lessons**
Exemplar 08	   	+ Maximizing natural daylight by using controlled south glazing with lightshelves + Diffuse north facing glazing + Kalwall skylights illuminate second and even first floor corridors + Non-traditional shape of the classrooms responding to true south and north orientation of glazing 
E09	**Newport Coast Elementary, California (Med/Temp)**	**Daylighting lessons**
Exemplar 09	 	+ Courtyard configuration + Deep eaves as shading device + Shaded walkways & colonnades 
E10	**Claire Lilienthal Elementary School, California**	**Daylighting lessons**

Exemplar 10	 	+ Courtyard configuration + Walkways pulled away from buildings to allow light into classrooms on both floors + Deep eaves & walkways as shading device + Lightshelves reflect daylight deep into classroom and improve the uniformity of light 
E11	**Santa Rita School, California (Med/Temp)**	**Daylighting lessons**
Exemplar 11	 	+ Each classroom has large clerestories as a source of diffuse light & they are placed immediately adjacent to the ceiling to maximize reflected daylight + Automatic light sensors to use electric light only as supplement + Deep eaves as shading device 
E12	**Reim Elementary School, Israel (Mediterranean)**	**Daylighting lessons**
Exemplar 12	 	+ Compact configuration with controlled openings + Small courtyard configuration – Only blinds as shading device

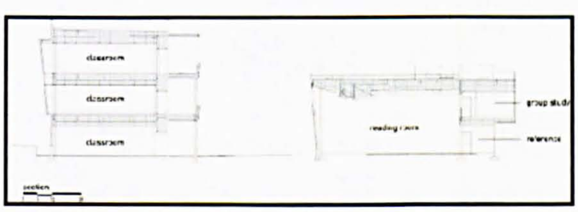
E13	**Hachoresh Elementary School, Israel (Med.)**	**Daylighting lessons**
Exemplar 13		+ Courtyard configuration + Controlled & small openings + Passage as shading device  – Lack of redirecting system 
E14	**Modiin Science School, Israel (Med.)**	**Daylighting lessons**
Exemplar 14	 	+ Courtyard configuration + Controlled fenestration + Covered passages + North facing windows for part of classrooms, hence, no shading device needed – Deep reveals & blinds as shading device for other classrooms – Lack of any redirecting system 
E15	**Galilee Catholic Learning Community, Australia (Temperate)**	**Daylighting lessons**

Exemplar 15	   	+ A range of windows of different heights, size, orientation and coloured glazing create a multi layered light filled environment + Clerestory windows, large floor to ceiling windows, sliding glass doors and a range of feature windows create a home-like place + Small feature eastern windows for students objects displays in changing eastern sunlight (two opposite lower photos) + Bay window as a small learning space stage + Courtyard configuration 
E16	**Rio Del Notre Elementary, California (Med/Temp)**	**Daylighting lessons**
Exemplar 16	 + Pyramid skylights with operable windows illuminate the classrooms with high ceiling + Limited glazing due to climate with interior blinds – Reflected daylighting opportunity is therefore missed (Curtis 2003, pp. 88-95)	+ Open courtyard configuration + Shaded colonnade walkways – Lack of any redirecting system – Lack of exterior shading devices 

Tab 7.2. Primary/Elementary school exemplars & Daylighting lessons in mild/dry sunny climates

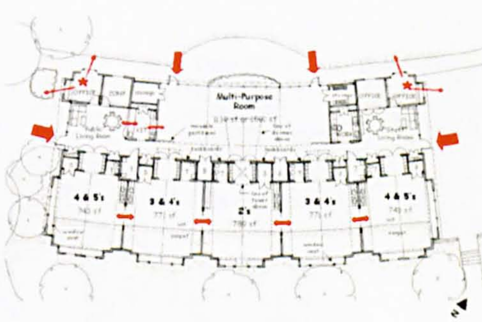
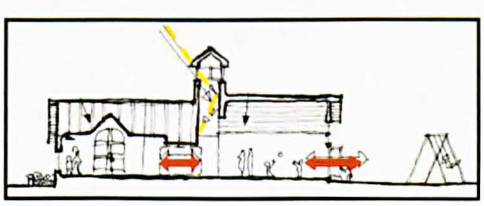
E17	Northwest Middle School, Utah (Med/Temperate)	Daylighting lessons
Exemplar 17	 	+ External lightshelves function as shading device as well as reflect sunlight deep into classrooms & improve lighting uniformity + Controlled openings due to climatic reasons – electric light might not be needed in a sunny day as in the opposite phone, hence, the lack of automatic light sensor for sustainability reasons
E18	**Silverado Middle School, California (Med/Temp)**	**Daylighting lessons**
Exemplar 18		+ Saw-tooth skylights providing 100% of the required lighting levels via diffused lighting + Naturally daylit circulation spine by a glass and metal roof + The advantage of light and colour for wayfinding
E19	**High Tech Middle School, California (Med/Temp)**	**Daylighting lessons**
Exemplar 19		+ Courtyard configuration + Shaded outside walkways – Lack of external shading or daylight redirecting systems 

Tab 7.3. Middle/Junior school exemplars & Daylighting lessons in mild/dry sunny clmates

E20	Little Elm High School, Texas (Hot & Dry)	Daylighting lessons
Exemplar 20	 	+ High ceilings and windows increases natural reflected light + Clerestory windows floods the main corridor with natural light – Lack of natural light redirecting systems in classroom openings
E21	**Vanden High School, California (Med/Temp)**	**Daylighting lessons**
Exemplar 21	 	+ Shaded Clerestories and sloped ceiling in classrooms improve reflected daylighting + Wide courtyard configuration + outdoors shaded walkways + Shaded outdoor learning area 
E22	**La Caçada High School, California (Med/Temp)**	**Daylighting lessons**
Exemplar 22	  	+ Full height north facing glazing brings glare free light in classrooms + Open courtyard configuration + North facing curving glazing brings in soft daylight into library + Walkways on the south as exterior shading device + Light supplement from south walkways to illuminate dark ends
E23	**Universidad de Monterrey: Preparatoria Unidad Valle Alto, Mexico (Temperate & Dry)**	**Daylighting lessons**

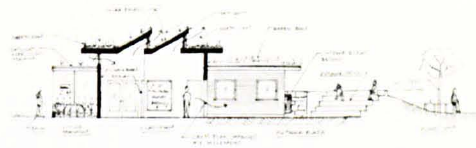
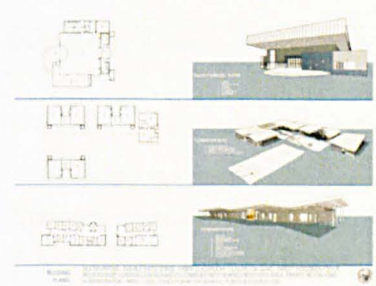
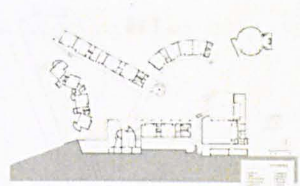
Exemplar 23	  	+ Exterior Brise-soleil shades the south walkway & classroom glazing + Classrooms have north and south faced glazing with proper shading + Large windows bring in abundant north diffuse light into library & classrooms + Small courtyards let natural light illuminate deep parts of the plan + Foliage of trees also cast shade on the south façade of classroom block 

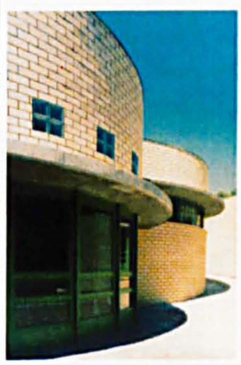
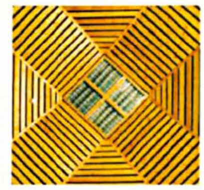
Tab 7.4. Secondary/High school exemplars & Daylighting lessons in mild/dry sunny climates

E24	Concord Children's Centre, Massachusetts (Med/T)	Daylighting lessons
Exemplar 24	 	+ A raised glass-panelled cupola floods the interior core with daylight + Bay window seat for kids + Transparent & daylit classrooms 

Tab 7.5. ECLE/Infant school exemplars & Daylighting lessons in mild/dry sunny climates

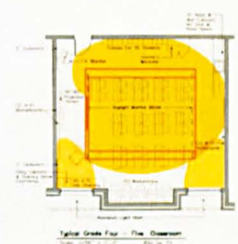
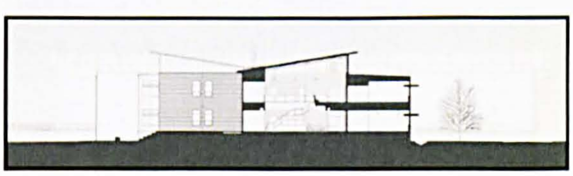
E25	The Living Classroom, California (Med/Temp)	Daylighting lessons

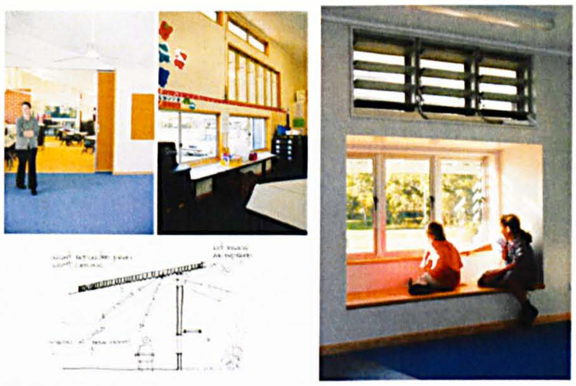
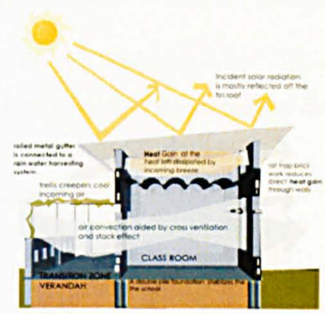
Exemplar 25	 	┼ North facing roof monitors to bring in even diffuse daylight ┼ Shaded high windows contribute to reflected daylighting ┼ A dozen skylight for daylighting & natural heating in winter 
E26	**Father River Academy, California (Med/Temp)**	**Daylighting lessons**
Exemplar 26		┼ Open courtyard configuration ┼ Cantilevered roof tops as shading device and shaded walkways ┼ Large windows to the north to admit abundant diffuse daylight ┼ High windows to conduct natural light into deeper parts of the plan ┼ Small windows & low fenestration – High ceiling but dark ceiling and lack of any daylight redirecting system forces electric lighting 
E27	**Chabad Hebrew Academy, California (Med/Temp)**	**Daylighting lessons**
Exemplar 27	 	┼ South facing roof monitor equipped with baffles along with north facing windows admit abundant diffuse light in classrooms ┼ Various shape courtyards ┼ Outdoor shaded walkways & South walkways as shading devices

E28	Broshim School, Israel (Mediterranean)	Daylighting lessons
Exemplar 28	   	+ Courtyard configuration + Minimum Fenestration + Overhangs/fins as shading devices + Indirect daylight via cubic cupolas  +Deep window reveals as shading device in the patio (opposite photo) + Geometric sunscreen on some windows to reduce discomfort glare + Circular skylight with brick glass roof and side walls floods the entrance lobby with diffuse light  – No daylight redirecting system
E29	**Lev Hasharon School, Israel (Mediterranean)**	**Daylighting lessons**
Exemplar 29	 	+ A ribbon of high windows (clerestories) in classrooms to illuminate while avoiding glare + Deep eaves of sloped roof as clerestories shading device + Open courtyard configuration + Overhangs/fins frames windows as shading devices

Tab 7.6. ALE/Academy school exemplars & Daylighting lessons in mild/dry sunny climates

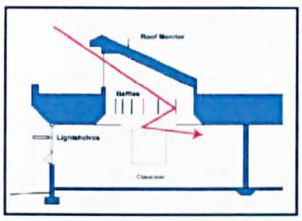
7.3. Exemplary Contemporary schools and daylighting in temperate/hot & humid (tropical) climates

E30	**Millbrook Elementary, North Carolina (Temperate & Humid)**	**Daylighting lessons**
Exemplar 30	  	+ North & south facing roof monitors equipped with translucent fabric baffles which eliminates glare & distributes daylight evenly + Aluminium lightshelves on south facing windows reflecting light deeper in the room which shading the lower view window + Automatic light sensors + Mid-pane blinds to control glare + TV monitors, computer workstations & teaching walls are located in darker walls of classrooms 
E31	**Poquoson Elementary, Virginia (Temp & Humid)**	**Daylighting lessons**
Exemplar 31	 	+ South facing façade to maximise daylighting potentials + Classrooms with north or south facing ribbon view windows + Lightshelves on south windows + Clerestories bring light into larger spaces like gathering hall + Daylight sensors to save energy + Limited openings on East and West facing windows
E32	**St Stephen's School, Queensland (Sub-tropical)**	**Daylighting lessons**

