FABRIC MEMBRANES AS DAYLIGHTING CONTROL SYSTEMS IN BUILDINGS

by

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ABSTRACT

The latter half of the 20th century saw the development of lightweight tensioned translucent membranes as shading devices and their increasing use in providing daylight and daylight control. Buildings with high lighting consumption and long operation hours in particular are including translucent membranes in their daylighting strategies. For this reason, the use of reliable tools for the prediction of the lighting environment experienced in daylit spaces, which exploit translucent membranes, has become essential.

To date most analytic efforts related to predicting daylighting performance has concentrated on the analysis of light penetration through glass openings. Little attention has been paid to the light transmission through fabric membranes. The membranes itself are normally in tensioned creating double curvature shapes. The simulation of light transmitted through membranes involves the modelling of complex geometries, which places significant demand to their modelling.

This thesis explores the daylighting performance of sports buildings that include translucent membranes as part of their daylighting strategy. Performance of these buildings has been assessed by field illuminance measurements, physical scale modelling in artificial sky and three-dimensional modelling using Radiance software. The accuracy of the simulation tools is assessed against the lighting data recorded in the field study.

Findings show that physical scale models tend to overestimate the illuminance levels and daylight factors of the sports halls. On the other hand, Radiance simulations proved to be accurate in terms of daylight factors and illuminance distribution in the playing areas.

Finally, a questionnaire has been distributed among occupants of the three case study buildings and one totally artificially illuminated sports centre. The purpose of this survey is to evaluate the users' satisfaction towards the lighting environment of the enclosures.

The ability to accurately predict the daylighting performance in membrane sports buildings is significant for the development of research in daylighting and sustainable architecture. In addition, the further use of translucent membranes for the control of natural light in all type of buildings relies on the possibility to confidently predict their daylighting performance.

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CONTENTS

One

1. INTRODUCTION

1.1 LIGHTWEIGHT STRUCTURES

The present project involves the study of fabric or membrane structures used in Sports Halls to control daylight penetration and quality. Fabric membranes are lightweight structures designed and built with two-dimensional tension resistant fabric. They are doubly curved saddle surfaces originally developed from soap bubble models[1]. Different kinds of textiles are stretched with cables on supporting structures that absorb the compression forces.

During the last three decades designers and engineers have concentrated all their efforts on the development of membrane material and structural systems that allow the construction of structures with longer span, more durability, less cost and minimum material. Nonetheless, the environmental performance of tensile membrane structures have been hardly studied, probably the main cause is the complexity of these structures and the wide range of possibilities their offer regarding geometric shapes, materials, colours, translucency, durability, etc. The correct understanding of their environmental properties, especially their optical properties, and the ability to predict their environmental behaviour would allow the designer to create more impressive, functional, energy efficient and sustainable membrane buildings.

The constant population growth in the planet is causing an unacceptable pressure on the environment, people need more food, more water, more transport facilities, more schools, more employment. Since our natural resources are not infinite, we must make some changes regarding our present life style in order to preserve our planet for future generations. Now, we face the challenge of combining economic growth with reducing the impact on the environment, nature and space[2].

1.2 THE NEED FOR SUSTAINABLE ARCHITECTURE

During the last decades, architects, engineers and designers have shown concern about the impact of the built environment on the natural environment; as a result, interest in the application of passive and active solar energy systems in buildings has increased leading to potential reductions in the use of fossil fuels as energy sources. Therefore, the concept of 'green' or 'sustainable' architecture has become widely acceptable among the building industry all over the world.

According to different authors[3] sustainability issues incorporate every level of decision-making affecting social, economic and environmental aspects of human life. Although there have been many definitions for the term 'sustainability', there is one used by the Brundtland Commission on Sustainable Development (1987) which is broadly accepted: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[4].

In order to save energy some building researchers have developed the idea of using minimum energy structures in our daily life and with many possibilities of being recycled. Their work is focused on lightweight structures and fibre-reinforced materials with the main aim to save energy thus reducing the impact on the environment[5]. However, for the appropriate performance of lightweight structures it is necessary to design them for a specific climate and a suitable activity. This involves the investigation of different topics such as materials technology, energy conservation, building geometry, orientation and design.

1.3 ORIGINS OF FABRIC ARCHITECTURE

Tents have existed since antiquity as transportable shelters mainly built with animal skins or woven fabric pulled over a stiff framework; some examples are the North American Indian tepee, the Mongolian yurt and the Bedouin tent[6]. In Roman times, tents were used in amphitheatres to provide shade to spectators.

Rice[7] has defined lightweight structures as a group of surface structures made from fabrics or tension or compression nets, which are the lightest structural materials capable of spanning in two directions. The efficient use of materials is one of the most important aspects of designing lightweight structures; which involves making them do what they do best. The construction system is also important, according to Beukers and Van Hinte[8] the best one-dimensional way of tension transfer is through short fibres twined together in threads, ropes and cables. Light materials can be used in tension structures; therefore the emphasis in light construction is on tension forces.

One of the first architects working with lightweight structures was the American Buckminster Fuller, who introduced new concepts to the architectural vocabulary such as: tensegrity (continuous tension compensated with discontinuous compression), developed with Kenneth Snelson; and dymaxion (maximum benefit with minimum energy)[9].

Rice[10] has classified lightweight structures into five main types:

1. Tents and prestressed cable networks
2. Air supported structures
3. Pneumatic structures
4. Grid shells
5. Heavyweight cable roofs

Until the end of the 18th century, there was little development of the tent due to the limitations of woven fabric, including limited tensile strength and problems of making joints capable of transmitting significant force. The popularisation of the circus as a major form of entertainment during the 19th century contributed to the evolution of large tents. Despite these mobile structures being geometrically simple, considerable knowledge of cutting patterns, joints and craft skills were developed. One of the most important companies of tentmakers was The Stromeyer Co., established in 1872 in Germany[11].

Many engineers and architects have developed the field of membrane and cable structures since 1950. The most important is Frei Otto from Stuttgart, Germany. Otto has studied similar structures available in nature and has developed form-finding techniques of membrane structures[12]. Since then, research has been carried out into the structural behaviour of tensile membrane enclosures, the improvement of tear resistance for a given tensile strength, extension of life durability and resistance against dust and UV radiation. Several fabrics and coating materials are now available in the market, each of them responding to specific design requirements.

1.4 THE INTERNAL ENVIRONMENT OF FABRIC ENCLOSURES

Until recently, designers have paid little attention to the environment inside membrane enclosures. Probably due to the temporary nature of these structures and the type of activities they shelter, research in this area has been limited. Research focused on thermal control and the performance of cooling techniques of a 8000 m^2 theatre and refreshment areas called 'Palenque' was developed by the University of Seville. The outdoor area is covered by a white PVC membrane cone-shaped structure, designed for the Seville Expo (1992) [13].

Furthermore, Harvie[14] in Cardiff University and Devulder[15] at the University of Nottingham have studied thermal aspects of membrane materials and membrane enclosures. However, little attention has been paid to the effect that optical characteristics of tensile membrane enclosures have on the lighting environment of daylit spaces. Usually fabric manufacturers provide lab based values for light transmission, reflectance and absorption, which are used as design parameters but have not been studied in their application to buildings with real occupants and specific weather conditions. The importance of knowing the environmental properties of fabric structures lies in the degree of comfort that should be reached according to the type of activities that are carried out in the building. In addition, an understanding of the thermal, optical, acoustic and wind response of membrane structures may potentially represent a contribution to the reduction of the energy consumption of the building.

The translucency of membrane materials is very significant. The penetration of daylight through a lightweight membrane roof can potentially result in a reduction of artificial lighting required. Fabric membranes can also be used to provide shading to avoid overheating; furthermore it is possible to take advantage of the membrane's reflectance characteristic to reflect solar radiation into the sky or to reflect it in some way beneficial to the building's occupants.

1.5 THESIS STRUCTURE

This project aims to assess different techniques to best simulate and predict the lighting performance of buildings, which have included fabric membranes to control daylight access. This research intends to provide design guidance for designers of membrane enclosures and buildings with high lighting requirements, regarding the best method to follow when using either scale modelling or computer modelling in order to obtain accurate results. For this purpose, **it would be necessary to evaluate the lighting performance of three daylit sports buildings selected as case studies**. The influence of different factors on their lighting environment is explored; these factors are, for instance, membrane materials, building geometry, building function and site characteristics. The general method to carry out this work is a comparison of field lighting measurements vs. results from scale and computer modelling of the three buildings.

Contemporary applications of fabric membranes include museums, art centres, airports, shopping centres, stadia, sports facilities, etc. Michael Hopkins and Partners have designed several fabric buildings with different functions, some of these are: The Schlumberger Cambridge Research Centre (1985), Lord's Cricket Ground Mound Stand in London (1987), The Dynamic Earth in Edinburgh (1990-1999) and the Saga Group Headquarters (1996-1998). Other fabric buildings are the Wimbledon

Practice Facility designed by Horst Berger and Partners and Ian King Architects (1988), the Millennium Dome in Greenwich by Richard Rogers Partnership (1999) and the Ashford Designer Outlet Village in Kent (1996-2000) also designed by Richard Rogers Partnership and Buro Happold.

Other applications of fabric membranes include their use to provide shading as in The Palenque at Seville Expo 1992; or to simulate different climates as in The Eden Project by Nicholas Grimshaw and Partners (2001); or to internally reflect light like in the Carmelo Pomodoro Offices and Showroom in New York designed by Todd Dalland (1992).

Fig. 1-1 'Palenque' structure at Seville Expo 1992 (photo: Rodriguez, G.)

Fig. 1-2 'The Eden Project', Cornwall, United Kingdom

Fig. 1-3 Carmelo Pomodoro offices and showroom, New York

Due to the extensive nature of this subject it was decided to concentrate this investigation on lighting aspects of membrane enclosures. Light levels and quality determine, among other factors, the environmental performance of buildings and the comfort of building occupants. People generally prefer to work and live in a well daylit space, with outside views. Natural light and a sense of time and exterior weather conditions through openings affect users satisfaction and work productivity. Due to the small thickness and translucency of membranes, large amounts of daylight can access the interior environment of a membrane enclosure creating bright spaces even under cloudy sky conditions.

One of the most common contemporary applications of membrane structures are sports buildings. Fabrics can cover long-span areas with no intermediate supports, can be used as temporarily or permanent structures, can be designed as deployable structures to be used only when needed, and allow to play during the whole year sports that are traditionally performed outdoors. This project studies the lighting performance of sports halls that have incorporated fabrics in their design to control daylight access. The selection of this type of building is based on different assumptions:

1. Lighting design is very important for appropriate performance of sports buildings, taking into consideration the fact that players, officials and spectators need to easily follow the action.
2. The speed of action demands high and specific lighting levels, avoiding discomfort glare and continuous eye adaptation when changing lighting levels are present.
3. The use of daylight within a sports area, if properly designed, could have positive effects on people’s mood.
4. Daylight availability reduces the use of artificial lighting providing energy savings in the building.
5. Sports halls are usually designed with attractive shapes to create a visual impact on people. Fabric membranes allow us to cover large

span buildings without intermediate supports, which is often a requirement in sports halls.

The research questions to be answered with this investigation include the following:

- Which design variables are relevant for the daylighting performance of buildings?
- How membrane's light transmittance influences the daylight availability and illuminance distribution inside the building?
- What are the advantages/disadvantages of physical and computer based modelling tools for daylighting studies of fabric buildings?
- How reliable are current performance simulation methods?
- How do occupants respond to the use of membranes and daylight in sports buildings?
- What are the environmental benefits of designing daylit sports halls using membranes to control daylight access?

The thesis begins in chapter 2 with background information regarding fabric structures and their use, including their architectural applications. In addition, the material's physical and environmental properties are discussed; together with the existing knowledge of the lighting behaviour of fabric enclosures.