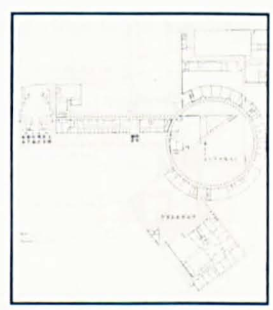
Exemplar 32		+ low-level shaded windows + Deep window reveals reduces contrast and glare in the classroom + Clerestories equipped with moveable louvres to direct daylight + High windows under the ceiling improved reflected daylighting + Sloped ceiling of classroom improves reflected daylighting
E33	**Eureka Elementary School, AID India (Tropical)**	**Daylighting lessons**
Exemplar 33		+ Bilateral daylit classrooms which improves natural ventilation + Vegetative cover veranda as solar shading of the south façade + High windows to help daylighting as well as natural ventilation 

Tab 7.7. Primary/Elementary school exemplars & Daylighting lessons in temp/hot & humid climates

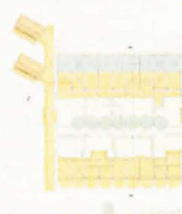
E34	**Heritage Middle School, North Carolina (Temperate & /Humid)**	**Daylighting lessons**
		+ East-west axis orientation + North or south facing roof monitors in each space + Metal overhang over south facing roof monitor's glazing for shading + Spaces translucent fabric baffles eliminate glare and distribute reflected daylight evenly + Curved drop wall under roof

Exemplar 34	  	monitors to control daylighting +TV monitors & projection screen in the darker zones of classrooms +Lightshelves on the south facing windows to shade lower view window and improve reflected light +Mid-pane blinds to control light 

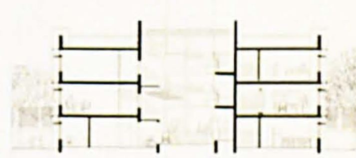
Tab 7.8. Middle/Junior school exemplars & Daylighting lessons in temp/hot & humid climates

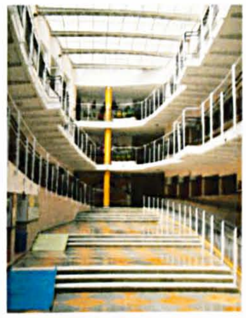
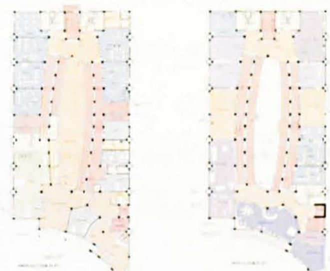
E35	North Fort Myers School, Florida (Tropical)	Daylighting lessons
Exemplar 35	 (Curtis 2003, pp. 156-163)	+Courtyard configuration +Covered walkways or colonnades acting as a shading device for classrooms and a buffer zone 
E36	**Bentley Park College, Queensland (Tropical)**	**Daylighting lessons**
Exemplar 36		+Deep roof overhang for sun protection +Brise-soleil to ensure shading +windows protected from the sun by overhang as well as fide fins

Tab 7.9. Secondary/High school exemplars & Daylighting lessons in temp/hot & humid climates

E37	**Great Beginnings Early Education Centre, Missouri (Temperate & Humid)**	**Daylighting lessons**
Exemplar 37	 	+ Tall clerestory windows in lobby + Controlled fenestration − Insufficient daylight in classrooms because of small windows (opposite) − Lack of exterior solar shade or daylight redirecting systems 
E38	**Druk White Lotus School, India (Sub-tropical)**	**Daylighting lessons**
Exemplar 38	 (Curtis 2003, pp.54 -57)	+ Courtyard configuration + Verandas & deep reveals as shading devices + Deciduous trees as natural solar control close to the building 

Tab 7.10. ELCE/Infant school exemplars & Daylighting lessons in temp/hot & humid climates

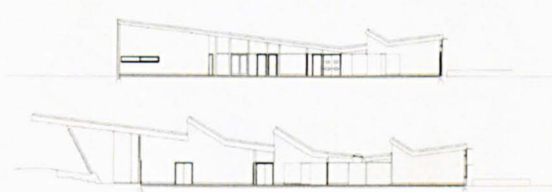
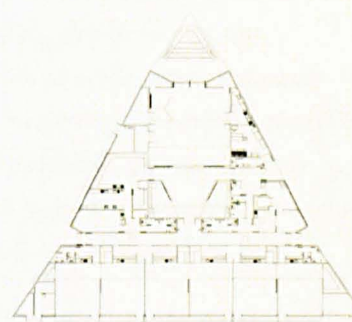
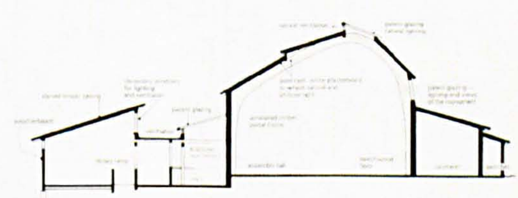
E39	**Disha Foundation School, India (Sub-tropical)**	**Daylighting lessons**
		++ Successful daylighting solutions + Lightshelves on allwindows 

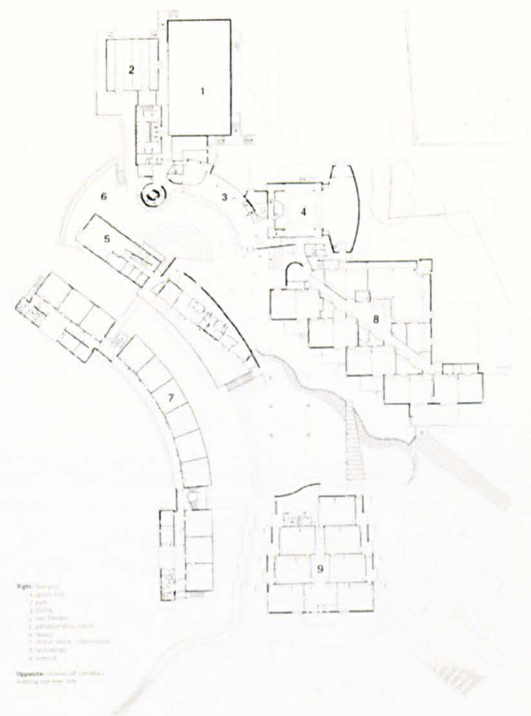
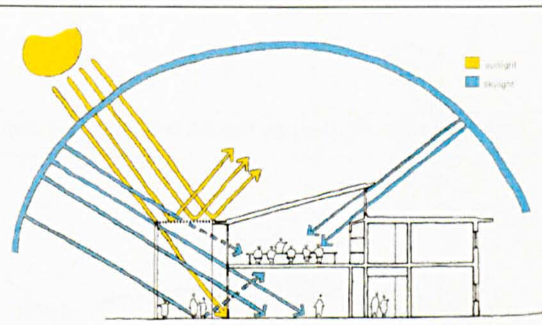
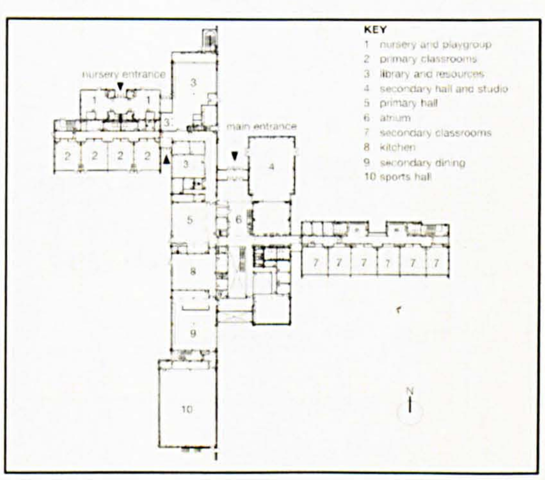
Exemplar 39	   	+ Shaded clerestories + glare-free daylight with even distribution in classrooms + Skylights illuminate the atrium + Shaded pergolas outdoors 
E40	**Mercedes Benz International School, India (Tropical)**	**Daylighting lessons**
Exemplar 40	  	+ Open courtyard configuration + Lightshelves incorporated in the deep window reveals separating view window from clerestory + some windows are shaded by walkways in front of them + Outdoor cafeteria with shaded roof (part of larger open courtyard) + Exterior light colours for thermal reasons also increase reflected light 

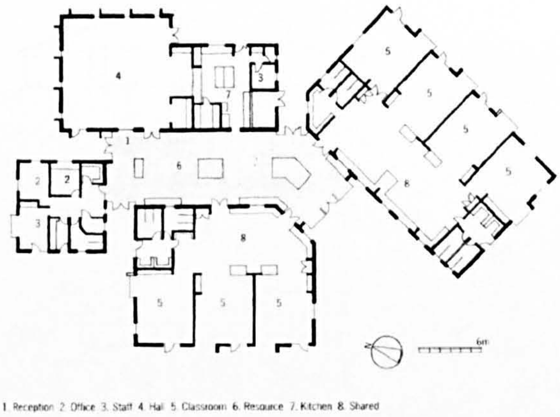
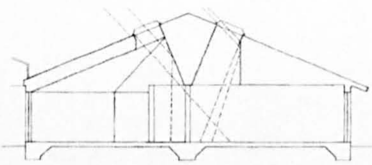
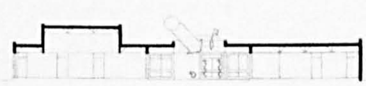
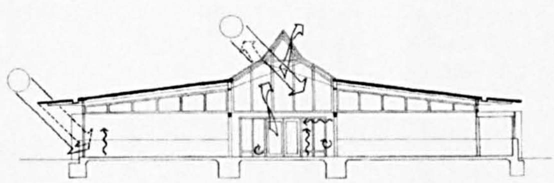
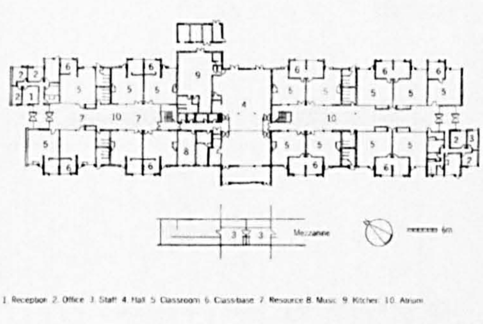
Tab 7.11.ALE/Academy school exemplars & Daylighting lessons in temp/hot & humid climates

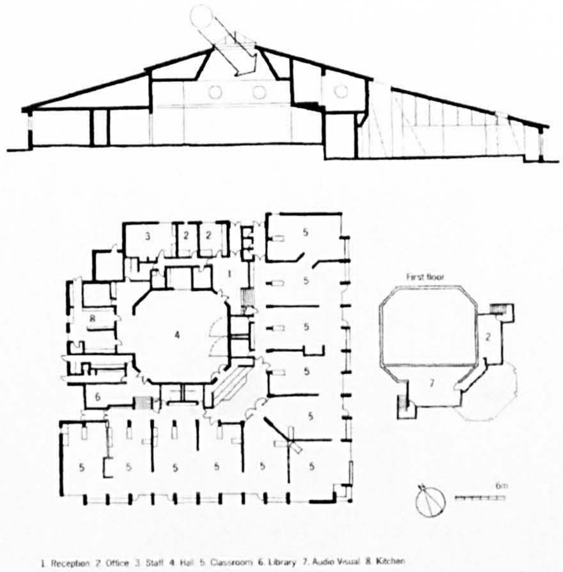
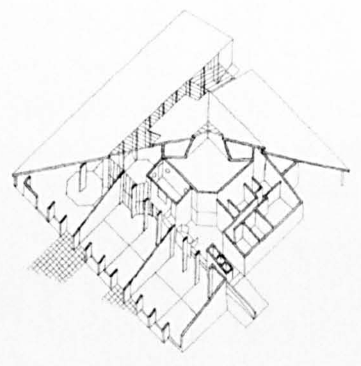
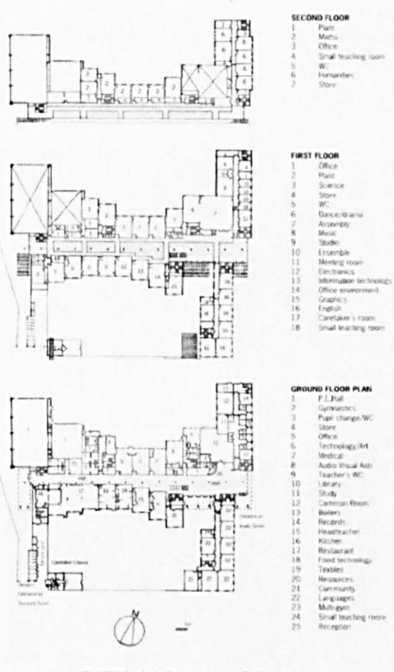
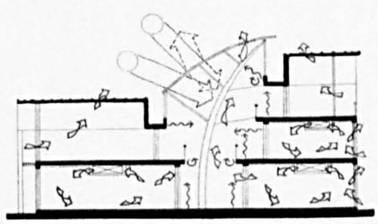
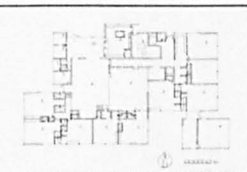
7.4. Exemplary Contemporary schools and daylighting in mild & cold climates

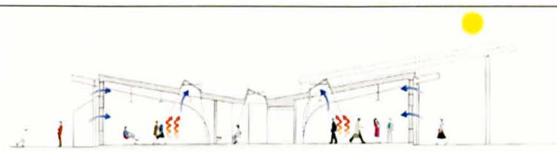
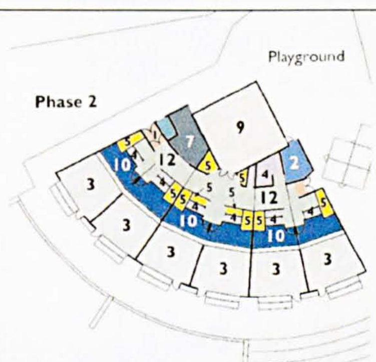
The majority of exemplar schools in this chapter (60%) are located in mild or cold, and humid, climates such as the UK. As mentioned earlier, the reason for their inclusion has been the lack of exemplar schools in warm and sunny climates and also common principles of daylighting in learning environments, which are almost the same in any climate. The difference lies in the manipulation of building envelope to respond to climatic features in order to provide daylighting conditions appropriate for learning environments. All exemplars are real buildings except 5 primary and 5 secondary schools which are visionary designs in the UK and are included because of their contributions to daylighting solutions in new schools (DfES 2003).

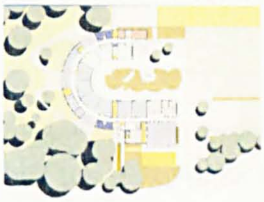
E41	Great Notley Primary School, Essex, England	Daylighting lessons
Exemplar 41	  (Curtis 2003, pp. 28-37)	+ A combination of view windows, clerestories, high ceiling and roof monitors creates well daylit rooms + Blinds & overhangs on the south view windows & clerestories as solar control devices 
E42	**Woodlea Primary School, Hampshire, England**	**Daylighting lessons**
Exemplar 42	 	+ Natural lighting is achieved through patent-glazing roof-lighting, clerestories and lanterns + White-painted sloping ceilings reflect daylight down to give even and glare-free lighting (Curtis 2003, pp. 114-117)

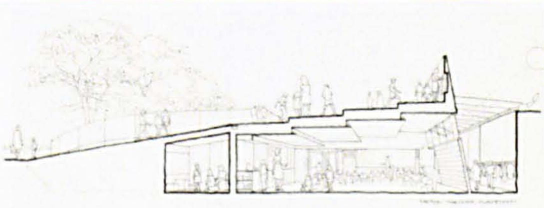
E43	Haute Vallée School, Jersey, England	Daylighting lessons
Exemplar 43		+ Classrooms get even daylight from large north facing windows as well as borrowed daylight from the south through corridor + External and internal blinds are used as solar control devices + Roof monitors & clerestories supplement daylighting in laboratory + Deciduous trees offer shade on the south side  (Curtis 2003, pp. 48-53)
E44	**Chafford Hundred Learning Campus, Essex, Eng.**	**Daylighting lessons**
Exemplar 44	  	+ North facing roof monitors + High classroom ceiling + South facing classrooms are shielded from the highest sunrays by brise soleil (opposite diagram) + Applicable daylighting solutions to sunny climates  (DfES 2002,BB95, p.12, 39, 48)

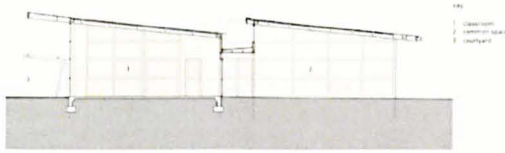
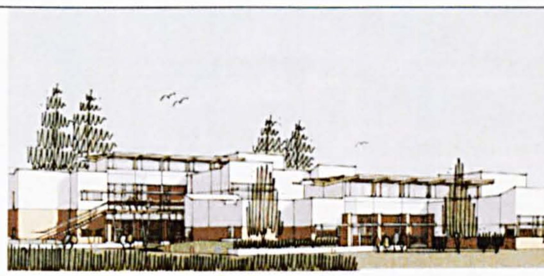
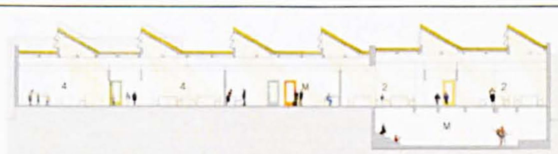
E45	Asplund Church Primary School, Wigan, England	Daylighting lessons
Exemplar 45	 (DFE 1994, pp. 39-41)	+ 57% of classrooms have two-sided windows allowing more daylight + Rooflights supplement daylight – Lack of daylight sensors, hence, electric lights are used unnecessarily – Lack of external shading 
E46	**Cherry Tree Primary School, Colchester, England**	**Daylighting lessons**
Exemplar 46		+ Covered courtyards configuration – Small courtyard makes small contribution to daylighting – Lack of external shading  (DFE 1994, pp. 49-50)
E47	**Hook Infants' and Junior School, Hampshire, Eng.**	**Daylighting lessons**
Exemplar 47	 	+ Deep eave as external shading + Central atrium between classrooms illuminates the back of classrooms through the clerestory glazing between classrooms and the atrium – Electric lighting is still required – Deep eave provides shade but reduces daylight levels while a lightshelf can both provide shade as well as conduct daylight deeper in classrooms (DFE 1994, pp. 58-60)
E48	**St Peter's Primary School, Essex, England**	**Daylighting lessons**

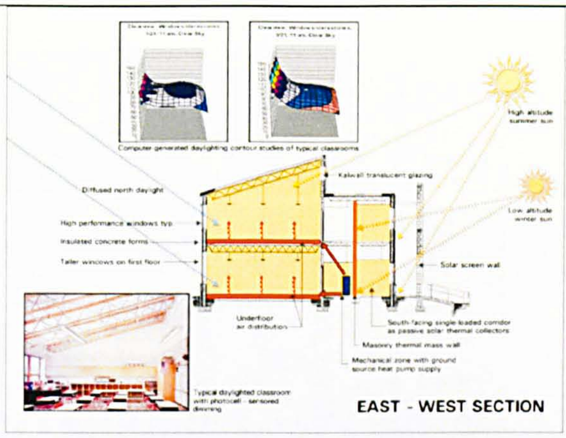
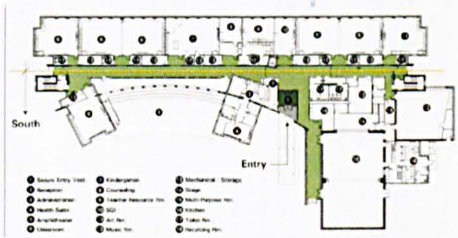
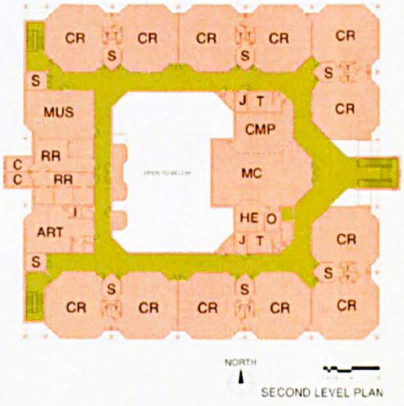
Exemplar 48	 (DFE 1994, pp.85-87)	+ Borrowed daylight to deep plan classrooms through roof glazed circulation spaces + Skylight illuminates the main hall − Extensive glazing for better daylighting but potential overheating 
E49	**Roach Vale Primary School, London, England**	**Daylighting lessons**
Exemplar 49	 (DFE 1994, pp. 88-90)	+ Okasolar double glazing with angled prisms to reflect light in summer and let in winter + Daylit unheated atrium + Bilateral daylit classrooms through large windows on one side and borrowed daylight from atrium through clerestories + External shading on the south + Energy efficient building 
E50	**Nazeing Primary school, Essex, England**	**Daylighting lessons**
Exemplar 50	 (DFE 1994, p. 69)	+ Small courtyard configuration − Lack of shading devices − One-sided daylit classrooms with nodaylight redirecting systems
E51	**Kingsmead Primary School, Cheshire, England**	**Daylighting lessons**

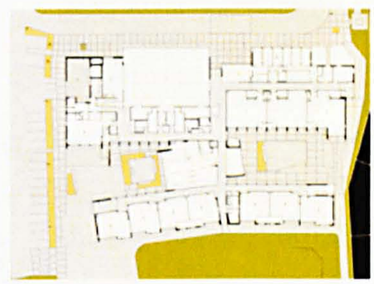
Exemplar 51	  (DfES 2006, pp. 12-19)	+ North facing classrooms illuminated with glare-free daylight via large view window & clerestory + Controllable Rooflights to illuminate deepest part of classrooms & solar gain in winter + Natural light in all spaces + Dimming effect of electric light connected to daylight sensors + High Post Occupancy Evaluation −Insufficient daylight when overcast 
E52	**Notley Green Primary School, Essex, England**	**Daylighting lessons**
Exemplar 52	 	+ Classrooms are daylit via view windows and high windows facing south-east to south-west as well as high level north facing roof monitors + Fixed overhand shading high windows & electrically operated shading on view windows + Internal blinds for view windows − Complaints of occasional discomfort glare from the sun & sky (DfES 2006, pp. 26-35)
E53	**Anns Grove Primary School, Sheffield, England**	**Daylighting lessons**
		+ All classrooms facing south-west + High ceilings & large windows + Rooflights to light the back of classrooms − Lack of external shading devices

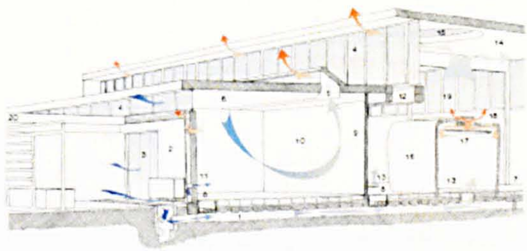
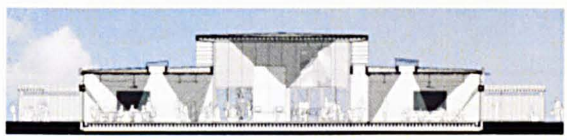
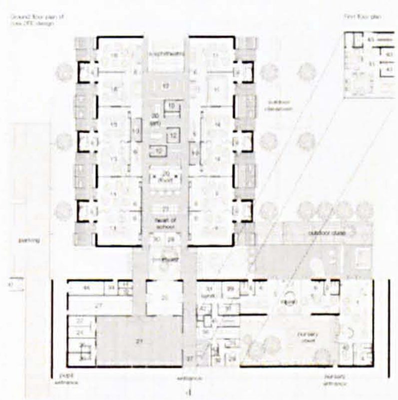
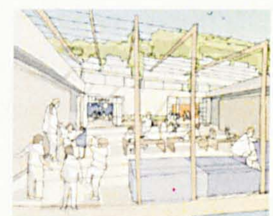
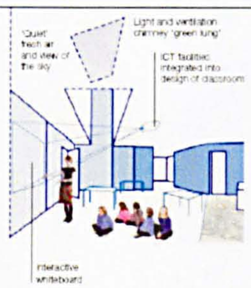
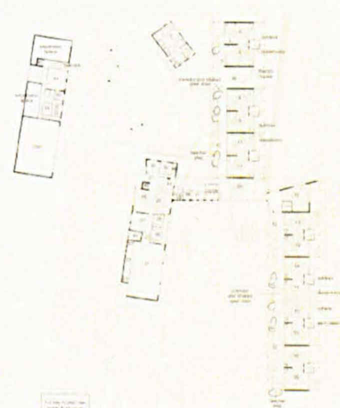
Exemplar 53		− Possibility of occasional overheating or lack of daylight 
E54	**Great Bingfield Primary School, Hampshire, Eng.**	**Daylighting lessons**
Exemplar 54	 (DfES 2002,BB95, p.39)	+ Glare-free north light is used + Blinds & overhangs are used to control direct sunlight + Roof monitors as daylight supplement 
E55	**Whiteley Primary School, Hampshire, England**	**Daylighting lessons**
Exemplar 55		+ South facing classrooms with extended roof for solar control + Rooflights deliver daylight to the back of classrooms − Shaded deck reduces daylight levels in the classrooms (DfES 2002, BB95, p.15)
E56	**Montessori school Ingolstadt, Germany (Cool & H)**	**Daylighting lessons**
Exemplar 56	(Curtis 2003, pp. 58-67) 	+ Open courtyard configuration + Over 70% glazing but controlled by a variety of shading devices + Exterior Venetian blinds + Interior Venetian blinds and curtains to control glare + Extended roof as external shading