The methodology of this project is described in chapter 3, including the purpose and selection of the buildings selected as case studies. The methods adopted for the on-site daylighting evaluation and the user's survey are also explained. Furthermore, an architectural description of the case studies is also incorporated in this chapter.

In order to understand the importance of lighting in the design of sports halls, chapter 4 offers an analysis of the lighting requirements for specific sports. A daylighting assessment of three case study buildings is examined.

Chapter 5 includes the comparison between the results of the field studies of the selected buildings and a physical modelling lighting analysis of the same case studies.

Chapter 6 discusses the accuracy of a lighting computer simulation software: Radiance[16]. This ray-tracing software was used in this project through the environment of Ecotect[17] to simulate the daylighting behaviour of the case studies mentioned earlier. A description of the software, its capabilities and limitations are examined in this chapter; together with the results obtained in the simulations and their comparison against the results of the previous chapter.

A comparative analysis between the accuracy of results obtained from the physical modelling analysis and the computer modelling results against the field measurements is presented in chapter 7. Advantages and disadvantages of both simulations are pointed out together with improvements to the adopted methodology for the better use of these daylighting prediction methods.

This project also intends to qualitatively evaluate the lighting performance of four sports halls located in England. Three of them are daylit buildings (previously mentioned as case studies) and the fourth one is a completely enclosed artificially lit building. A questionnaire was designed and distributed among occupants of the case study buildings and the responses were analysed with SPSS statistical software. This analysis and the results obtained are discussed in chapter 8.

Chapter 9 reviews the work reported in the other chapters and assesses the different techniques available to predict daylighting performance of buildings with fabric membrane roofs. In addition, the importance of carrying out a post occupancy evaluation study is examined here. Further work is suggested regarding the many possibilities of using fabric membranes to control daylight penetration, including their use in other climates. Chapter 9 includes the extent and conclusions of the thesis.

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1.6.1 Figures

1-1 'Palenque' structure at Seville Expo, 1992, photo: Rodriguez, G. Available at http://protos.dis.ulpgc.es/~gustavo/viajes/fotogif/epo92/expo92/expo25.htm (last accessed: 22.01.06)

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Two

2. SUBJECT BACKGROUND

"…we will make a contribution to sustainability by focusing on lightness, elegance and use of minimal means." [1]

2.1 FABRIC STRUCTURES

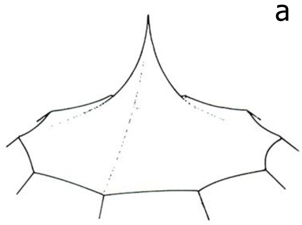
Lightweight structures are a group of structures usually defined by two main characteristics: their surface covering material is very *light* and *flexible*. The lightness produced by the tension applied to fabric structures minimising the amount of material used, is probably the main reason of their acceptance among designers and users. However, fabric structures are extremely limited due to their thermal transmission characteristics.

Tensile membrane structures (TMS) or tension roofs have been defined by Vandenberg[2] as: *"…those in which every part of the structure is loaded only in tension, with no requirement to resist compression or bending forces."*

According to Vandenberg[3] there are three basic types of tension roof:

- **Fabric roofs or canopies** (Figures 2-1a & b). These are thin, flexible membranes that are designed to support loads under tension. They can act simultaneously as structure and as protection against solar radiation, rain, etc.

a



b

Fig. 2-1a & b Tent structure and Carlos Moseley Music Pavilion, New York. FTL Happold.

- **Cable net roofs** (Figure 2-2a & b). In this case a structural net is held in tension, and carries a non-structural layer of weather-shielding elements such as acrylic glass sheets, wooden shingles, and so on.

a

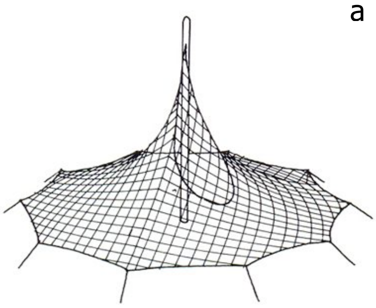
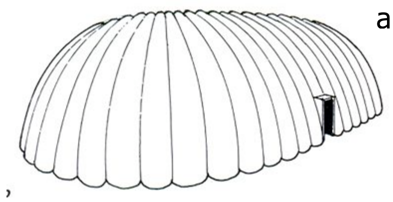


Fig. 2-2a & b Cable net structure and Munich Olympic Stadium, Frei Otto.

- **Pneumatic roofs**. In this type of structure a single membrane is held raised by air pressure or two membrane layers with air pressure inside form a inflated structure (i.e. tubes or ETFE cushions) (Figures 2-3a&b, 2-4).

a



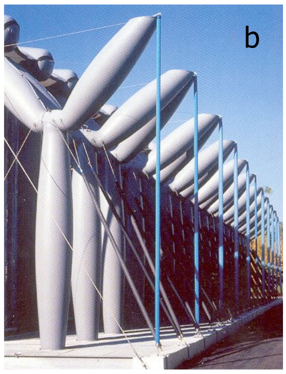


Fig. 2-3a & b Pneumatic structure and Pneumatic Hall, Esslingen-Berkheim, Germany, Festo.

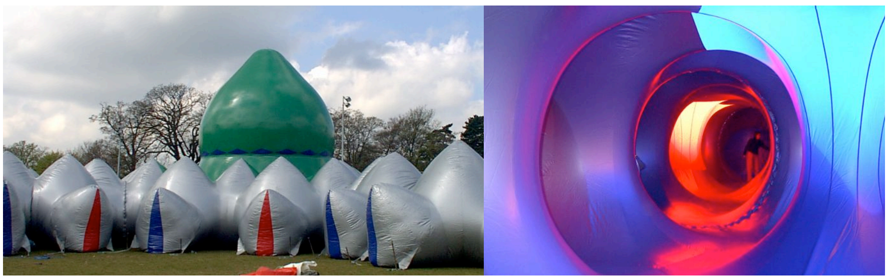


Fig. 2-4 Exterior and interior views of an air-supported structure by Architects of Air, Nottingham, 2002

Advantages of TMS

The advantages that TMS offer have been explained by Schock[4]:

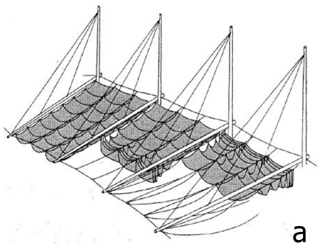
- Short construction period and erection
- They are large span structures which are able to form large column free spaces
- Their relative low cost especially when used for large buildings
- Attractive exterior form
- They can be used in both hot and cold climates, allowing the use of daylight, natural ventilation and solar protection due to the high reflectivity of the materials used.
- Good earthquake resistance and easy transportation through their small mass.

Despite the importance that membrane structures have achieved in the building industry, knowledge of their environmental performance is less well understood than that of more "traditional" construction.

Membranes are generally made of fabric, which is made from warp and weft yarns. The use of fabric for building purposes has increased due to its improved durability, water resistance, fire and dirt resistance; these characteristics have been achieved through coating the fabric[5].

2.2 HISTORY OF ARCHITECTURAL FABRIC STRUCTURES

For many centuries fabric or membrane structures have protected people from the weather, through the provision of traditional awnings and tents. According to Vandenberg[6], awnings of substantial size and sophistication were built at least two thousand years ago, when Roman theatres and amphitheatres were fitted with retractable shade structures made of linen fabric. More recently woven awnings known as "toldos" have been used to provide shade over the streets and houses of Spain and other places with a hot climate.


a

b

c

Fig. 2-5a Detail of a Roman shade structure (by Rainer, Horst, B. p. 23)
Fig. 2-5b 'Pallum' toldo by Parasol®
Fig. 2-5c Retractable horizontal toldo, by AntisolarsCasc

In nomadic societies where portable and light shelters were needed, tents made of animal skins or woven materials were used. Some examples include the Native American tepee, the yurts used by the Turks, Tatars and Mongolians, and the Black Tent used by desert nomads of the Sahara, Arabia and Iran (Fig. 2-6a&b). The oldest example of a tent has been found in Moldova, Russia, and has been dated at approximately 40,000 B.C. These shelters were built with animal skins suspended from poles made of large bones. As stated by Berger[7], the Arabs, through the development of the black tents, showed the most advanced tensile technology of the pre-industrial age, which consists of a woven fabric cover that is draped over ropes supported by masts located in the centre and along the edges. Ropes transfer the loads from the fabric to the stakes placed on the ground; these stakes hold the structure down and outward.

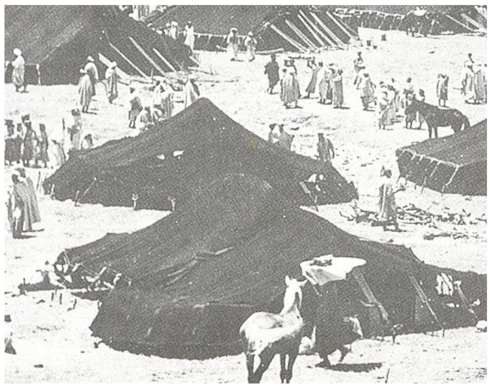

a

b

Fig. 2-6a North American Indian Tepee and **2-6b** Black tents in the Sahara desert.

The traditional tepee is probably the first tent structure with environmental considerations in its design and erection. These structures could adapt to various weather conditions. Tepees could be closed or opened; the cone-shape skin is always set at a steeper angle to the rear for wind resistance and the top flaps could be adjusted to control air flow. Double layer skins can have insulation in between, and a fence placed surrounding the tepee provides protection in the winter[8] (Figure 2-7). These environmental control strategies are currently used in buildings aiming at adapting the interior environment to the different climatic conditions throughout a year. Passive control systems using daylight, natural ventilation, the thermal properties of earth or water are nowadays widely used in the design of the built environment.

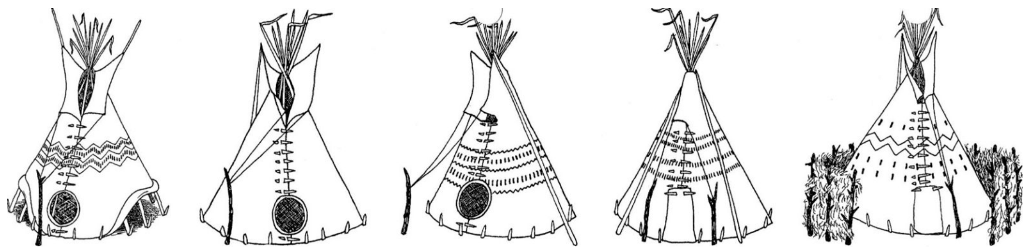


Fig. 2-7 Environmental control in a tepee(8)

After the industrial revolution the demand for large tents and the availability of stronger materials increased[9]. The use of membranes as temporary structures remains important for different purposes, such as: mass entertainment in circuses, to provide shelter for the armies all over the world, for religious and social events and for shading structures. This is due to the lightweight and quick erection of these structures, which also allow covering large areas with no intermediate supports.

2.2.1 Innovations during the Twentieth Century

After the Second World War the development of more light and flexible fabric materials, allowed the design and construction of more stable pre-stressed membrane structures.

Vandenberg[10] has recognised two prime innovators of modern tensile membrane structures; the architect and engineer Frei Otto who in 1957 founded the Centre for the Development of Light-weight Construction in Berlin, followed in 1964 by his Institute for Lightweight Structures at Stuttgart University; and Peter Stromeyer, whose family firm has been one of Europe's most important manufacturers of large tents since 1872. According to Berger[11], Frei Otto clearly understood the indispensable principles of fabric architecture:

- The structural and architectural forms are inseparable
- Flexibility is strength not weakness
- The surface material must be more flexible than the supporting elements

At the beginning of his experimenting work with lightweight structures, Otto made and tested scale models with materials such as soap bubbles, nets and elastic membranes. One of his earliest realised projects was the music pavilion at the Federal Garden Exhibition at Kassel, Germany, in 1955 (Fig. 2-8). Although Otto's first large built project, the German Pavilion at the World's Fair in Montreal, Canada in 1967 (Fig. 2-9), had some technical problems, his later designed structures opened a new era of architectural technology and beautiful solutions for large span enclosures, small canopies and for temporary and permanent buildings.

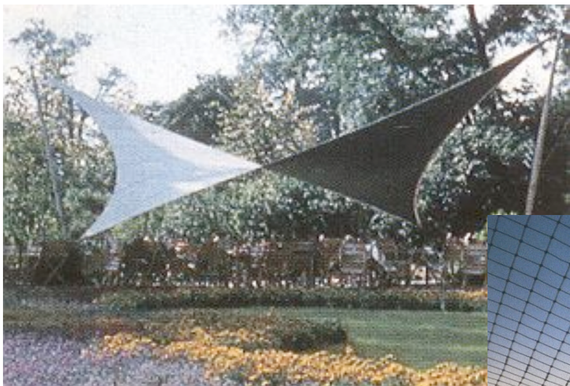


Fig. 2-8 Music Pavilion at the Federal Garden Exhibition in Kassel in 1955

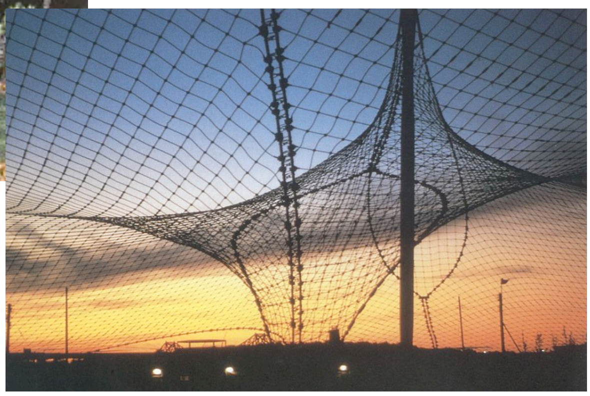


Fig. 2-9 German Pavilion in Montreal, 1967

In 1966, Otto's team together with the architect Rolf Gutbrod won two major design competitions. One project was the German Federal Pavilion for Expo'67 in Montreal, using a free form cable net supported by masts and clad with translucent PVC coated terylene. The second project was the Conference Centre for Mecca in Saudi Arabia, where a more complicated cable structure was developed including a highly insulated cladding to cover the air conditioned spaces and a structure for shading protection to cover the open spaces[12].

As a result of the design of several projects such as canopies for garden shows, trade shows and national exhibitions, Otto developed a series of new and improved ideas about shape, erection techniques, stressing method, materials and jointing. One of his most important projects is the roof of the Munich Olympic Stadium, which was built for the 1972 Olympic Games (Fig.2-10). This project is a catenary hung from flying masts suspended by cables that run from the tall masts against the whole catenary. The tall masts create high points enhancing the vaulted forms of the membrane[13].

Fig. 2-10 Munich Olympic Stadium, 1972

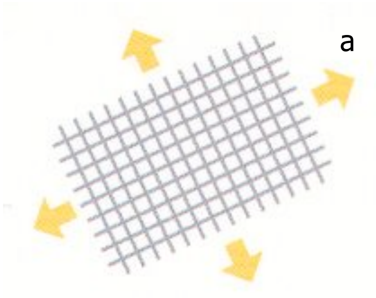
New design possibilities of tensile membrane structures have been developed as a result of technological research carried out in several areas, particularly in the fabric technology field. Today there is a broad range of materials from which membranes are made. Some of these materials are textiles made of natural or synthetic fibres. Nowadays, PVC coated polyester, polytetrafluorethylen (PTFE) coated glass fibre and ETFE fabric (ethylen-tetrafluorethylen) are the most common fabrics used for membranes[14].

2.2.2 Structural concepts and geometry

Modern fabric tensile structures began in Germany with Frei Otto. He developed tensile structures where lightweight and minimal materials were the most important principles.

The second half of the twentieth century represented a big step towards the development of tensile membrane structures as both temporary and permanent structures. Temporary structures have been built with similar applications as in the past, for shading purposes, entry canopies, fair and exhibition enclosures, garden festivals, etc. Moreover, permanent tensile membrane buildings have become widely accepted and structures with applications such as sport stadiums, airport terminals, shopping centres, office buildings and laboratories have been successfully built. These examples suggest, according to Berger[15], a much broader range of the TMS applications. In addition, the same author suggests a number of industrial applications that can be met with fabric enclosures, such as grain storage facilities and cooling towers.

The structural stability of TMS is based on two fundamental concepts: pre-stress and curvature. The components of a tensile structure need to be arranged in a specific geometric form while being subjected to a specific pre-stress pattern. According to Berger[16] once the support points and pre-stress pattern are selected, there will be only one surface shape under which the structure is in equilibrium. This configuration is calculated in a mathematical process called form finding, which can be developed through physical modelling or computer calculation. The pre-stressing forces and forces from loads in membrane structures are carried in both directions of weave, in warp and weft (Fig. 2-11).



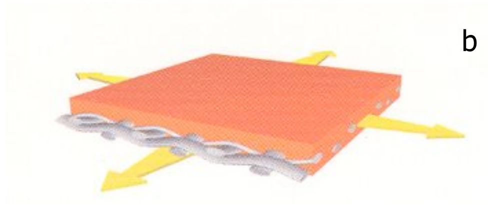


Fig. 2-11a & b Tension applied to Ferrari Précontraint textiles.

Depending on the type of pre-stress, the Gaussian curvature of the membrane surface can be positive (synclastic) or negative (anticlastic) (Figure 2-12). Synclastic membrane shapes have the centres of the radii of the principal curvatures on the same side of the surface. The tensile forces of the membrane are in equilibrium with the inside pressure, creating spherical or cylindrical shapes. This type includes air supported structures and inflatable. In the case of anticlastic shapes the centres of the radii of the principal curvatures lie on different sides of the surface.

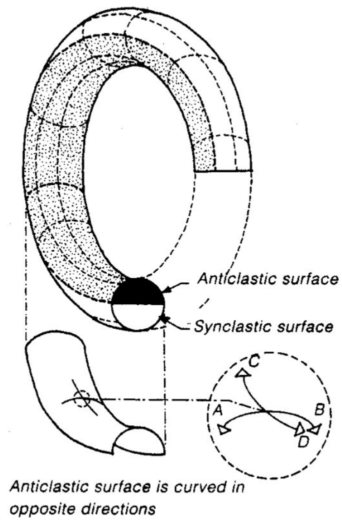
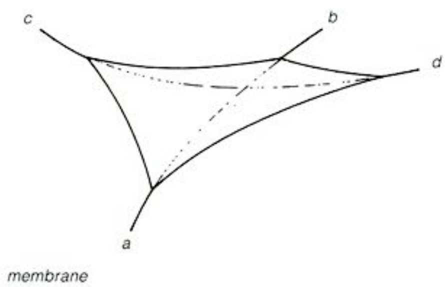


Fig. 2-12 Anticlastic and synclastic surfaces. Below: saddle membrane.



The most basic anticlastic structure is the saddle shaped sail stressed between four points, one of which lays outside the plane of the other three.

It is important to reach an equilibrium stage between the tension forces: pre-stress and load forces. In this case it is necessary to pre-stress the membrane[17]. Vandenberg[18] has stated that there are two basic ways of creating pre-stress:

- Laterally expanding the base;
- Pulling up or pushing up the apex.

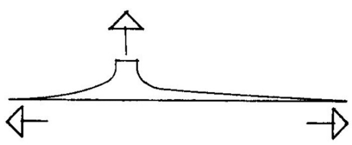


Fig. 2-13 Methods of creating pre-stress.

Pre-stress could be also induced by a combination of the two methods. In order to select the best way in a particular case, some elements have to be taken into consideration: membrane shape, fabric material and external loads.

The European Design Guide for Tensile Surface Structures[19] gives a classification of tensile membrane constructions according to the main function of the membrane construction.

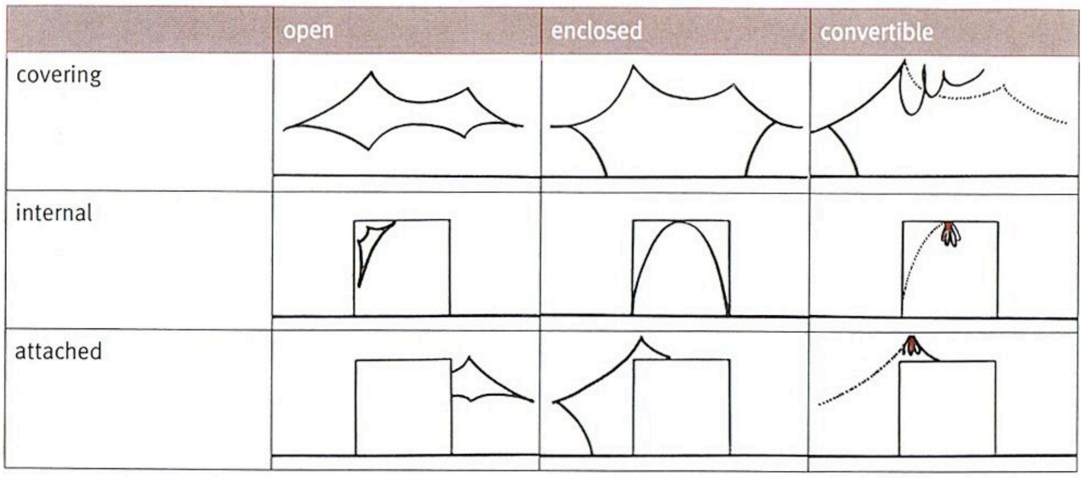


Fig. 2-14 Classification of tensile membrane constructions

2.3 FABRIC MEMBRANE MATERIALS

Technological improvements in materials used to create TMS, has been one of the factors that have determined the development of this type of structure. There is a close relationship between the design principles of tensile membrane structures and the material properties of coated fabrics. These materials have different uses according to their characteristics and cost.

The development of plastics technology has led to increasing numbers of innovative membrane projects, where materials with great strength allow the construction of large-span, translucent and light structures without the support of intermediate columns[20]. Some companies (Architen Landrell, Ferrari, Skyspan Ltd., Kayospruce Ltd., Birdair, Koch Membranen, Mehler Haku, and Dupont) have developed new fabric materials and coating products. Dupont, for instance, utilised the high strength of glass-fibre and extended its life by coating it with Teflon. In addition, a higher translucency and reflectivity were achieved, an extremely stiff fabric and virtually dirt free due to the anti-dielectric characteristic of Teflon[21].

2.3.1 Types of membranes used in architecture

Moritz[22] has divided the products used for membranes into two main groups: anisotropic materials and those that approximate an isotropic state. Anisotropic membranes are usually in the form of "technical textiles" of various kinds; the second type is generally thin thermoplastic foils or metallic sheeting. These materials may be divided into three types according to the nature of their manufacture:

1. knitted
2. woven
3. non-woven

Woven fabrics have an orthogonal thread structure where each of the threads consists of several individual fibres. The fibres may be natural, mineral, metallic or synthetic. Surface coatings and seals can affect the tearing strength and the buckling resistance of the fabric. According to Moritz[23], coatings protect the base fabric against UV radiation, moisture, fire, and fungal attack; they also contribute to the life extension of the fabric and allow the colouration of the membrane through surface printing or through the addition of pigments. Nowadays, the most common coatings are polyvinyl chloride (PVC), polytetrafluoroethylene (PTFE) and silicone; the last two materials present no significant signs of ageing over a period of 25 to 30 years, while PVC is sensitive to weathering. Other coatings materials rarely used include THV (a fluoropolymer sheeting), PVF (Polyvinyl fluoride), acrylic esters, polyurethane and rubber.