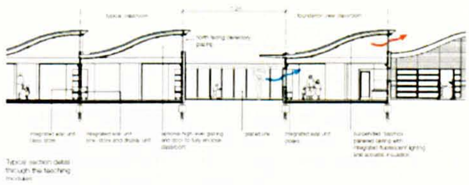
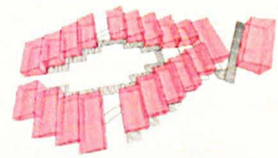
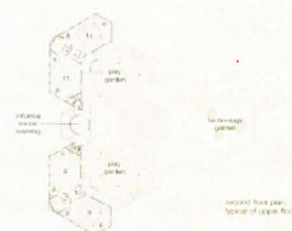
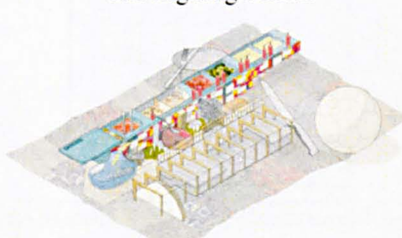
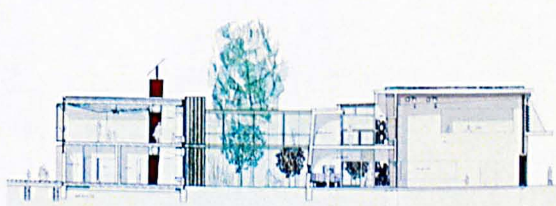
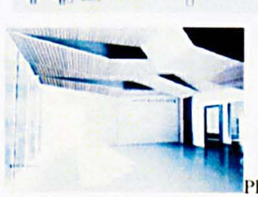
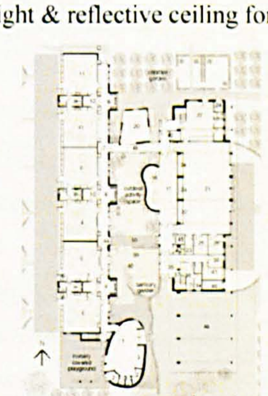
E57	**Ballifield Community Primary School, Sheffield**	**Daylighting lessons**
Exemplar 57	  (DfES 2002, p.66)   Photos © Farshad Ai, Main hall-L, Reception of the new extension-R	+ Red 'Box bay' window to control daylight & as a window seat alcove + White ceiling to reflect light + Two rows of clerestories illuminate the classroom (below) + Skylight revives the new reception – Clerestories' blinds are pulled at a sunny day and electric lights are on  (Chiles and Care 2006, p.45)
E58	**Mossbrook Special School, Sheffield, England**	**Daylighting lessons**
Exemplar 58	  (DfES 2002, p.70)	+ Wide stripes of view windows protected from solar gain via deep window reveals structure (opposite) + Sloped stripe of clerestories  (Chiles and Care 2006, p.45)
E59	**Brunswich Primary School, Sheffield, England**	**Daylighting lessons**
Exemplar 59	 (DfES 2002, p.68)	+ Well daylit corridor via skylights + Clerestories deliver borrowed daylight to the classroom + Stepped form of the ceiling to receive most daylight at the entry

E60	Willowbank Primary School,New Zealand (Mild/H)	Daylighting lessons
Exemplar 60	   Shaded veranda & Daylit teaching space with mirrors	+ Deep overhangs & veranda canopies provides shade to classrooms & protects exterior circulation space + High windows & clerestories admit daylight deep in classrooms + Pop-up Rooflights in multipurpose space & library flooded with light  
E61	**Terrace Park Elementary, Washington, US (M &H)**	**Daylighting lessons**
Exemplar 61	  	+ Bay windows equipped with lightshelves provide shade as well as deeper daylight penetration + High windows shaded by deep eave contribute to daylighting + High ceiling improves reflected daylighting + Open courtyard configuration
E62	**Bronx Charter School of Arts,New York (Cool & H)**	**Daylighting lessons**
Exemplar 62	  	+ North-facing roof monitor offering even & diffuse daylight + High ceiling improving reflected daylighting in classrooms (below) – Lack of external shading devices on the façade (opposite) 

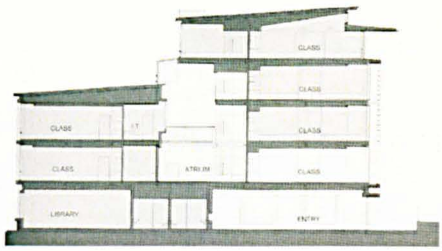
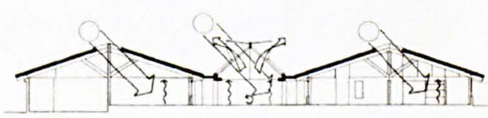
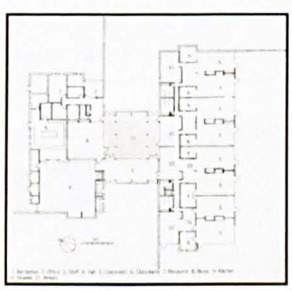
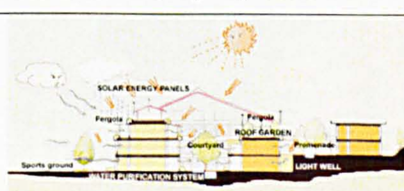
E63	Clearview Elementary School, Pennsylvania, US (Cool & Humid)	Daylighting lessons
Exemplar 63	  	+ East-west axis orientation + Daylight photocell sensor with dimming effect & occupant sensors + Daylight factor exceeds 2.0 in all occupied classrooms + Diffuse north light with high performance windows + Clerestories on first floor classrooms + High & white-painted ceiling + Even distribution of daylight + Integrated sundial of south façade + **Solar screening wall** shading classroom windows & the walkway 
E64	**New Salina Elementary School, Michigan(Cold &H)**	**Daylighting lessons**
Exemplar 64	 	+ Enclosed courtyard configuration + Colourful hanging panels to control glare from skylights (below)  – Insufficient daylight due to corner location of windows & lack of any daylight redirecting system (below) 

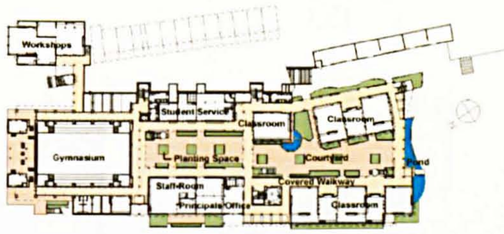
E65	**Thomas L. Wells Public School, Ontario, Canada (Cold & Humid)**	**Daylighting lessons**
Exemplar 65	   	+ East-west axis orientation to maximise daylighting + Open courtyard configuration + Façades designed for daylighting effectiveness and solar control + Lightshelves shade high summer sun & reflect low winter sun deep into classrooms + Lightshelves are incorporated into the façade (opposite) + Daylight sensors save electricity + Electric light are used rarely + Large windows & clerestories on the north façade to admit diffuse daylight 
E66	**Chugach Optional Elementary School, Alaska (Cold & Humid)**	**Daylighting lessons**
Exemplar 66	   	+ Window seats & clerestories + Extended roof as shading device on south façade (Opposite) – Insufficient daylight in classrooms & reliance on electric light 

	5 Visionary Exemplar Primary school Exemplars **UK design consultants**	
E67	**Walter & Cohen Architects -** Suburban site	**Daylighting lessons**
Exemplar 67	   (DfES 2003, pp. 30-35)	+ Operable clerestories for good daylight distribution & ventilation + Operable roof monitors for improved daylight distribution + Rooflights for flexible partitioning & for intermediate zone between classrooms & the hall + High ceilings for improved reflected daylighting & ventilation  Outdoor classroom 
E68	**Cottrell + Vermeulen Architecture -** Sloping site	**Daylighting lessons**
Exemplar 68	   	+ Bilateral daylit classrooms + '*Green lung*' or daylighting and natural ventilation chimneys + Verandas as shading device & outdoor classroom  (DfES 2003, pp. 36-41)

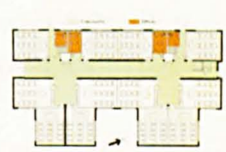
E69	**Marks Barfield Architects** - Rural site	**Daylighting lessons**
Exemplar 69	 	+ North-facing clerestory glazing + Optional high level glazing + Pergolas as shading devices & outdoor teaching space + Private Courtyard configuration  (DfES 2003, PP. 42-47)
E70	**Building Design Partnership** – Tight urban site	**Daylighting lessons**
Exemplar 70	Beehive School  	+ Classbases are daylit by diffuse north light via large windows as well as clerestory light (opposite)  (DfES 2003, pp. 48-53)
E71	**Sarah Wigglesworth Architects** – Larger urban site	**Daylighting lessons**
Exemplar 71	The Big Rug School    Photos courtesy of Sarah Wigglesworth	+ Green open courtyard feature + Manually operated blinds to control daylight + External solar louvres + Full height glazing to maximize daylight & reflective ceiling form  (DfES 2003, pp. 54-59)

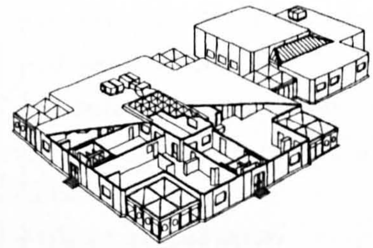
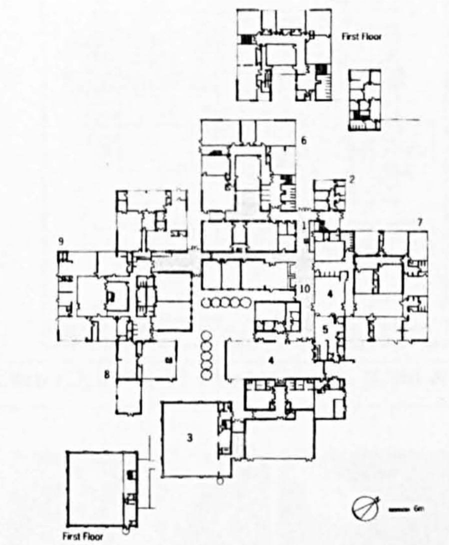
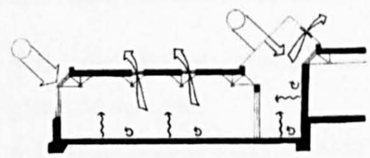
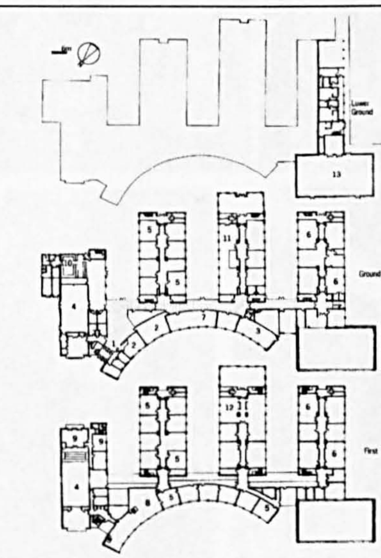
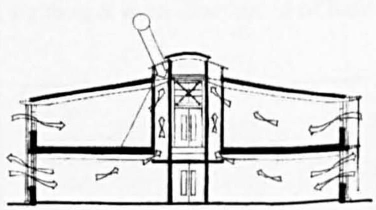
Tab 7.12. Primary/Elementary school exemplars & Daylighting lessons in mild/cold & humid climates

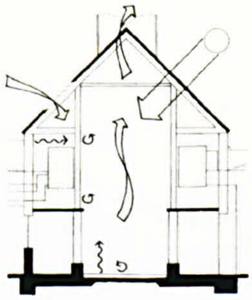
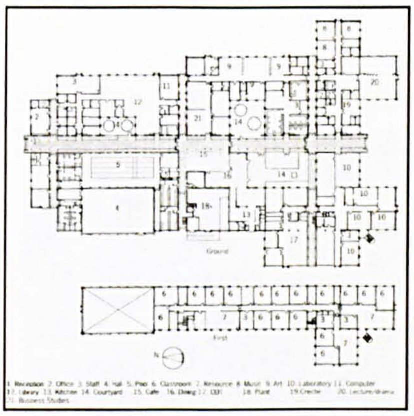
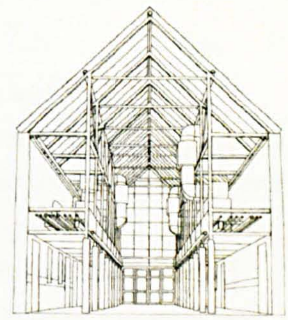
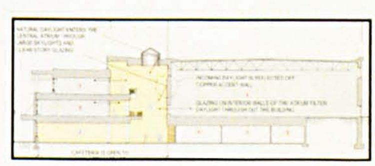
E72	St Aloysius Junior School, Glasgow, Scotland	Daylighting lessons
Exemplar 72	 	+ Five storey south elevation designed to maximise natural light & air and yet provide shade & privacy + External moveable curved louvres + Daylit atrium brings natural light deep into plan + South facing classrooms have full height window wall divided into two bays: one has fixed blinds to maximise light but reduce glare & reduce distraction by filtering view; the other has computer controlled enamelled glass louvres which provide solar shading but offer clearer view to outside (Curtis 2003, pp. 96-101)
E73	**Newlands Junior School, England**	**Daylighting lessons**
Exemplar 73	 	+ Small unheated central atrium + Substantially daylit by glazed gable ends and central ridge Rooflight + Deep eave as external shading – Lack of sufficient external shading on the south and no daylight redirecting system (DFE 1994, pp. 76-78)
E74	**Burgoyne Middle School, Bedfordshire, England**	**Daylighting lessons**
Exemplar 74		+ Roof monitors in different directions illuminate deep plan + Clerestories or high level glazing (DfES 2002, p.10)
E75	**Tajimi Junior School, Japan (Cold & Humid)**	**Daylighting lessons**
		+ Courtyard configuration + Trees in courtyard provide shade + Pergolas as shading & buffer zone + Covered walkways + Window seat alcove