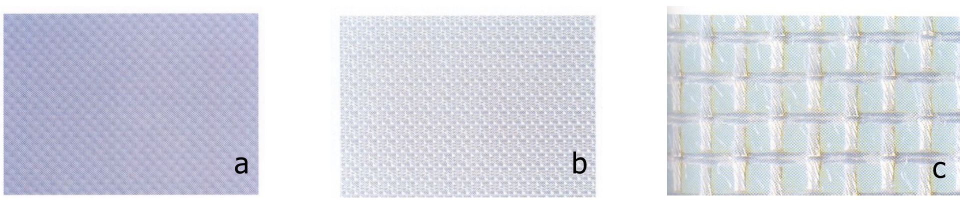


Fig. 2-15a PVC coated polyester; **2-15b** Silicone-glass fibre; **2-15c** PTFE glass.

Moreover, Moritz[24] has determined a series of characteristics that have to be taken into consideration when developing new membrane materials, some of these are:

1. Recycling properties of the membrane
2. Fire protection
3. Light transmission, reflection and absorption
4. Thermal and acoustic properties
5. Mechanical properties
6. Appropriate jointing techniques
7. Weight per unit area
8. Manufacturing dimensions
9. Surface texture and coloration possibilities
10. Resistance to soiling
11. Permeability to vapour and moisture
12. Resistance to chemical and biological substances
13. Resistance to vandalism
14. Availability in case of large scale projects
15. Economic viability
16. Environmental impact

A table with the general properties of membrane materials commonly used in fabric architecture was published in the European Design Guide for Tensile Surface Structures[25], and it has been included here as a reference to currently available fabric membranes (Table 2-1).

Table 2-1 General comparative properties of materials for tensile membrane.

	PVC coated polyester fabrics	**PTFE coated glass fabrics**	**Silicone coated-glass fabrics**	**PTFE coated PTFE fabrics**
Tensile strength warp/weft (kN/m)	115/102	124/100	107/105	84/80
Fabric weight (g/m²)	1200 (type 3)	1200 (type G5)	1100	830
Trapezoidal tear warp/weft (N)	800/950	400/400	960/700	925/925
Visible light transmission (%)	10-15	10-20	< 80	19-38
Flexibility/crease recovery	High	Low	High	High
Fire reaction	M2 (NFP 92 503) B1 (DIN 4102)	M1 (NFP 92 503) B1/A2 (DIN 4102)	A (ASTM E-108) no toxicity of smokes	
Cleaning	Easier with top coats	Self cleaning	Self cleaning	Self cleaning
How to make the seams	By high frequency	thermally	vulcanisation	Stitching
Life span (years)	> 15-20	> 25	> 25	
Cost	low	high	high	

Finally, Moritz[26] assumes that membrane construction will advance as a construction system with the development of multilayer fabric systems in combination with other technologies such as installations that exploit solar energy and other thermal insulation systems. Although there is a wide range of coated materials available on the market, designers and manufacturers are seeking to develop lighter, more durable, more resistant and translucent fabric materials. However, there is still some concern regarding the environmental impact caused by the manufacturing process of architectural membranes. Although membrane materials can be recycled reducing their environmental impact, environmentalists are still concerned about the environmental damage caused during the manufacturing process of materials such as PVC.

Recently, some papers regarding the relationship between PVC and sustainability have been published[27,28], stating that it is possible to chemically recycle PVC products, especially when a large piece of a single type of material is found. This can be done taking advantage of its durability, producing long life products. The researchers have pointed out that for keeping recycling plants working it is essential that a market for reused PVC exists. However, none of the literature revised has studied the actual impact of generating plastics.

2.3.2 Environmental properties of fabric architecture

Little research has been carried out regarding the environmental properties of fabric materials and spaces enclosed by membrane structures. Their complex geometry and the small thickness of the fabric material have made difficult the understanding and proper study of the environmental behaviour of these structures.

Bedouin tents were designed to meet the physical requirements of their environment. According to Forster[29] the side walls of the tents present a simple technique that allows their adjustment or removal according to the need for shade, ventilation or warmth; these walls are made of strips, which are joined to the roof fabric by wooden pins. However, the thermal resistance of the structure is reduced almost to zero due to the low absorption and high conduction of the material causing heat loss when it is cold outside and heat gain when exterior temperatures are high.

In order to properly design a membrane building, it is important to consider the local environmental conditions and the desired internal environmental criteria[30].

Two characteristics that affect the internal environment in a space enclosed by a fabric membrane are:

- A membrane surface can gain heat very easily and
- Can also lose it almost instantaneously when the heat source is removed.

A single fabric skin gives very limited thermal control and the possibility of condensation in certain conditions; alternatively, double membrane layer or glass fibre insulation could be used. The disadvantage of using these methods is that translucency is considerably reduced and condensation may also occur between layers. Another possibility for hot climates, where excessive heat gain has to be prevented, is to choose a highly reflective outer skin to act as a shading structure and at the same time allowing some diffuse daylight penetration. A second skin can also be effective in preventing excessive heat gain, especially if the gap between the layers is ventilated[31].

Research regarding the thermal behaviour of fabric membranes has been carried out by Harvie[32], who has stated the importance of developing a thermal analytical method especially designed for membrane enclosures. The main goal of his PhD thesis was to identify how the thermal behaviour of such spaces might best be predicted. The complex geometry of fabric structures and its effects on their thermal behaviour and internal environment forced Harvie to divide his study in two different analyses:

1. The monitoring and modelling of the thermal behaviour of fabric membranes.
2. The monitoring and modelling of the thermal behaviour of spaces enclosed by fabric membranes.

It was noted that membranes are highly sensitive to changes in environmental conditions and in particular to thermal radiation. Furthermore, Harvie presented a model showing the thermal behaviour of fabric membranes, which results entirely from their surface heat transfers and their thermal optical transmission attributes (Fig. 2-16).

A similar but simpler figure was developed by Wu, Boonyatikarn and Engen in 1984[33], showing the elements that influence the heat transfer calculations of fabric membranes (Fig. 2-17). Compared to Harvie's, this model does not account for the solar radiation that is internally reflected, nor the diffused solar radiation or the light that is transmitted through the fabric and reflected back into the sky.

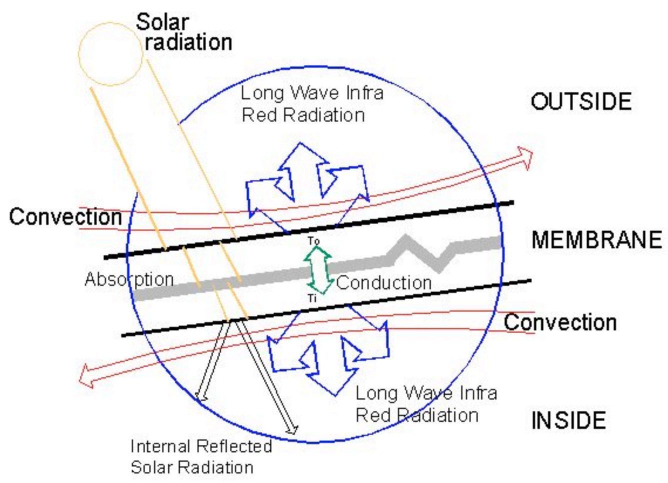


Fig. 2-16 Harvie's model of the thermal behaviour of fabric membranes.

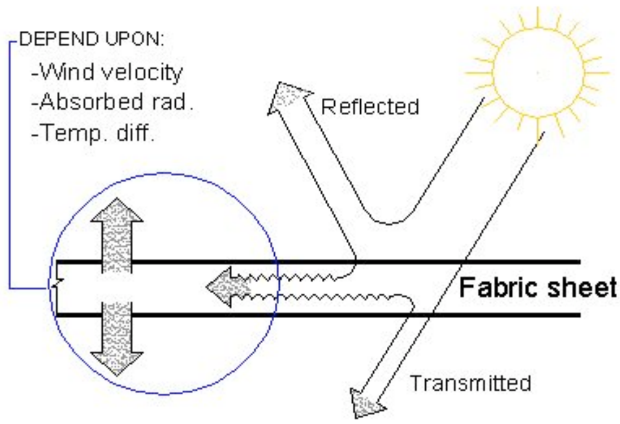


Fig. 2-17 Wu, Boonyatikarn and Engen model of thermal behaviour of fabric membranes.

More recently, Devulder[34] developed a model capable of simulating the thermal behaviour of single and double layer membrane enclosures. His investigation was developed in four stages:

- Monitoring of the thermal performance of two full-scale tensile membrane buildings
- Monitoring of the thermal response of a textile construction under a controlled environment
- The creation of a numerical tool to simulate the monitored behaviour
- Validation of the accuracy of the tool against the monitored data

Devulder's work demonstrated an extreme responsiveness of the membrane constructions monitored to variations of external conditions, in particular to the effect of solar radiation during daytime and to long-wave radiation exchanges during clear nights. Moreover, it was proven that the addition of a second membrane layer could reduce the amplitude of the temperature fluctuations of the internal skin, but that the thermal behaviour of the two layers are largely linked by long wave radiation processes. The model developed was found to provide stable predictions when validated against the monitored data of the real buildings.

2.4 LIGHTING BEHAVIOUR OF FABRIC MEMBRANES

Different studies carried out regarding light intensity and quality of fabric membranes will be described in this section.

2.4.1 Daylighting performance

Some fabric membranes allow considerable amounts of daylight to penetrate their surface due to the translucency and small thickness of the material, typically less than 1 mm. How daylight affects the perception and performance of the interior space of buildings with fabric membranes is a largely unanswered question. Probably one of the reasons is the difficulty of predicting and modelling the daylighting performance of fabric membrane structures due to their rather complex geometry and the diversity of the elements that may influence the behaviour of light inside a membrane building.

Fordham[35] has pointed out one of the main characteristics of single storey buildings such as wide span structures: all the spaces can be roof lit. In addition, the same author has mentioned the importance of avoiding uniformly bright light inside a building that could be caused by the diffusing properties of fabrics, so the eye can distinguish a light differentiation between planes and objects. The light contrast between the inside and outside of a building is another important factor because it allows one to see the shapes and shadows on an object even when the object has a uniform surface[36].

Care must be taken when designing a building with a translucent diffuse skin. Excessive solar heat gain could become a problem as well as excessive internal light levels. Fordham believes that a wide span, single storey building with a light transparency of 2 to 25% can offer adequate light[37]. Finally, the same author considers essential to develop a lighting strategy to reduce direct sunlight improving the overall thermal efficiency of the skin.

Furthermore, this last consideration must include the lighting performance of the building, where problems of glare can be caused by direct sunlight. Regarding the idea of avoiding uniform light in order to perceive three dimensional shapes, it can be questioned if the function of the building requires uniform levels of light so that the eye does not need to constantly adapt to changing levels.

An example of the latter are the Indoor Cricket Schools designed by David Morley Architects, where the designers tried to exclude most direct sun and to give a minimum of 1000 lux even on an overcast day, with a daylight factor of 5% to 6%. Fabric louvres located under transparent areas of the sawtooth roof diffuse daylight and restrict the access of direct sunlight. These projects will be discussed later in this thesis.

Fig. 2-18 Interior of the Indoor Cricket School at Lord’s Ground

2.4.2 Light quality and distribution

Croome and Moseley[38] have also indicated that the quality of light must be a primary consideration when designing a space for people to live or to work. This is defined by its directional qualities and its spectrum.

These authors studied the relationship between the solar radiation angle of incidence (¿)[a] and the solar transmission coefficient of membranes in air houses (Fig. 2-19a). They suggested that, beyond an angle of incidence of 45°, the solar transmission coefficient decreases quickly (Fig. 2-19b). The energy entering the enclosure by absorption and transmission reduces considerably when increasing the angle of incidence, and energy reflected from the surface increases.

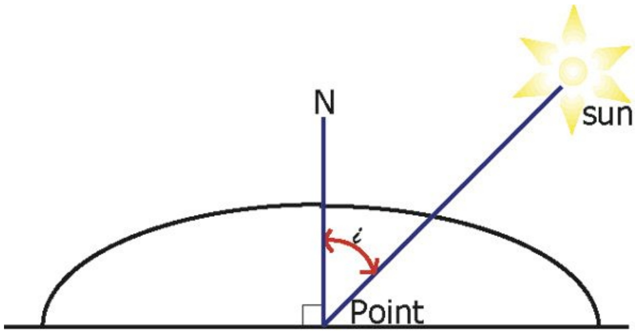


Fig. 2-19a The angle of incidence between the normal to the plane and the ray from the light source [reproduced from 40, p.290].

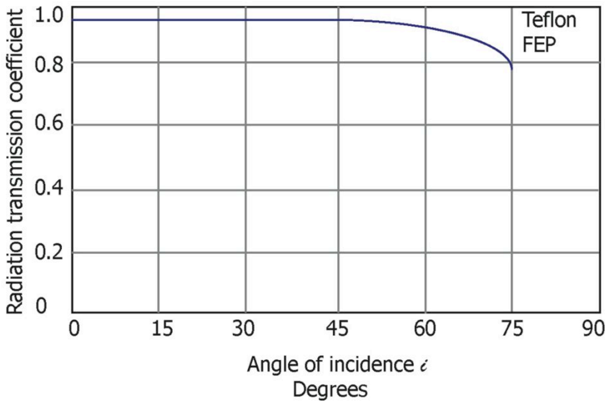


Fig. 2-19b Transmission of solar radiation through "Teflon" FEP film for various angles of incidence. Radiation is perpendicular to film at incidence of 0°.

According to Croome and Moseley there are four different means by which daylight can enter the interior of a membrane structure[39]:

1. Through the translucent or transparent membrane (Fig. 2-20)
2. Special lighting strips (Fig. 2-21)
3. Rigid windows (Fig. 2-22).
4. Glazed windows in the membrane (Fig. 2-23)

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[a] The solar angle of incidence ¿ is the angle between the normal to the plane and the ray of light coming from the source [40].

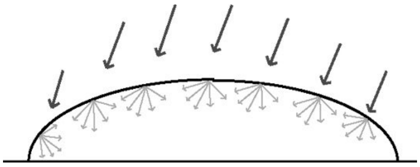


Fig. 2-20 Lighting through a translucent membrane.

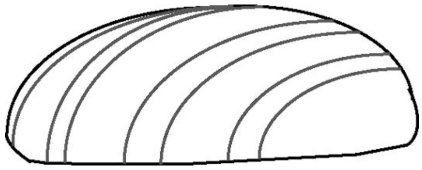


Fig. 2-21 Lighting through transparent strips.

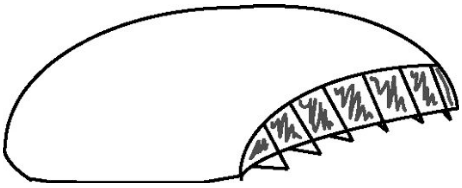


Fig. 2-22 Lighting through rigid windows.

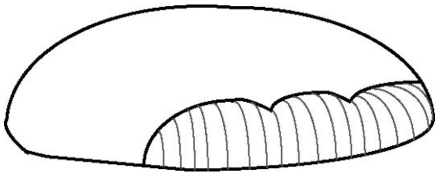


Fig. 2-23 Lighting through glazed windows in membrane.

Martin Wilkinson from the University of Bath has analysed the natural lighting behaviour under translucent domes and air supported structures[40]. He is convinced of the relevance of these studies to achieve a complete acceptance of this type of structure from designers and from the buildings occupants.

Wilkinson proposed a simple way of predicting internal illuminance in lightweight structures. A simple model air house (Fig. 2-24a) was used to prove that the average illuminance under an air house could be easily predicted. The author assumed the material to be a uniform diffuser and the flux transfer was considered to occur only between two surfaces, the envelope and the ground. The following equation (2.1) was developed to obtain the average Daylight Factor:

$$DF_{av} = \frac{\phi_g \text{ x } 100\%}{\pi (R \sin \theta)^2 E_{sky}} \qquad (2.1)$$

Where ϕ_g is the flux to ground, R is the radius of the spherical cap of the air house, θ is the angle subtended by spherical cap and E_{sky} is the sky illuminance (Fig. 2-24b).

The plotted figures of the results obtained applying Equation 2.1 for various values of θ, ρ_e (reflectance of envelope material), α_e (absorptance) and a ground reflectance of 0.15 (Fig. 2-25 & 2-26) show that, for most conditions, the transmittance of the envelope material is the major determinant of the illuminance within an air house. On the contrary, neither the shape of the air hall nor the sky distribution have much effect on it.

However, Wilkinson has admitted the importance that other factors represent when predicting daylighting behaviour: the skill of the designer, the lighting transmission of the material envelope, the control of glare and diffuse light and the accumulation of dirt which could result in transmission loss.

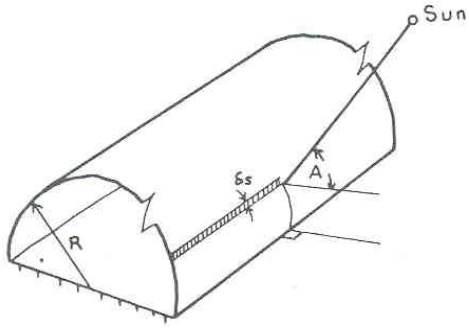


Fig. 2-24a Sunlight incident on a long air house model.

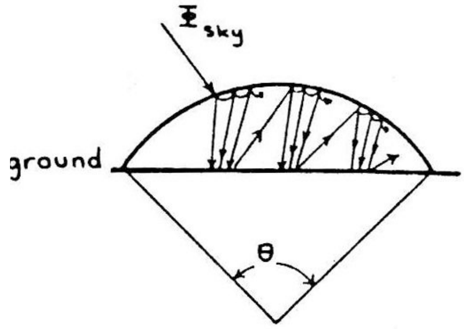


Fig. 2-24b Angle subtended by the spherical cap of the air house and flux intercepted by envelope from sky.

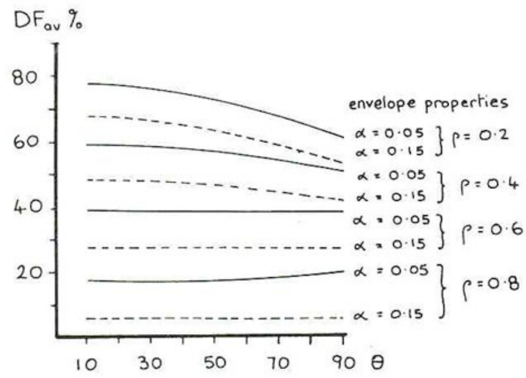
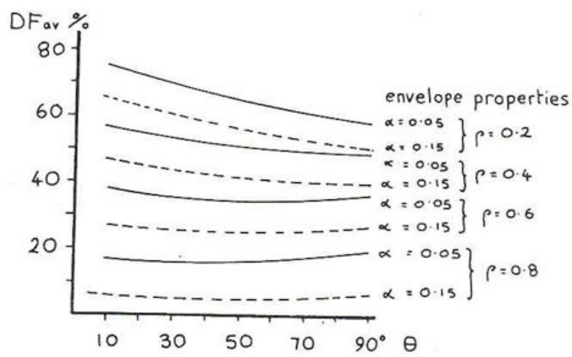


Fig. 2-25 Average daylight factor in an air house under a CIE sky



Note: ρ is the material's reflectance; α is its absorptance and θ is the angle subtended by spherical cap.

Fig. 2-26 Average Daylight factor in an air house under a uniform sky.

Wilkinson[41] has also provided a method for assessing the effects of shape, transmittance and reflectance under three types of natural light:

1. The light flux incident on the outside of a dome from a uniform sky;
2. The light flux incident on a dome from an overcast sky;
3. Light flux incident on a dome from sunlight.

This method has proven to be useful for predicting the illuminance under domes with a half angle greater than 60° or when the solar altitude angle is low. Otherwise, the author suggests using a simpler model assuming that the dome and ground act as two parallel surfaces. However, his methods are limited since it was restricted only to dome structures, and fabric buildings are often designed with a more complex and irregular geometry such as double curvature structures; or with a combination of glass or other transparent materials.

Boonyatikarn, Wu and Engen[42] recognise three factors that influence the luminous performance of the fabric roof:

1. the availability of outside daylight;
2. light transmission of the fabric material;
3. the reflection and absorption of surfaces inside the space.

The maintenance of the fabric together with the geometry and orientation of the building are also significant factors that must be considered when utilising fabrics to control daylight access. Moreover, external obstructions and their reflectance factors can also play an important role in the lighting performance of the building.

The authors developed a prediction and evaluation method of natural lighting in a fabric roof structure: the Unidome building in Cedar Falls, Iowa. In order to consider the above variables, the authors selected typical sky conditions to take luminance values of selective areas on the inside of the entire roof at various hours and for various sky conditions. A coefficient of utilization (the ratio of the total lumens available on an equivalent horizontal work plane and the total lumens from the fabric surfaces) was determined using the following equation (2.2):

$$\text{Coeff. Util.} = \frac{\text{Total lumens on work plane}}{\text{Total lumens from the fabric surfaces}} \quad (2.2)$$

In addition, a regression equation was also developed relating total solar radiation available on the surface in lumens to total daylight illuminance (ILLUM) in lux (2.3):

$$\text{ILLUM} = (104.8/10.76) + (31.007 * 200.04 \text{ lumens}*10.76/10.76\text{m}^2) \quad (2.3)$$

And the luminance on the interior surface of the dome was calculated using the following equation (2.4):

$$\text{Luminance inside} = (\text{Illuminance outside}) * (\text{Transmission}) \quad (2.4)$$

In order to obtain the illuminance levels of the dome the researchers divided the dome into six zones and each of them was computed separately. Hence, the total lumens from the roof in each zone were multiplied by an appropriate coefficient of utilization. The product was divided by area of each zone and the results showed the illuminance on the work plane for the time and zone calculated. They found that lighting levels on the playing field of the Unidome varied significantly. For instance, the peak level of the illumination curve appeared under the brightest area of the interior skin and it moved during the course of the day following the sun path (Fig. 2-27).

Boonyatikarn, Wu and Engen[43] concluded that the effectiveness in utilising natural lighting in the air-supported dome depended on its usage pattern and the lighting requirements. According to their calculations, 64% of the lighting energy required to illuminate the dome could be supplied by natural light. This figure depends on occupancy and location of the building.

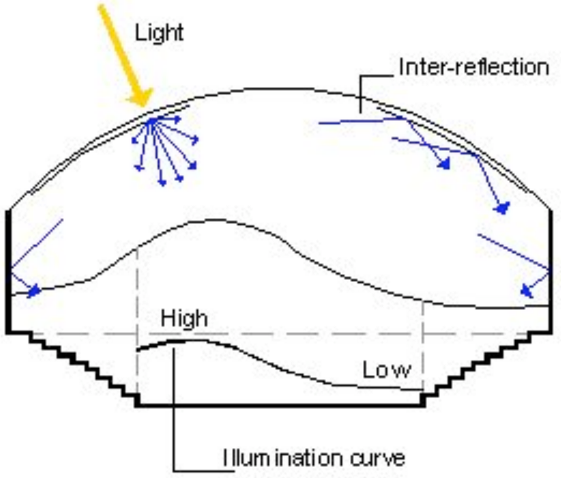


Fig. 2-27 Illumination curve at the Unidome (reproduced from [42] p.199).