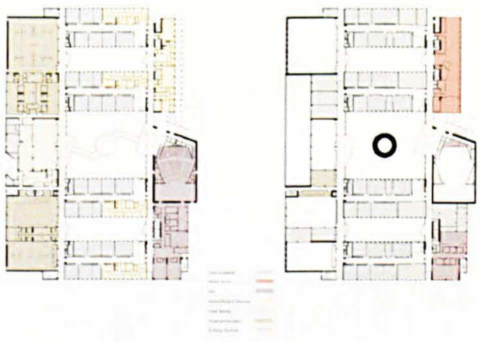
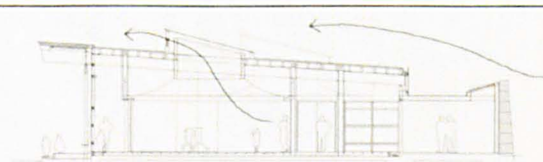
Exemplar 75		┼ Window seat alcove 

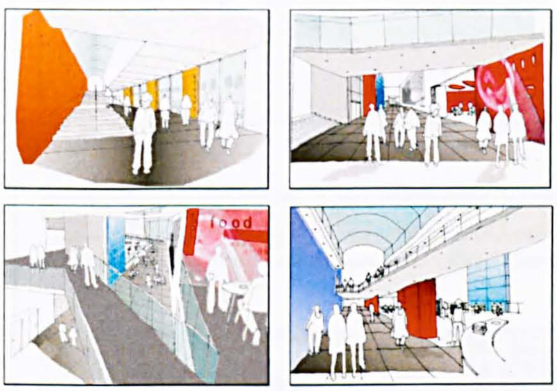
Tab 7.13. Middle/Junior school exemplars & Daylighting lessons in mild/cold & humid climates

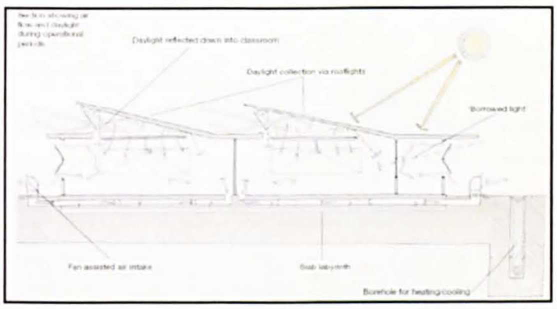
E76	Venerable Bede Secondary School, Sunderland Eng.	Daylighting lessons
Exemplar 76	 (DfES 2006, pp. 42-49)	┼ Courtyard configuration with two teaching wings either side chosen for its daylighting potentials ┼ Fixed solar shading ┼ Openable Velux windows bring daylight into first floor circulation 
E77	**Broomsgrove Senior School, England**	**Daylighting lessons**
Exemplar 77		┼ Adequate daylight, DF=2.5 ┼ Partially glazed central street ┼ Clerestories & tall windows ┼ Mid-pane blinds to control glare 
E78	**Swanlea Secondary School, Essex, England**	**Daylighting lessons**
		┼ Glazed central atrium ┼ On upper floors classrooms have high curved ceilings & tall windows letting in plenty of daylight (DfES 2002, p.37)

Exemplar 78	 (DFE 1994, pp. 91-94)	
E79	**Thorpe Bay High School, Essex, England**	**Daylighting lessons**
Exemplar 79		+ Glazed & controlled courtyard configuration + Roof glazed circulation streets + This exemplar shows, in cool or cold climates, covering courtyard & circulation spaces offers amenity & energy-saving values (DfES 2002, p.98)  (DfES 2002, pp. 95-98)
E80	**John Cabot City Technology College, Bristol, Eng.**	**Daylighting lessons**
Exemplar 80		+ Bilateral daylit classrooms + 65% of external wall glazed by extensive motorized translucent solar blinds + Open courtyard configuration + Extensive clerestories & high level glazing  (DfES 2002, pp. 45-48)

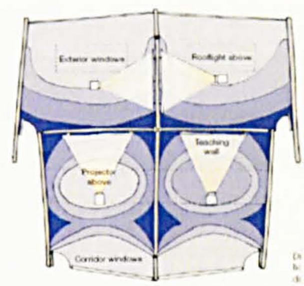
E81	**Leith Academy Secondary School, Edinburgh**	**Daylighting lessons**
Exemplar 81	 	+ Glazed learning street (opposite) + All rooms are daylit + Clerestory glazing on corridor walls to offer borrowed daylight to the back of classrooms + Glazed unheated atrium + Substantial solar gains  (DfES 2002, pp. 61-63)
E82	**Auburn High School, Massachusetts (Cold & H)**	**Daylighting lessons**
Exemplar 82	    	+ External overhangs control solar glare and heat gain + Daylight photocell controllers to activate electric lights when needed + Expansive clerestory glazing + Three large skylights help illuminate the atrium + Classrooms are daylit by large windows, clerestory glazing & glass partitions for borrowed lighting + Recessed ground floor windows are protected by the shaded walkway + High ceilings help reflected lighting & even distribution of light 

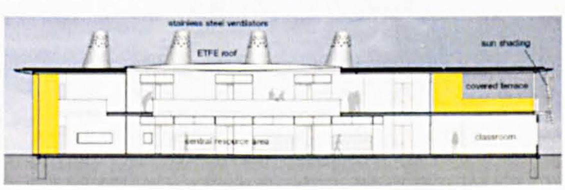
E83	Little Village Lawndale High School, Illinois (C&H)	Daylighting lessons
Exemplar 83		+ Multiple courtyard configuration + Well daylit corridor by windows and clerestories 
E84	**Barberton High School, Ohio (Cool & Humid)**	**Daylighting lessons**
Exemplar 84		+ Courtyard offers natural light to classrooms, hallways & cafeteria + Expansive clerestories in the hall + Extended roof or shaded colonnade as shading devices 
E85	**Chugiak High School, Alaska (Cold & Humid)**	**Daylighting lessons**
Exemplar 85	 	+ Deep plan classrooms are daylit by tall clerestories with a curve reflective surface + Light-wells bring natural light into to all levels of circulation spaces
E86	**Bournemouth 'Classroom of the future' - C. White**	**Daylighting lessons**
		+ Extended roof as external shading device (opposite) + Skylights, clerestories and borrowed daylight from the corridor

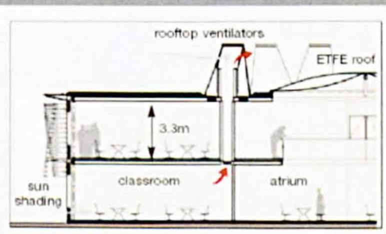
Exemplar 86		are main sources of classrooms daylighting + Orientation & position of windows to make use of beneficial solar gain while protecting against overheating  (DfES 2002, PP. 16-21)
E87	**Yewlands Secondary School, Sheffield, England**	**Daylighting lessons**
Exemplar 87		+ Plenty of diffuse daylight through vault skylights and clerestories + Well daylit circulation space and common area by mainly skylights +Glazed interior dividers  (DfES 2002, pp.74-75)
E88	**The Lord Silkin Secondary School, Telford and Wrekin 'Classroom of the Future' project, England**	**Daylighting lessons**
Exemplar 88		+ South facing full height glazing with extended roof as shading device + clerestories under the roof to improve uniformity of daylighting (DfES 2002, pp. 78-79)
	5 Visionary Exemplar Secondary school Exemplars UK design consultants	
E89	**Mace (RTKL) Architects –** Suburban Site	**Daylighting lessons**
		+ Courtyard as the heart of school + Balanced daylighting through a combination of view windows, clerestories, Rooflights and skylights (view opposite sections)

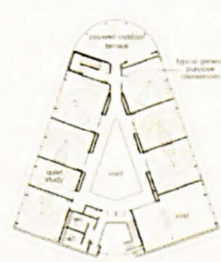
<table>
<tr>
<td>Exemplar 89</td>
<td>



</td>
<td>+ Daylight is reflected down into classrooms through Rooflight clerestories and then diffused through semi-glass panels

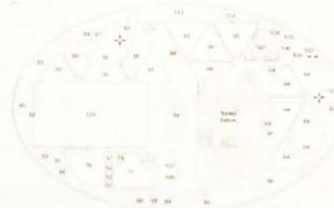
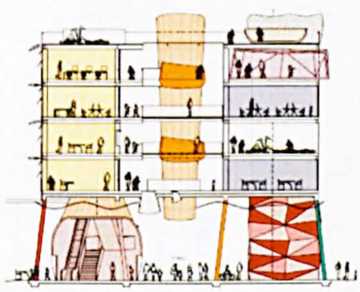
+ Borrowed daylight through corridor to the back of classrooms


+ Projection screens are located in dark corners of classrooms (above)
(DfES 2003, pp. 62-69)</td>
</tr>
<tr>
<td>E90</td>
<td>Wilkinson Eyre Architects – Sloping site</td>
<td>Daylighting lessons</td>
</tr>
<tr>
<td>Exemplar 90</td>
<td>

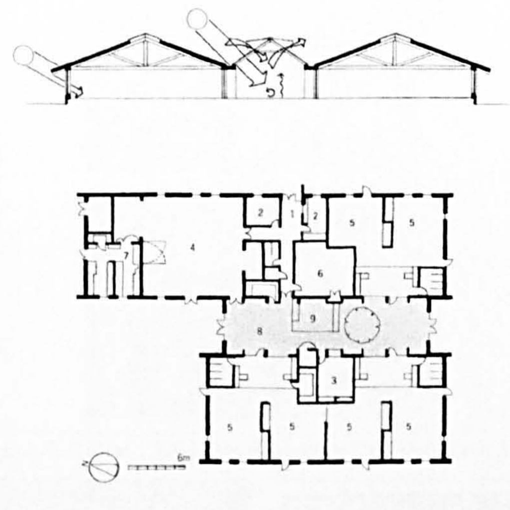
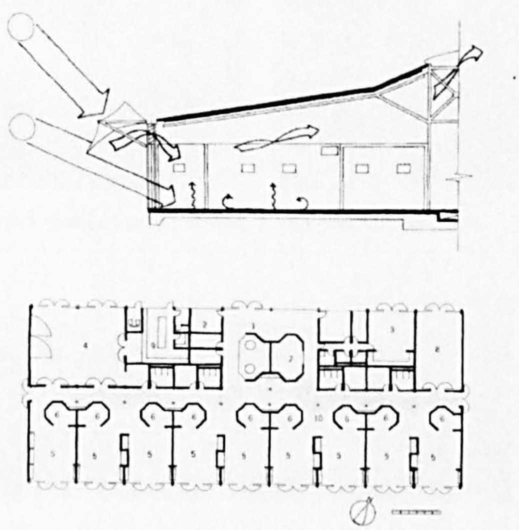
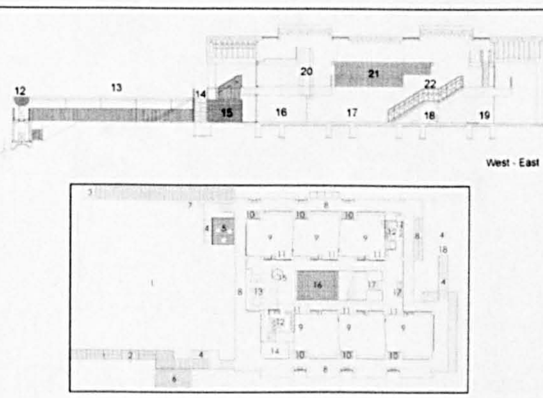


</td>
<td>+ Brise-soleil, overhangs and roof extension as exterior solar shading
+ Covered walkways linking learning clusters (below)
+ Open courtyard configuration


(DfES 2003, pp. 70-77)</td>
</tr>
</table>

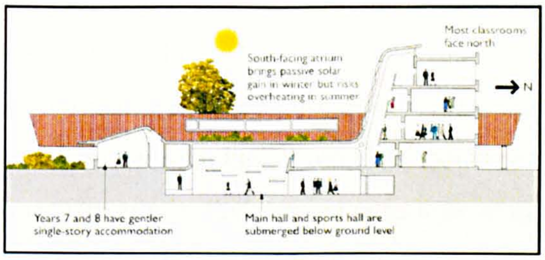
E91	**De Rijke Marsh Morgan Architects** – Rural site	**Daylighting lessons**
Exemplar 91	 	+ A dome roof, *dura*, transfers a special quality of controllable daylight deep into the whole plan via a 66% transparent variable skin effect roof. (DfES 2003, pp. 78-85) 
E92	**ALSOP Architects** – Tight-urban site	**Daylighting lessons**
Exemplar 92	 	+ Well daylit atrium via skylights + Moveable colourful external louvres and overhangs as shading device and redirecting daylight + Borrowed daylight through high glazing to the back of classrooms + Shaded learning street underneath  (DfES 2003, pp. 86-93)
E93	**Penoyre & Prasad Architects** – Larger urban site	**Daylighting lessons**
Exemplar 93	 	+ Double height daylit circulation + Venetian blinds within triple glazing to prevent overheating & reflect daylight up to the ceiling by using light bending technology such as *Serraglaze* or reflective Venetian blinds. (DfES 2003, pp. 94-101) 