2.4.3 Lighting properties of fabrics

Recently, new coated fabric materials have been developed in order to meet the design and environmental requirements for temporary and permanent tensile membrane structures. One of the main characteristics that fabrics offer when enclosing a space is that they provide an approximately uniformly translucent roof. The following table shows some of the fabric's characteristics that influence their light transmittance:

Table 2-2 Characteristics of fabrics that influence their light transmittance.

1	Type of weave and pre-stress
2	Type of base material
3	Type of coating material
4	Tension applied to fabric
5	Number of fabric layers
6	Colour
7	Thickness of fabric
8	Maintenance of fabric (dirt and stains)

For instance, PTFE coated glass fibre fabric provides a translucency of approximately 13%, PVC of around 15%, silicon coated glass cloth can provide between 40 and 50% translucency, while foils can provide a 95% translucency[44]. This data is available from the fabric manufacturers but their measurement techniques are not clear, therefore it seems appropriate to make independent verification of the optical properties of fabric materials and research the behaviour of light inside a building enclosed by a membrane structure. Some authors such as Campbell[45] have pointed out the importance of obtaining daylight through a lightweight translucent roof, such as a membrane skin, in order to reduce the lighting consumption of a building, particularly when the building will be in use during most of the year. In order to take advantage of these optical properties of membrane materials, designers must be able to refer to design parameters and modelling techniques that allow a better understanding and energy efficient design of tensile membrane structures.

Considering the translucency of fabric membranes and the opportunity they offer for daylight transmission all over the building envelope, the dramatic shapes that can be constructed, and the extreme response of membranes to changes in exterior weather conditions, it is clear that recommendations for daylighting design in glazed buildings are not applicable for membrane enclosures[46].

In addition, depending on how the fabric membrane is used, either as a membrane structure covering a long span building or as internal or external fabric louvres, the orientation and inclination angle of the structure or the louvres have a significant role regarding the amount of light penetrating the space. The following figures developed for this thesis show the behaviour of fabric membranes when exposed to daylight.

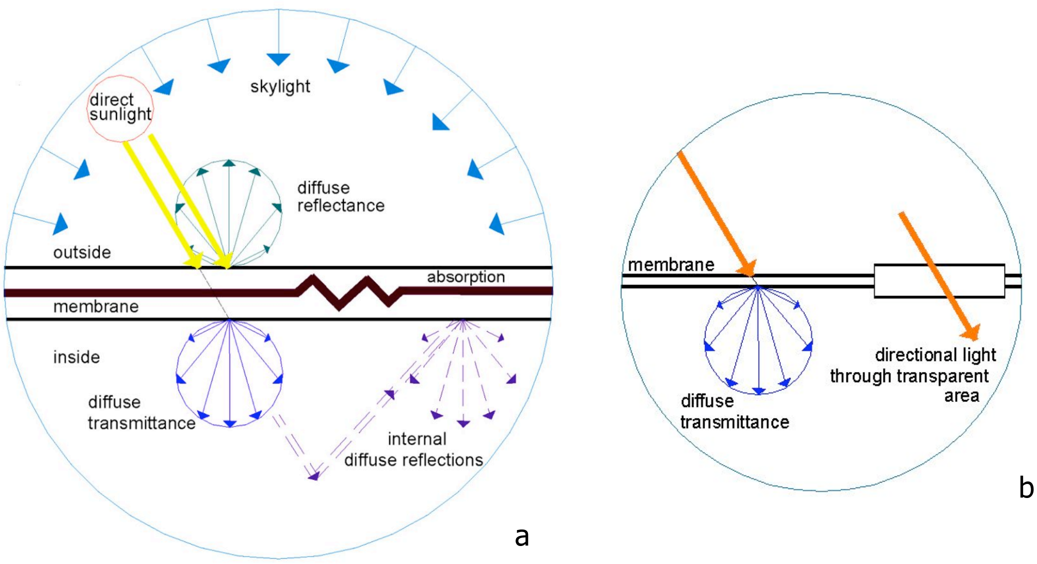


Fig. 2-28a Light diffused through the membrane and reflected internally and externally
Fig. 2-28b Light coming through transparent area

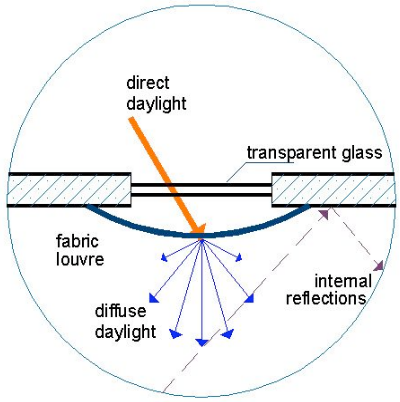


Fig. 2-28c Light coming through transp. area and diffused by an internal fabric louvre

c

2.4.4 The behaviour of light in fabric structures

According to Scheuermann[47], it is important first to analyse the quality of light that penetrates through the membranes. In order to avoid direct light, we usually use lampshades or blinds, which help to avoid direct solar rays or discomfort glare. Lampshades are made of different materials such as foils and fabrics, which are very good at diffusing light. Membranes are foils and fabrics, which act like a lampshade for daylight; they diffuse light due to the cloth's properties and also because of the internal reflections originated by the double curvature of the membrane surface.

During some periods of the year a high translucency fabric could represent a problem, causing the surface to appear brighter than the rest of the interior space. Consequently, it is important to distribute the light inside the building; this may be done with proper design of the surfaces (reflectance factor, colour and interior spatial distribution), which reflect light into the lower parts of the space, such as walls and floors[48]. The transmittance factor of the membrane influences its durability and structural resistance, which is reduced with higher translucency fabrics. If the material is used as interior louvres, then practically any light transmittance factor can be used because the material is not supporting any load and does not need any outdoor coating, only requires fire retardant coating, which does not significantly affect the light transmission of the fabric. In this case the lighting levels required for the specific use of the building are the main concern.

Shadows are very important for appreciating textures, shapes and dimensions; they also create a sense of movement by the rhythm they generate with their alternation with light. Therefore, the introduction of direct light is also important to create a balance, which can help us to see the materials' details. Furthermore, the relationship between the inside and the outside of an enclosed space is fundamental for the comfort of the occupants. This visual connection can be achieved through windows and transparent sections within the membrane structure, which sometimes are also convenient for the structural design of the building. Due to the almost endless number of different shapes that tensile membrane structures can have, there is a wide range of possibilities to integrate transparent areas into the structure (Fig. 2-29).

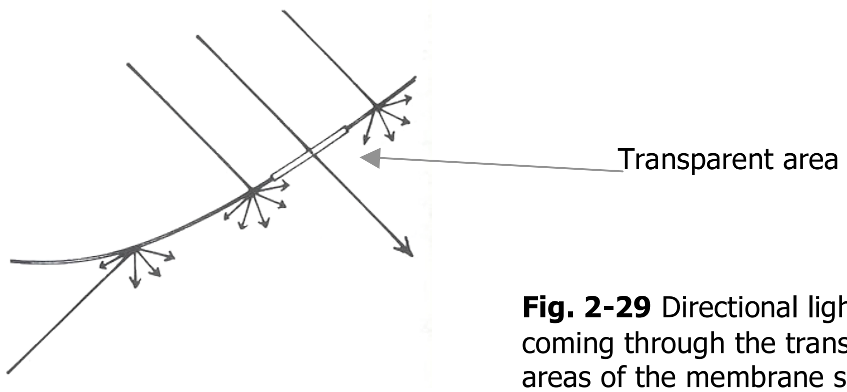


Fig. 2-29 Directional light coming through the transparent areas of the membrane surface

Another possibility of lighting design in fabric buildings is hidden light sources. These sources are not necessarily important for the quantity of light they can provide, but for the quality of the light, which can be helpful to enhance the readability of the membrane shape (Fig. 2-30). This has to be minded in order to avoid creating a dull interior space caused by the highly diffused light that can come through the membrane. One way of solving this problem is to select an appropriate texture for the membrane surface. Two options are suggested by Scheuermann and Boxer[49]: if the surface material is rough enough it can cause a delicate variation of the reflected light at different angles; and in the case of a smooth surface, the light can leave some patches of glare on the curved surfaces (Fig. 2-31).

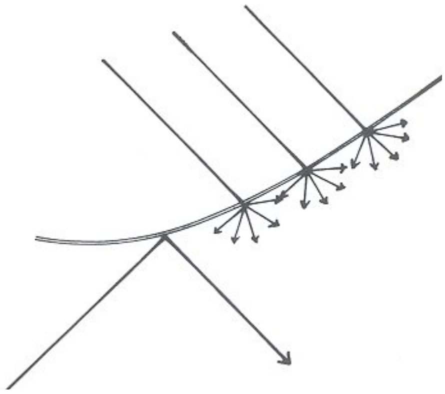


Fig. 2-30 Light from hidden light sources.

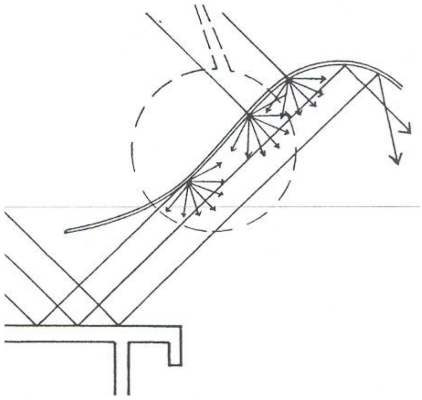


Fig. 2-31 Indirect light helps for the readability of the membrane

At night, tensile membrane structures lit by artificial light sources become a totally different experience. Large amounts of light penetrate the membrane now from the interior to the exterior of the structure transforming the building into a nocturnal light source. Uplighters are used to illuminate the membrane surface and welding lines[50]. On the other hand, Scheuermann[51] has stated that up to 30% of the light will penetrate the translucent membrane from the interior to the exterior; therefore it is necessary to introduce additional down light sources to illuminate the space below.

a  b

Fig. 2-32a & b Amenity Building of the Inland Revenue Centre, Nottingham.

Both daylight and artificial lighting affect the perception of any membrane structure, the illuminance inside the building, its thermal performance and the comfort of the occupants. The understanding of these properties and the capacity to control the access and quality of natural light with fabrics will encourage designers to introduce daylight in projects of any type even when high lighting levels are required.

2.4.5 Visual perception in fabric structures

Stone[52] has highlighted the significance of meeting human visual, perceptual, subjective and biological needs when designing buildings; where illuminance is only one factor of the visual environment. Some of the basic human visual requirements where light has a crucial role are:

a. A need for detailed visual information about the internal environment
b. A need for visual information about the external environment
c. A need for visual comfort
d. A need for visual variety and interest
e. A need to preserve bodily rhythms and sleep
f. A need to control ultra-violet light.

Control over daylight, sunshine and views is essential to avoid overheating, glare or poor lit areas. The continuously changing quality, intensity and colour of daylight experienced inside a space provide information about external conditions, which produce a relief from the sense of enclosure. Hence, the internal environment becomes a non-static atmosphere where change is an essential aspect for the senses and the nervous system. It has been proven that changing the conditions of lighting can encourage interactions between biological rhythms and some psychological conditions such as the syndrome called Seasonal Affective Disorder (SAD) caused by the lack of light during winter[53]. Stimulation by daylight, sunlight and views help to preserve people's motivation and comfort.

A survey carried out among groups of architecture students and users of four different fabric membrane buildings incorporated the evaluation of different aspects of membrane architecture, such as: permanence, durability, affordability, security, attractive materials, attractive technology, attractive shapes, peacefulness, privacy and daylight quality[54]. This study concluded that feeling cold was the most frequent cause of discomfort followed by noise annoyance produced by rain or strong winds. Glare was only mentioned as a cause of discomfort by the users of the office building covered by a double roof system: exterior glass roof and interior fabric ceiling (Table 2-3 and Fig. 2-33).

According to this study, the most clear advantages and strengths of membrane enclosures are attractiveness and innovation, the daylight within the building, and the flexibility of the space. Finally, the survey has revealed that, in general, people are aware of the importance that the presence of daylight represents in a membrane structure. Users, who have regularly experienced the space, rated this quality better than the student group.

Table 2-3 Building features and typical causes of discomfort.

BUILDING FUNCTION	PARTICULAR FEATURES	TEMPERATURE CONTROL APPROACH
B1 Office building	-Double roof system: exterior glass roof and interior fabric ceiling	-Central heating but not air conditioning
B2 Leisure and Sport facilities	-Single membrane	-Assisting passive environmental control
B3 Art gallery	-Double layer system with insulation layer in between	-Central heating and air extractor
B4 College	-Single membrane	-Passive environmental control

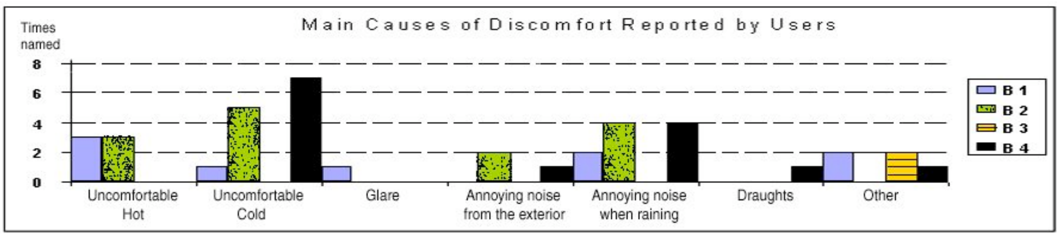


Fig. 2-33 Causes of discomfort in fabric buildings

Certainly, fabric membrane enclosures represent a very different visual and spatial sensation compared to conventional buildings. In fact, they also look different from the outside and from the inside of the fabric building. Translucent fabrics allow daylight penetration providing a well-lit and bright interior environment, while permitting a closer relationship between the occupants and the exterior environment. Furthermore, during daytime the exterior side of the membrane looks opaque and uniform, offering a soft and light skin image. At night time the sensation is completely different, translucent membranes show the internal artificially lit environment to the outside, allowing the building to become a focal point in the surrounding environment.

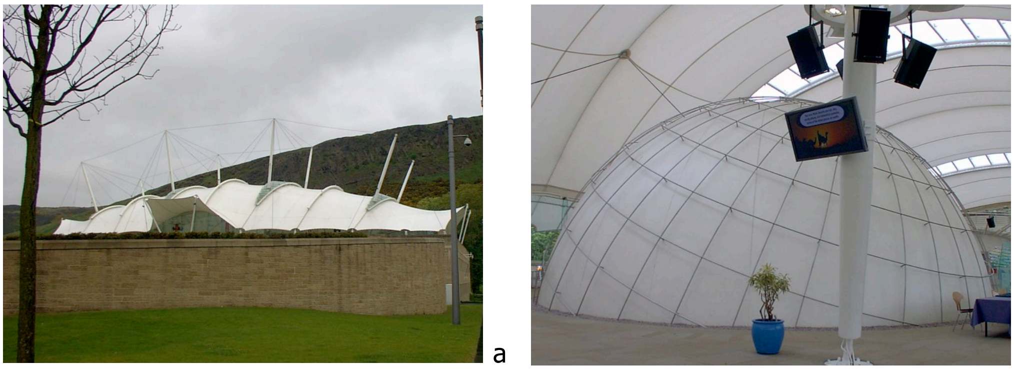
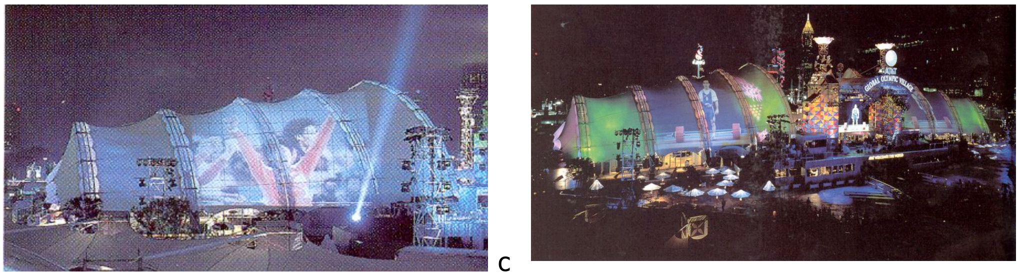

a b

Fig. 2-34a & b Exterior and interior views of the Dynamic Earth, Edinburgh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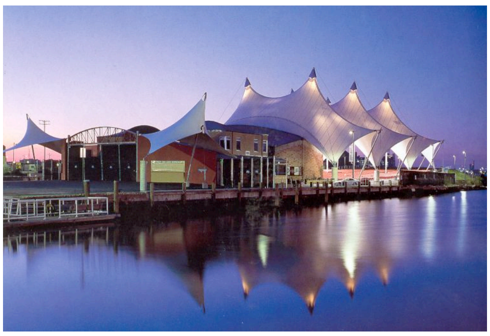
e

Fig. 2-34c & d AT&T Global Olympic Village
Fig. 2-34e Pier Six Concert Pavilions, Baltimore.

Fabric structures can considerably enrich our built environment offering many possibilities for shapes, materials and applications. Nonetheless, there are still some issues that have to be investigated in order to design environmentally controlled fabric buildings with minimum ecological impact.

2.4.6 Contribution of fabric membranes as indoor lighting modifiers to the energy efficiency of buildings

In any building, light influences the visible performance, the thermal performance and the energy efficiency of a membrane structure. Some authors have considered membrane structures as 'environmental filters' which moderate and regulate the external climate[55]. Because of the environmental sensitiveness of the fabric it is important to define the lighting design approach according to the climatic conditions of the site: for hot climates the aim should be to lose heat, whereas in cold climates it should be the opposite. The penetration of solar radiation into a building with membranes represents heat gain for the internal environment and daylight availability in the spaces covered by a fabric skin. These two characteristics could signify an important way to save energy from electrical lighting and heating, contributing to the energy efficiency of the building and the preservation of our natural environment, minimising the use of fossil fuels as energy sources. Energy savings due to the reduction of electrical lighting are more evident in buildings with high lighting levels and/or high occupation rate (i.e. buildings used during the evenings and weekends).

The incorporation of glazed areas in a membrane covered building helps to improve the readability of the membrane shape through the transmission of direct sunlight into the building, where appropriate. On the other hand, light is diffused into the interior space through the translucent fabric membrane or interior fabric louvres, providing large amounts of light that is distributed throughout the internal space. It is also necessary to consider the quality of light that penetrates the membrane skin. According to Scheuermann and Boxer[56] daylight contributes to the creation of a more stimulating and healthier environment inside the building. It is possible to control the quality of daylight with the strategic location of transparent areas and translucent fabric areas, carefully chosen according to the location of the project. In order to avoid direct sunlight penetration, uniform daylight from the north can be harnessed and probably be enough to create a bright interior environment.

The colour of light can also have a strong influence on the visual and spatial comfort of the occupants. Generally, a space seems comfortable when is lit by "warm" light ('fire-like') rather than "cold" light (from the blue sky); numerically the colour appearance is indicated by the colour temperature of the source, values below 3300 K are classified as warm and values above 5300 K as cold[57]. The colour of light depends on the coloured surfaces that reflect and transmit light.

The relevance of developing further studies on the lighting behaviour of membranes relies on the importance that this knowledge could represent for the energy efficient design of the building and the comfort of the occupants. Moreover, it is of primary importance to achieve a balance inside the occupied space between diffuse, direct and reflected light, in order to avoid overheating and glare in the building.

The CIBSE Code for Lighting[58] points out the importance of providing a suitable visual environment while saving energy without compromising the adequate lighting performance and human effectiveness. The Code also mentions two ways of achieving energy efficiency:

1. By using the most efficient lighting equipment for the specific lighting requirements.
2. By using effective controls so the operation period is reduced to a minimum. Automatic switching or dimming in relation to occupancy and daylight availability is advisable. In offices, for instance, lighting controls can represent energy savings of 30-40%[59].

In addition, Littlefair[60] has recommended the following types of lighting control for a managed (such as the case studies analysed in this thesis) daylit space with high or low occupancy: photoelectric dimming, time switching and centralised manual control. Managed spaces have someone in charge of the lighting, but they are frequently too busy to control it, and users are not supposed to control the lighting.

The BRE Good Building Guide: Lighting for Non-domestic buildings[61] gives some general suggestions for all applications, these include:

- Choosing appropriate standards without over-lighting.
- Choosing light-coloured finishes to improve inter-reflections.
- Selecting efficient lamps and fittings.
- Integrating automatic controls with daylight.

Lighting in the European Union accounts for 5% of the total primary energy consumed including that for transport and industry. Though, in some buildings such as offices, 30-60% of the primary energy is consumed by lighting[62]. Therefore, in order to reduce these figures it is necessary to integrate daylighting design and lighting controls into a passive solar design strategy.

2.4.6.1 Fabrics and renewable energy technologies

Recently, some researchers have made a few attempts regarding the integration of renewable energy technologies into membrane-covered spaces. Architects and engineers are concerned about the importance of using passive and active solar energy in architecture in order to avoid the environmental damage that fossil and nuclear fuel are causing to our planet.

Renewable energy has been defined by the UK Renewable Energy Advisory Group (REAG) [63] as "the term used to cover those energy flows that occur naturally and repeatedly in the environment and can be harnessed for human benefit. The ultimate sources of most of this energy are the sun, gravity and the earth's rotation".

Nowadays one of the most widely used renewable energy technologies in buildings is solar photovoltaic. Photovoltaics are capable of generating electricity directly from solar energy through the use of PV cells, which consist of a junction between two thin layers of semi conducting materials usually made from silicon[64].

In 1998 FTL Happold designed a 9.6 meters-high tensile membrane structure for the exhibition called "Under the Sun" in New York City[65]. The structure integrates amorphous silicon PV film arrays bonded to a fabric membrane (PVC mesh Ferrari fabric) designed to provide shade and demonstrate the potential of PVs as off-grid power systems (Fig. 2-35a & b). The effect of the PV arrays on the visual, lighting and spatial comfort of the users of this tent has not been specified or probably, has not been even considered. Although the reduction of daylight penetration is obvious, the temporary state of the structure has not permitted to monitor the PV system performance and its influence on the illuminance levels under the tent. However, this technology seems to have great potential in countries with high solar gain. This type of structure could provide shade while generating electricity.

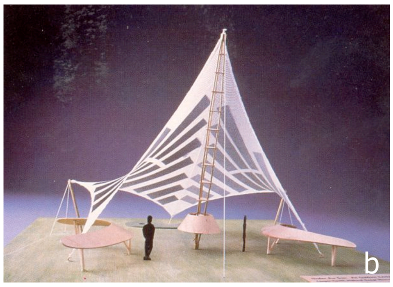

Fig. 2-35a Membrane structure with PVs for the "Under the Sun" Exhibition, FTL Happold
Fig. 2-35b Scale model of the project

In addition, flexible PV modules composed of silicon solar cells have been developed in Japan for use in membrane structures. The flexible PV modules are joined to the membrane material using the heat welding method that is generally used to join the membrane materials themselves. A study of the effects on architectural design and indoor lighting performance as a result of integrating PV modules into membrane structures was developed using computer graphics and a computer simulation of illuminance distribution. The researchers found out that the illuminance distribution inside the membrane building was considerably affected by the area covered with PV modules; hence, according to the authors the disposition of PV modules should be determined at an early design stage considering aesthetics and indoor illuminance requirements[66].