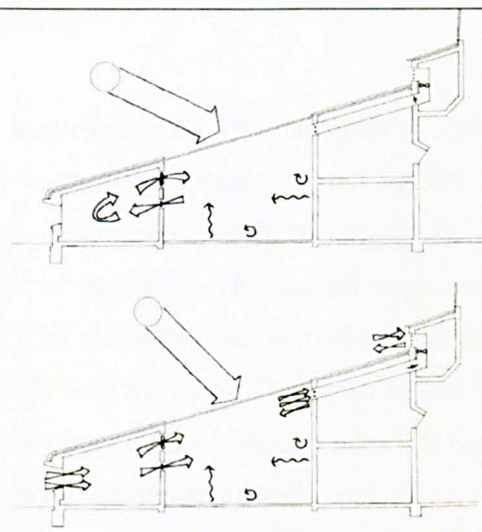
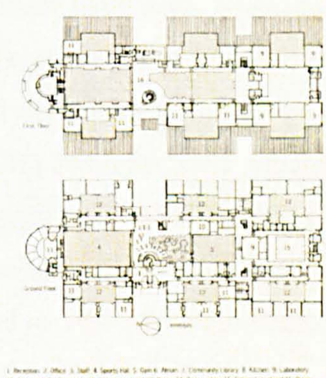
Tab 7.14. Secondary/High school exemplars & Daylighting lessons in mild/cold & humid climates

E94	Barnes Farm Infants, Essex, England	Daylighting lessons
Exemplar 94	 1. Reception 2. Office 3. Staff 4. Hall 5. Classroom 6. Resource 7. Kitchen 8. Atrium 9. Library area	+ All classrooms receive borrowed daylight from central atrium via large glazing dividers + 50% of classrooms receive daylight from 3 sides + Solar resistant double glazing Rooflight plus gable ends glazing flood the atrium with natural light – Possible discomfort glare in a south-east classroom (DFE 1994, pp. 42-44)
E95	**Fleet Infant School, Hampshire, England**	**Daylighting lessons**
Exemplar 95	 1. Reception 2. Office 3. Staff 4. Hall 5. Class-base 6. Quiet area 7. Library 8. Music 9. Kitchen 10. Shared	+ External stretched fabric awnings on the south side as shading device + Moveable louvres of high level clerestory redirects daylight deep into classrooms + Lighting is principally by daylighting from perimeter glazing and central Rooflight – High energy use because of mechanical ventilation (DFE 1994, pp. 51-53)
E96	**Yuyu-no-mori Nursery School, Japan (Mild & H)**	**Daylighting lessons**
		+ Well daylit classrooms via windows and Rooflights + Well daylit atrium via Rooflights + Stripes of Rooflights & clerestories create a playful mixture of daylight and space for children + Indirect electric lighting by uplighters

Exemplar 96	 	
E97	**First National Child Development Centre, Nebraska**	**Daylighting lessons**
Exemplar 97	 	+ Well daylit learning street by clerestories + Extended roof shading device + Large 'Window Box' seats 
E98	**Riverhead Infants School, Sevenoaks, England**	**Daylighting lessons**
Exemplar 98	 	+ South facing classrooms + Brise-soleil & overhanging eaves as external shading device + Rooflights illuminate schools two winter gardens & circulation spaces + Low window sills for child-oriented scale + An exemplar of sustainable design   (DfES 2006, pp.92-97)

Tab 7.15. ECLE/Infant school exemplars & Daylighting lessons in mild/cold & humid climates

<table>
<tr><th>E99</th><th>Academy of St Francis of Assisi, Liverpool, England</th><th>Daylighting lessons</th></tr>
<tr><td>Exemplar 99</td><td>


</td><td>
+ Most classrooms face north with generous glazing with diffuse light
+ Borrowed daylight from the atrium to the back of classrooms
+ South facing atrium brings passive solar gain in winter but risks overheating in summer
+ 'Solar funnels' bring a small amount of reflected daylight into the underground areas
+ Impressive daylight factor,7.8 %, for year 7 & 8 classrooms; Good daylight factor for other classrooms, 4.5 % and DF 3.6% for science labs
(DfES 2006, pp. 50-57)
</td></tr>
<tr><th>E100</th><th>Perronet Thompson Comprehensive, Hull, England</th><th>Daylighting lessons</th></tr>
<tr><td>Exemplar 100</td><td>

(DFE 1994, pp. 80-84)
</td><td>
+ Six semi-glazed courtyards
+ 60% courtyard roofs is glazed
+ Unheated atria

</td></tr>
</table>

Tab 7.16. ALE/Academy school exemplars & Daylighting lessons in mild/cold & humid climates

7.5. Daylighting lessons and conclusion

The above tables (7.3-7.16) have summarized daylighting solutions of 100 school case studies which can mainly be considered as exemplars. There are obviously common solutions among case studies in terms of their approach towards admitting daylight to classrooms. The aim of this section is to look at all exemplars in a comparative study analysis and highlight daylighting lessons and principles which can be learnt from them. The exemplars' daylighting lessons are categorized and analysed based on the aforementioned four sets of components which are derived from previous chapters. It is important to note that borrowed lighting is observed in a number of case studies as a remarkable way of illuminating the back of classrooms. Borrowed lighting was addressed in daylighting systems in schools in chapter 3 but not discussed or explored in previous chapters. Borrowed light from corridors or atria is an important aspect of lighting design in schools and there is enough empirical evidence in the above exemplars to support the inclusion of this method in the proposed design guidelines in the final chapter.

Tab 7.17 summarizes all 100 exemplar's daylighting lessons in four groups. This showsthat in the first group , 51 out of 100 case studies have high windows or clerestories which admit daylight deeper into classrooms, and help give an even distribution of daylight. The second most common feature in the first group are rooflights, roof monitors (with or without diffusing baffles) and light wells which are included in 32% of the cases. These act as part of top lighting for the highest level or single storey classrooms where they admit or conduct daylight into deep plan schools. Skylights (with or without diffusing baffles) are included in 19% of case studies, but only 16% of exemplars have borrowed daylight at the back of classrooms via corridors or atria. 14 out of 100 schools have bilaterally daylit classrooms and 11 out of 100 schools have most of their classrooms facing north to benefit from diffuse daylight. It should be noted that skylights, in this research, refer to large central toplighting components which are usually horizontal, while rooflights refer to the glazing in the roof pop-up structures or the glazing placed on different angles of the roof.

	G1-Deep penetration & Even Distribution of Daylight						G2-Daylight Redirection Systems (Shading)					G3-Shading devices						G4-General features affecting Daylighting				
	Skylights: With or without Baffles	Rooflights/Roof monitors baff.,Light-wells	North facing glazing of Classrooms	Borrowed light from corridor/atrium	High windows/ Clerestories	Bilateral daylit classrooms	Lightshelves-Interior/Exterior/Incorporated	Curved/ Sloped ceiling	External/ Internal Louvres	Venetian Blinds- Interior/ Exterior	Mid-pane blinds	Overhang/Deep eave/Canopy/Deep reveals	Vertical shading/ Fins/ Deep reveals	Brisee-Soleil	Shaded walkways/colonnades	Verandas/ Shaded decks/ Pergolas	Deciduous Trees/ Foliage	Courtyard- Enclosed/ U form/ Open	Low Fenestration & Controlled opening	Relatively high ceiling	Daylight Compensation/photocell sensors	Bay window seats
E01					•							•			•			•	•	•		
E02	•				•							•										
E03	•																	•	•			
E04												•					•	•	•			
E05		•	•		•							•								•	•	
E06	•											•			•		•	•	•			
E07	•							•											•			
E08	•		•		•		•										•			•		
E09												•			•			•				
E10					•		•					•			•			•		•		
E11					•			•				•					•			•	•	
E12	•																	•	•			
E13					•			•							•			•	•	•		
E14			•									•	•		•			•	•			
E15					•													•				•
E16	•														•			•	•			
E17					•		•												•	•		
E18	•																					
E19															•			•	•			
E20					•															•		
E21					•			•				•			•	•		•				
E22			•	•		•									•			•				
E23						•								•			•					
E24		•																				•
E25	•	•			•																	
E26			•		•							•			•			•	•			
E27		•													•			•				
E28	•											•	•					•	•			
E29					•							•	•					•				
E30		•			•		•				•									•	•	
E31					•		•													•	•	
E32					•			•	•			•	•							•		
E33					•	•						•			•							
E34		•					•				•	•										
E35															•			•				
E36												•	•	•								
E37					•														•			
E38												•	•			•	•	•				
E39	•				•		•					•	•			•				•		
E40					•		•									•		•	•	•		
E41		•			•							•								•		
E42		•			•																	
E43		•	•	•	•	•				•							•			•		
E44		•												•						•		
E45		•				•																
E46																		•				
E47				•		•						•										
E48	•			•		•						•										
E49				•		•						•										
E50																		•				
E51		•	•		•															•	•	
E52		•			•							•										
E53		•						•												•		

	Deep penetration & Even Distribution of Daylight						Daylight Redirection Systems (Shading)					Shading devices						General features affecting Daylighting				
	Skylights: With or without Baffles	Rooflights/Roof monitors baff., Light-wells	North facing glazing of Classrooms	Borrowed light from corridor/atrium	High windows/ Clerestories	Bilateral daylit classrooms	Lightshelves-Interior/Exterior/Incorporated	Curved/ Sloped ceiling	External/ Internal Louvres	Venetian Blinds- Interior/ Exterior	Mid-pane blinds	Overhang/Deep eave/Canopy/Deep reveals	Vertical shading/ Fins/ Deep reveals	Brisee-Soleil	Shaded walkways/colonnades	Verandas/ Shaded decks/ Pergolas	Deciduous Trees/ Foliage	Courtyard- Enclosed/ U form/ Open	Low Fenestration & Controlled opening	Relatively high ceiling	Daylight Compensation/photocell sensors	Bay window seats
E54		●						●				●						●				
E55		●										●				●						
E56										●		●						●				
E57	●				●																	●
E58					●							●	●							●		
E59				●	●																	
E60		●			●							●				●				●		
E61					●		●											●		●		●
E62		●						●												●		
E63			●		●											●				●	●	
E64	●																	●				
E65					●		●					●	●					●		●	●	
E66												●										●
E67	●	●			●											●				●		
E68		●				●										●						
E69		●			●											●		●				
E70			●		●																	
E71					●	●			●	●		●						●				
E72			●						●													
E73		●										●										
E74		●			●																	
E75				●											●	●	●	●				●
E76		●										●						●				
E77					●						●											
E78								●												●		
E79		●		●														●				
E80					●	●				●		●										
E81				●		●																
E82				●	●							●			●					●	●	
E83					●													●				
E84					●							●			●		●	●				
E85		●			●			●				●										
E86	●				●							●										
E87	●				●																	
E88					●							●										
E89	●	●		●	●							●						●				
E90												●		●	●			●		●		
E91				●																●		
E92	●			●					●			●										
E93											●											
E94		●		●		●																
E95		●		●	●				●			●								●		
E96		●			●																	
E97					●							●										●
E98		●										●		●								
E99		●	●	●		●																
E100												●						●				
Total	19	32	11	16	51	14	10	10	5	4	4	46	9	5	17	12	9	39	15	30	8	7

Tab 7.17. Comparative study of 100 exemplar daylighting principles in four main groups

Table 7.1 illustrated three main climate groups used to classifying the exemplars: sunny in yellow, temperate/warm & humid in beige, and mild/cold & humid in green. The sunny climate includes 29 schools out of 100 and the temperate/warm and humid zone includes only 11 while the mild/cold and humid climate includes the majority of 60 schools. It is important to take the number of each climate case study into account when comparing their total features. Therefore, a coefficient value has been calculated to make the share of each major climate group one third of the total for statistical reasons. On this basis, there are two charts representing each group. The first one illustrates the total number of exemplar schools which have used the specific daylighting features in comparison with the total in all climates. The second one takes into account the coefficient and illustrates each climate's proportion of the specific design features as if each climate had the same number of case studies in the total 100 schools.

Coefficient value= 100/ 3×N (number of each climate case study)

The following charts (Fig 7.2 and 7.3), firstly, show the popularity of clerestories and rooflights in all climates among the selected exemplars. Secondly, it shows the sunny zone has the largest proportion of skylights, while it has the smallest share in borrowed daylighting. On the other hand, mild/cold and humid climate zone has the largest proportion of rooflights, borrowed daylight and bilateral daylit classrooms while it has the lowest proportion in north light classrooms. Clerestories seem to have been used about the same frequency in the 3 climate groups, with the temperate zone having a slight edge. It is important to take into account that these results are not conclusive as they are based on case studies chosen from limited references. Even so, the analysis suggests some features within each climatic zone which have been used successfully within what are considered well-designed schools.

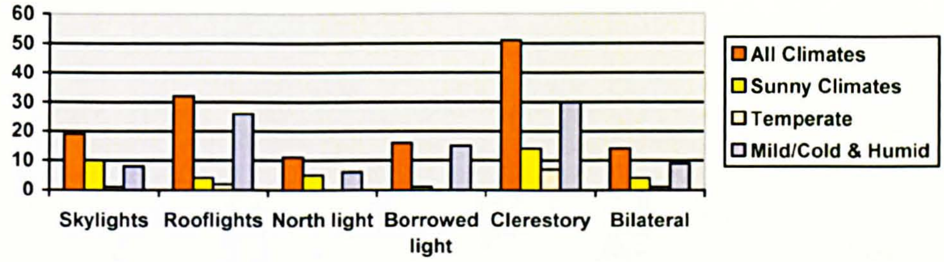


Fig 7.2. All climates and each climate number of exemplars with specific features in group 1

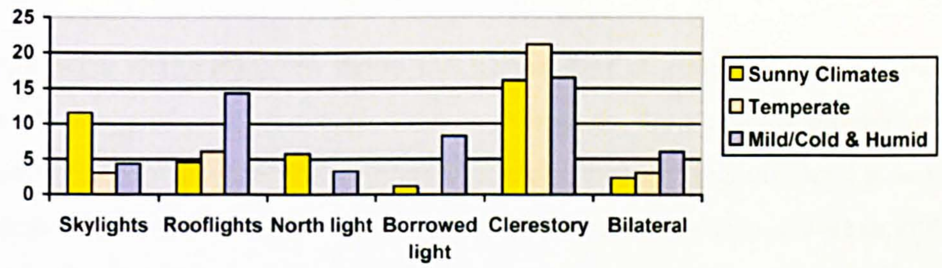


Fig 7.3. Each climate portion of exemplars with specific features in group 1

The second group includes daylight redirection systems some of which provide shading as well. Figures 7.4 and 7.5, firstly, show the popularity of lightshelves and sloped/curved ceiling as means of redirecting daylight or sunlight. Secondly, it shows that sunny climate case s tudies have only taken advantage of lightshelves and curved/sloped ceiling to redirect light deeper in classrooms. Based on the case studies, temperate zone climate have the largest proportion of lightshelves while cold & humid zone has the smallest proportion. This indicates the necessity of redirecting sunlight via lightshelves in sunny and temperate zone, while it is not crucial in overcast climates.

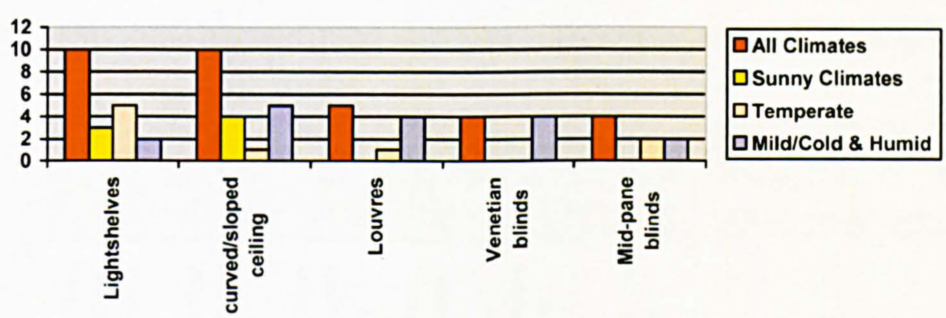


Fig 7.4. All climates and each climate number of exemplars with specific features in group 2

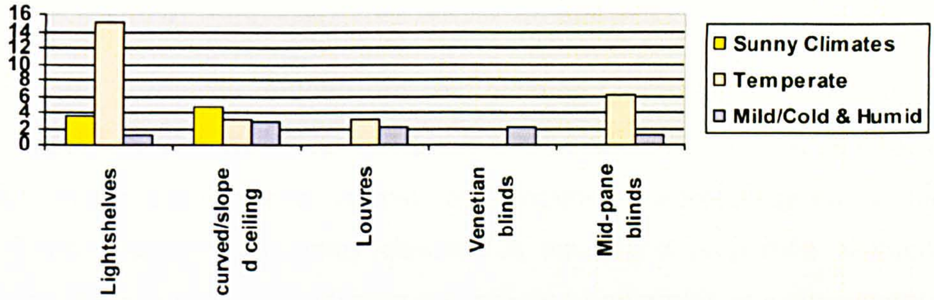


Fig 7.5. Each climate portion of exemplars with specific features in group 2

The following charts (Fig 7.6) shows that almost half of all climate exemplars have taken advantage of shading devices such as overhangs, deep eaves, canopies or deep reveals. Shaded walkways and colonnades are also popular shading devices but with less popularity than in the first sub-group (i.e. overhangs/deep eave/canopy/deep reveals). Fig 7.7 illustrates the large proportion of shaded walkways and colonnades in sunny climates compared with the other two. Sunny climates have also a large proportion of deciduous trees as shading devices; these are sensible solutions in such climates to deal with the harsh sunlight. It also shows each climate group has almost the same proportion of the overhang sub-group of shading devices, showing that they are the most popular shading devices to use in all climates in this study.

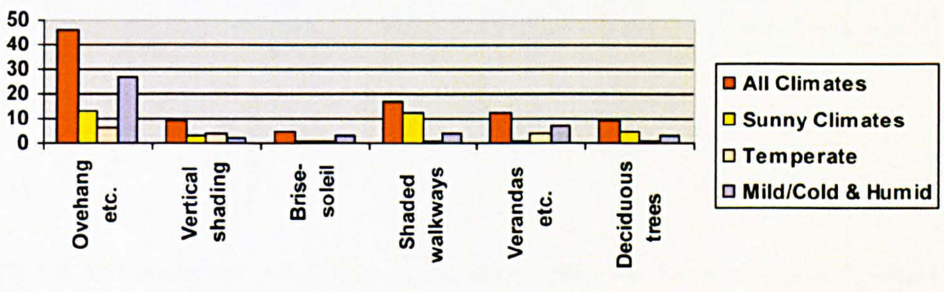


Fig 7.6. All climates and each climate number of exemplars with specific features in group 3

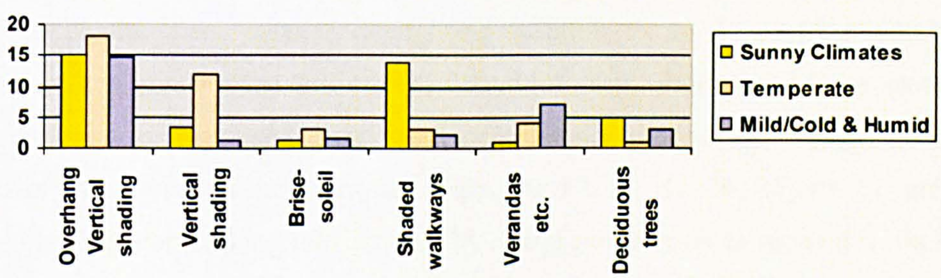


Fig 7.7. Each climate portion of exemplars with specific features in group 3

The last group includes other general features which affect daylighting of classrooms indirectly. The sub-group features are not as related as in previous groups. Fig 7.8 illustrates the popularity of courtyard configuration (enclosed, U form or open) as well as relatively high classroom ceilings in almost all three climates. It also shows low fenestration and controlled opening as a common feature of the sunny climate. Fig 7.9 also illustrates the sunny climate has the largest proportion of courtyard solutions, which is a sensible option to use reflected daylighting as well as controlling the harsh sunlight.

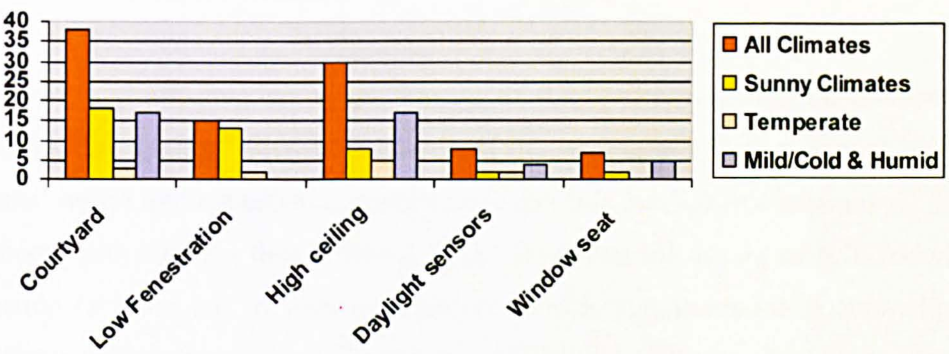


Fig 7.8. All climates and each climate number of exemplars with specific features in group 4

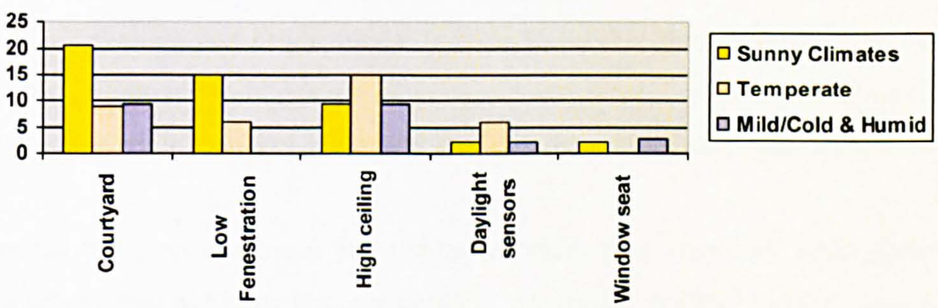


Fig 7.9. All climates and each climate number of exemplars with specific features in group 4

In summary, clerestories and high windows as well as Rooflight and roof monitors prove to be the most popular daylighting solution to admit daylight deeply in classrooms and improve the uniformity of daylight. Lightshelves and room geometry (sloped/curved ceiling) have been used occasionally to redirect daylight and the results of using them in the exemplars (E08, 10, 17, 30, 31, 34, 39, 40, 61 and 65) shows they are worth taking into account by designers not only to redirect sunlight or daylight and improve light uniformity but also to provide shade on the view window. The study of group 3 indicates the popularity of usual shading devices such as overhangs, deep eaves etc. but in some exceptional cases such as case study 63 (E63) a solar screen wall is designed to provide both horizontal and vertical shade as well as a shaded walkway. And finally, low fenestration seems to be a feature of the sunny climate case studies. However, very few attempts have been made in these cases studies to design façades with high fenestration which take the most advantage of the natural light while preventing discomfort glare and overheating. For example, Exemplar 39 (Dish Fountain School in India) has a well designed façade which takes advantage of sunlight and admits it as diffuse light into classrooms via lightshelves, overhangs and careful fenestration.

Finally, it is worth mentioning the impact of ICT and new education methods on classroom daylighting. Chapter 3 addressed the beneficial effect of natural light on students' health and educational performance and it is evident that students do better in schools with daylight than artificial light. However, the advent of ICT and video projection facilities has its own requirements which sometimes are in contradiction with previous arguments about daylighting in schools. For example, in a visit to the Ballifield Primary school (E57) by the author, it was found that students spend most of their time in a fairly darkened space in the classroom to be able to see the video projection screening in a bright sunny day. In Venerable Bede School (E76) there is adequate daylighting but blinds are often closed at teachers' request, sometimes to use the interactive whiteboards or to prevent students from distraction (DfES 2006, p.44).

Of course, this does not mean that the use of video projection and room darkening should be avoided but it encourages creating thoughtful design of classrooms where such facilities could be placed in a designated darker corner of classrooms while students can still benefit from natural light. Exemplars no. 30 (Millbrook Elementary), 34 (Heritage Middle School) and 89 (MACE Architects school) are a few suggestions in how to incorporate such technology in a well daylit classroom.

Chapter 8 will summarize the findings and conclusions of previous chapters in order to develop guidelines of reflected daylighting in schools in the warm dry climate of Iran.

Chapter 8: Conclusions & daylighting design guidelines

8.1. Guidelines for daylighting design in schools

This section suggests a set of guidelines for daylighting design in schools in general. It is based on the literature review findings in Chapter 3, together with the empirical and analytical studies in the subsequent chapters. These guidelines consist of 3 elements: principles, practical solutions, and daylighting systems. Table 8.1 illustrates a summary of the basic daylighting principles in schools as well as some of the practical solutions in regard to the issues raised by the principles. Table 8.2 which was discussed in Chapter 3 (Tab 3.6) summarizes daylighting systems in schools in three categories: sidelighting including view window, clerestory and clerestory with lightshelf; toplighting including wall wash, central, patterned, linear toplighting and tubular skylights; and borrowed lighting. These systems are general guidelines for different ways of admitting daylight to school buildings and are not definite solutions to school daylighting.

For instance, table 8.2 suggests the use of high sidelighting or clerestories in classrooms in order to increase daylight penetration in all school spaces. On the other hand, clerestories can cause visual contrast between the high glazing and the dark wall under the glazing and hence cause discomfort glare. Therefore, a better design solution can be developed by combining the wall wash system with the clerestory. Figure 8.1 illustrates a stepped ceiling profile which integrates a wall wash solution with the clerestory. It can be used in multi-storey school buildings to overcome the problem with the dark lower wall of the clerestory. This is just one example of the flexibility of the system of daylighting classification, because daylighting systems can be combined to create unique solutions to their specific daylighting design problems.

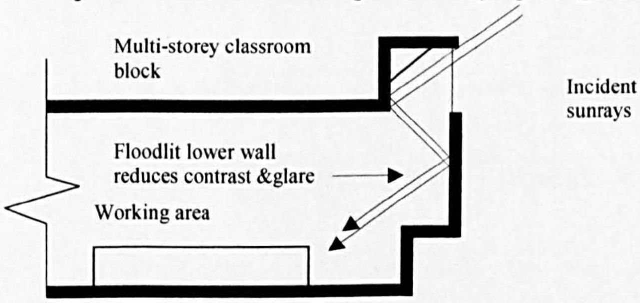
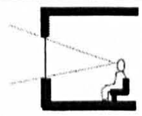
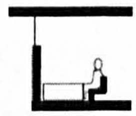
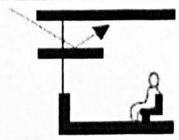
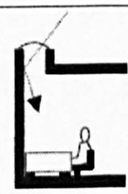
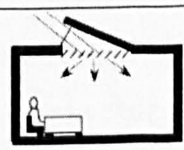
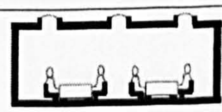
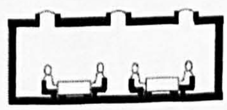
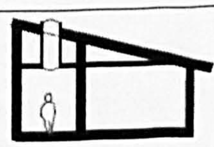
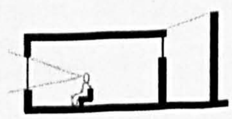


Fig 8.1. Stepped ceiling solution which incorporates wall wash with clerestory system

	Basic Daylighting Principles	Reasons & Practical Solutions
1	Avoid Glare	►Avoid glare to provide a balanced luminance distribution (some contrast but not excessive) ►Avoid excessive high contrast which causes glare ►Obscure bright views by blinds, louvers, etc. ►Reduce the contrast between the windows and their surroundings by using splayed light coloured reveals or a window in an adjacent wall ►Reduction of sky luminance by shading devices ►Place daylight apertures next to reflective surfaces ►Use splayed window reveals or skylight wells ►Avoid punched small windows in the middle of a wall ►Windows on chalkboard wall should be avoided
2	Provide Gentle, Uniform Illumination	►Balanced diffuse daylight across the space ►Use walls & ceiling as reflective surfaces ►Use light coloured surfaces to help reflection ►Use daylighting systems such as light shelves
3	Provide Control of Sunlight & Daylight	►To avoid visual & thermal discomfort except in non-task based areas ►Using shading devices to provide some protection from excessive direct heat and glare Solar control devices should be placed outside the window for optimum sun protection ►Devise variable apertures that respond to daylight changes or use blinds and shades inside or outside Provide teacher's access to blinds or shades controls
4	Daylight quality	►Offering a unique character to an interior ►Distribution of light enhances the visual field ►Directional properties of light from side windows are a significant attribute contributing to the modeling of the interior and providing brightness to vertical surfaces
5	Provide sufficient daylight quantity	►Use of rooflights and clerestories to improve distribution of light in the space
6	Integrate with Electric Lighting Design	►To create high quality lighting & produce energy savings
7	Plan the Layout of Interior Spaces	►Locate work areas where appropriate daylight exists from sides or above
8	Exterior visual contact	►To avoid claustrophobia and provide visual relaxation & view

Tab 8.1. A summary of principles of daylighting in schools & practical solutions

	Daylighting Systems	Description & applicability	Illustration
SIDELIGHTING	**1. View Windows**	Vertical glazing at eye level Essential in most school spaces Applicable in all climate regions	
	2. Clerestory (High Sidelighting)	To increase daylight penetration Can be used in all school spaces Applicable to all climate regions	
	3. Clerestory With light Shelf	To improve daylight distribution It keeps the contrast and glare low Applicable to most school spaces and all climate regions	
TOPLIGHTING	**4. Wall Wash Toplighting**	Daylight through a linear skylight or monitor to wash an interior wall To balance daylight from window walls Applicable to classrooms, libraries, etc. Applicable in all climate regions but must be planned in schematic design	
	5. Central Toplighting	To provide high levels of even daylight Daylight is diffused by glazing or baffles Applicable to single story or top floor classrooms, libraries, multipurpose spaces & administration offices Applicable in all climatic regions	
	6. Patterned Toplighting	To provide low glare even illumination across large spaces such as the gym, or Library, multipurpose or cafeteria Applicable in all climatic regions	
	7. Linear Toplighting	To provide high intensity daylight Suitable for walkways or large spaces Applicable in all but hot climate regions unless provide diffused or shaded light	
	8. Tubular Skylights (Sun-ducts)	Clear domes skylight with reflective ducts, Suitable with areas with deep roof cavities, Applicable to small spaces such as toilets, kitchen, etc. All climates	
	9. Borrowed Lighting	To illuminate the deep end of classrooms remote from window wall Applicable in spaces near an atrium and all climatic regions	

Tab 8.2. Daylighting systems in schools: a typological approach

As we have seen, this thesis recommends an integrative approach toward daylighting classification as explored in Chapter 4. The above classification of daylighting systems in schools as well as other classifications of daylighting components in general, which were explored in Chapter 4 (Tab 4.11, 4.12, and 4.13), can all be considered as a typological approach which aim to categorise the above systems or components into a more limited number of choices. As was discussed in Chapter 4, this typological approach can restrict the designers' imagination and creativity by encouraging them to choose from a table of ready made choices; but it does at least provide an easily understandable set of parameters and options, which when combined can give rise to unique and contextually appropriate solutions. However, this classificatory system does not address the experiential aspect of the lived space and, therefore, it might exclude the subtleties of experiencing daylight in an interior space.

This is where the phenomenological approach can respond to the above subtleties and address any deficiencies in the typological approach. This approach is not as straightforward as the typological approach, because it has less strict parameters and relies more on interpretation than the strict rule of measure. Therefore, the integrative approach, as proposed in Chapter 4, takes the typological approach as a basis for designers and the phenomenological approach as an evaluative method to assess and promote the experiential aspects of daylighting component typologies.

8.2. Guidelines of daylighting design in primary schools in the warm-dry Climate of Iran

Climatic considerations of daylighting and specific features of daylighting design in the warm-dry climate of Iran were explored in Chapter 2. Having addressed the vernacular architecture and the strategies evolved for daylighting in such a climate, it was seen that daylight is treated as a part of a whole design solution for the built environment, and cannot be fully assessed and understood except in relation to other architectural elements such as heating or ventilation, materials and configuration, and so on. Therefore, a holistic approach was suggested, as a lesson from the vernacular architecture of the region, which does not separate different elements of climatic design but studies their interconnected effects.

In terms of daylighting design guidelines, this research recommends reflected daylighting as an appropriate way of admitting sunlight in schools in the warm-dry climate of Iran. General and specific factors which have an influence on reflected daylighting of school buildings have been discussed in Chapter 5. In terms of general factors such as building configuration and orientation, the following guidelines can be considered in order to improve reflected daylighting of school buildings in the warm dry climate of Iran:

1. Ground reflected sunlight is an important source of illumination in the warm dry climates. The ground reflecting effect is more important in southern orientations since it provides the first set of reflection rays whereas the wall reflecting effect plays an important role in northern orientations. Therefore, in an Iranian urban context, where the school site is occupied by other multi-storey buildings and also where classrooms are usually placed at both sides of a corridor in a linear configuration, it is recommended that the classroom block be located at the north part of the site.
2. In a courtyard configuration school building, a wide courtyard profile or canyon proportion (P=0.5 to P=0.6) has a higher amount of reflected light (Ew/Es) in the south to the east orientation; while a deep canyon proportion (P=1 to P=1.5) has a higher amount of reflected light for the east to north orientation. This also means the classroom block can be multi-storey and located on the north wing of the site, while the south wing of the school can be shorter in order to increase the ground reflecting effect on the classroom façade. The north facing classrooms in the block will also receive sufficient reflected daylight from the surrounding multi-storey buildings because of the deep street profile.

In terms of specific factors influencing reflected daylighting, daylight apertures, shading devices, innovative daylighting systems and surface features have been discussed in Chapter 5 and the following guidelines can be suggested:

3. As far as reflected lighting is concerned, most daylight apertures need shading devices to control direct sunlight, except a few zenithal apertures which can be

found in table 5.3 (p. 145). Among shading devices, lightshelves, internal lightshelves, and overhangs are recommended on the basis of their performance in terms of conducting daylight at the back of the room, glare control as well as allowing view (see table 5.5, p. 149).

4. Innovative daylighting systems are recommended for reflected daylighting in schools in the warm dry climate of Iran. Core daylighting systems such as lightshelves, prismatic glazing and holographic systems are appropriate systems to redirect sunlight as well as daylight. Beam daylighting systems such as light pipes and mirrored systems are also possible solutions for reflected lighting in schools in such a climate. The applicability of the above systems in schools in the warm-dry climate of Iran is discussed in Chapter 5.

Chapter 6 examined a range of vernacular and historic schools in the warm dry climate of Iran in order to draw design principles and lessons for daylighting design. The following guidelines are suggested for environmental design of schools in general and daylighting in specific in the warm dry climate based on the observational study as well as ECOTECT simulations of the historic schools:

5. Courtyards are an appropriate building configuration in this climate. Tall deciduous trees and plants act as natural shading devices and climatic controls, and the use of water cools down the temperature and make the inner climate more pleasant and tolerable.
6. Porticoes are recommended for southern façade of schools in such a climate. They perform as shading devices as well as transitory spaces between classrooms and the courtyard, and could be used for small group discussion when in the shade. ECOTECT simulations highlight the significance of the portico as a shading device (a combination of horizontal and vertical shading surfaces) not only in terms of sun protection but also for daylight distribution. The light coloured surfaces of the porticoes also help reflect the light inside the room. These porticoes are not specific to the historic schools, but are an important generic element in the vernacular architecture of this climate.

7. High windows or clerestories in porticoes conduct light to the back of classrooms and they are also protected from direct exposure to sunlight by porticoes. At some positions in which clerestories are exposed to direct sunlight due to the low angle of the sun, latticed screens filter the light and also reduce glare. ECOTECT simulations verify the importance of clerestory in conducting light deeply in the room as well as creating a more even distribution of light which is more appropriate for a learning environment.
8. The tall height of the Hojras (average 4 meters) is a common feature which allows the light bounce off the surfaces and provides an even distribution of light as well as better air circulation inside the room. ECOTECT results concluded that the tall height of Hojra improves daylighting performance of the room in terms of quantity as well as quality (uniform distribution of light in the room).
9. The geometry of the ceiling has a considerable effect on the reflected lighting. Alterations to ECOTECT models show that a sloped ceiling lowering toward the façade improves both the average daylight factor and the internal reflected light compared to a flat ceiling or a sloped ceiling lowering toward the back of the classroom.

Chapter 7 explores the empirical evidence for the aforementioned general and specific features which can influence reflected daylighting of schools. Specific features are classified in 3 groups based on the findings of previous chapters: deep penetration and even distribution features, daylight redirection systems, and shading devices. A variety of exemplar contemporary school buildings have been studied in order to identify the application of the above groups of features as well as the frequency of their usage. The following guidelines are based on the observational study of the exemplar schools.

10. Clerestories and high windows as well as Rooflight and roof monitors are the most popular daylighting solutions to admit daylight deeply in classrooms and improve the uniformity of daylight.
11. Lightshelves and room geometry (sloped/curved ceiling) have been used occasionally to redirect daylight and the results of using them in the exemplars show that they are worth taking into account by designers not only to redirect

sunlight or daylight and improve light uniformity, but also to provide shade on the view window. Most of lightshelves used in the exemplars are located in sunny climates.

12. The study of the shading devices group indicates the popularity of usual shading devices such as overhangs, deep eaves etc. but in some exceptional cases such as case study 63 (E63) a solar screen wall is designed to provide both horizontal and vertical shade and well as a shaded walkway.
13. Low fenestration seems to be a feature of the sunny climate case studies. However, very few attempts have been made in the exemplar cases studies to design façades with high fenestration which take the most advantage of the natural light while preventing discomfort glare and overheating. Exemplar 39 (Dish Fountain School in India) is a good example of a well designed façade which takes advantage of sunlight and admits it as diffuse light into classrooms via lightshelves, overhangs and careful fenestration.

8.3. Limitations of the thesis and suggestions for future research

The focus of this thesis and the limited time of PhD research necessarily restrict the scope of the results. The choice of the climate was the first limitation as the research question was narrowed down to the warm-dry climate of Iran and its daylighting design issues. Therefore, parts of the results of this thesis associated with climate do not apply to all Iranian schools. As discussed in Chapter 2, Iran has a varied climate and new research need to be undertaken to address the specific issues of daylighting design in other Iranian climatic zones.

This research has proposed some daylighting design guidelines for school designers in the warm-dry climate of Iran. However, in terms of the practical outcome of the research, further work needs to be done to compile the findings of the thesis chapters into a design manual which can be of assistance to school designers. This manual can be complied digitally and can also include a wider range of database to assist designers. This will possibly be done in a further stage by the author.

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