Further research about the integration of photovoltaic systems into membrane covered enclosures and their effects on the lighting performance of buildings must be developed in order to provide design recommendations for the use of PVs in membrane structures without compromising the use of daylight for illumination purposes and the reduction of electricity consumption used for artificial lighting.

2.5 BUILT EXAMPLES OF FABRIC ENCLOSURES

2.5.1 New Bangkok Airport

An example of a complex fabric building where the interior environment was carefully designed is the New Bangkok Airport currently under construction. It was designed by Murphy/Jahn Architects from Chicago and the energy and comfort design was developed by Transsolar Energietechnik GmbH from Stuttgart.

Bangkok's climate is humid and hot with temperatures varying between 25 and 35°C, and with solar altitudes near the zenith. The aim of the project was to achieve indoor climate conditions of 24°C room temperature and 50 to 60% relative humidity. The penetration of diffuse natural light was included in the concept together with consideration of views from the terminal to the outside. The designers try to adjust daylight incidence into the building avoiding the use of artificial lighting during daytime even with overcast skies; and reducing the overall illuminance and possible glare effects[67].

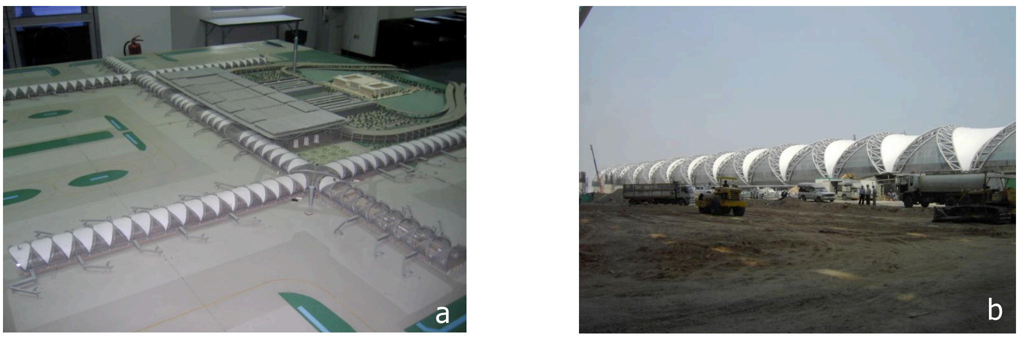

Fig. 2-36a Scale model of the New Bangkok Airport.
Fig. 2-36b The Airport under construction.

Passenger concourses were solved alternating two materials: transparent glass for outside views and a translucent membrane roof for daylighting (Fig. 2-37). This membrane roof is constructed with a multi-layer membrane system that allows the penetration of diffuse light into the building. The outer membrane is Teflon coated glass fibre and the inner is made with a thin transparent foil with a low-emissivity coating on its inner surface. In between these two membranes, translucent sound baffles are mounted with an air gap on both sides, acting as sound protection from the aircraft noise outside. Superlite and Radiance were used for daylighting simulations, and the results show minimum illuminance levels of 300 to 400 lux on the lower level of a typical concourse segment under an overcast sky except for areas under the upper level walkways (Fig. 2-38).

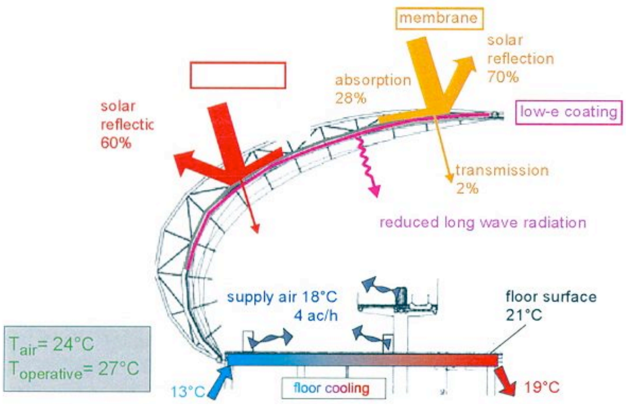

Fig. 2-37 Energy concept for the concourse areas.

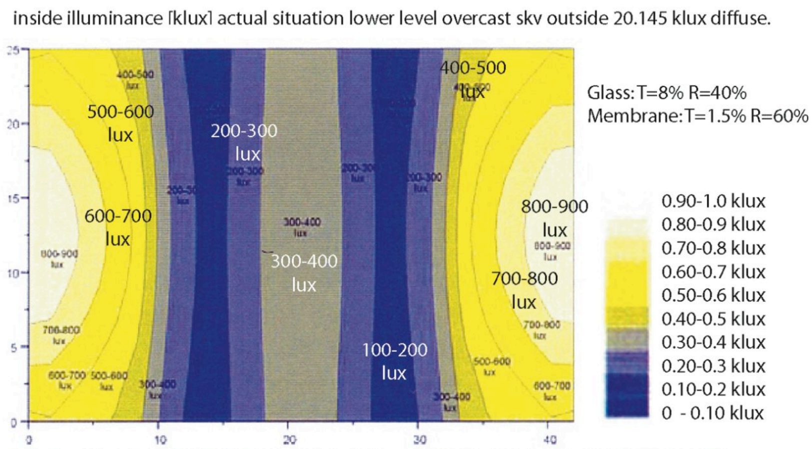

Fig. 2-38 Illuminance levels on the lower level of a typical concourse segment under overcast sky.

2.5.2 Amenity Building of the Inland Revenue Centre, Nottingham

An example of the integration of glazing areas into a membrane structure is the Amenity Building of the Inland Revenue Centre in Nottingham. The architectural design was carried out by Michael Hopkins and Partners and the engineering work was developed by Arup Engineers, in 1994. The Amenity Building is approximately 3,000 square metres in area and is covered by a PTFE/glass membrane, which is divided into three different segments; the central membrane is the largest one and covers the sports hall.

This shape discontinuity emphasises the lightness of the structure and the integration of glazing areas in between which act as joining points. The main roof form is generated by four elliptical glazed ladder trusses located at the top of the membrane. These trusses provide an interesting combination of diffuse and direct light captured from the sky (Fig. 2-39). The trusses are suspended by steel rods from four big masts, which pass from inside the building to outside through the glazed area of the ladder trusses.

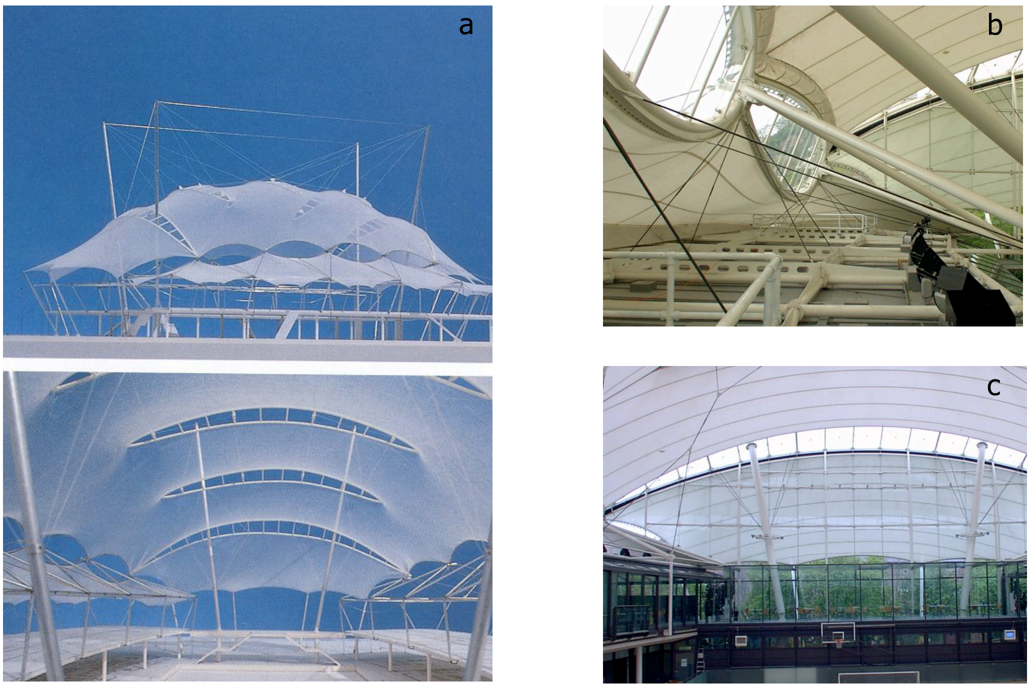

Fig. 2-39a Scale model; **fig. 2-39b & c** Interior views of the Inland Revenue Centre, Amenity Building. Nottingham, UK.

2.6 SUMMARY

Improvements in fabric structures have included the development of a broad range of membrane material, from metallic foils to natural or synthetic textile fabrics; the extended life expectancy of membrane buildings, costs reduction and structural efficiency. All these factors have made possible the construction of permanent tensile membrane structures for different purposes under different climate conditions. However, one of the fields that has, to some extent, evaded regarding membranes design is the environmental behaviour of these materials and the spaces enclosed by them.

One of the most significant areas of fabric design is the lighting behaviour of membrane-covered spaces. Light transmittance and reflectance are the most important optical characteristics of membranes; their proper understanding could result in users comfort, energy reduction and dramatic appearance of membrane structures. Previous research regarding the lighting behaviour of fabric membranes has been very limited due to the complex geometry of these buildings and the difficulty of simulating daylight. Most of the investigations presented have studied only the lighting behaviour inside dome structures; but more complex fabric buildings have been designed and built to date. The design of the New Bangkok Airport is the only example found where daylighting has been simulated in a fabric building; but no validation has been done regarding this topic. For this reason, an assessment of different daylighting prediction techniques for membrane buildings will be subsequently discussed.

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2-19a The angle of incidence between the normal to the plane and the ray from the light source. **WILKINSON, M.,** "Lighting within Air-Supported Structures" Proceedings of the Conference The Design of Air-Supported Structures, Bristol, UK, July 1984, p.290.

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2-20 Lighting through a translucent membrane. Ibid., p. 222.

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2-24b Angle subtended by the spherical cap of the air house and flux intercepted by envelope from sky. WILKINSON, M., Ibid., p. 292.

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2-28a Light diffused through the membrane and reflected internally and externally.

2-28b Light coming through transparent area. Based on **SCHEUERMANN, R. & BOXER, N.** Tensile architecture in the urban context. Oxford: Butterworth-Heinemann, 1996, p. 52.

2-28c Light coming through transparent area and diffused by an internal fabric louvre.

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2-34e Pier Six Concert Pavilions, Baltimore. **KRONENBURG, R.** FTL Softness Movement and Light. Architectural Monographs No. 48. Great Britain: Academy Editions, 1997, p. 30.

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2-36a Scale model of the New Bangkok Airport. Photo: F. Kreuter, March 2005.
2-36b The Airport under construction. Photo: F. Kreuter, March 2005.
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Table 2-2 Characteristics of fabrics that influence their light transmittance.
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Three

3. METHODOLOGY

3.1 INTRODUCTION

In chapter 2 an overview of the advantages and development of fabric membrane structures was presented. In addition, the existing knowledge regarding the environmental performance and the lighting behaviour of fabrics and the spaces enclosed by this type of material was discussed. The distinctive visual environment produced by this architecture and the future integration of renewable energy technologies into fabrics were also explored. This analysis suggested the importance of understanding the environmental behaviour of these structures and materials in order to answer to the increasing demand for fabric architecture and for environmentally responsive buildings.

In this chapter, a general methodology developed to structure the research carried out and presented in this thesis is described. Due to the wide field of study regarding both daylighting and fabric membranes, this study concentrates only on sports buildings that have included fabrics to control the access of daylight.

3.2 ANALYSIS OF CASE STUDIES

3.2.1 The purpose and selection of the case studies

The lack of existing research concerning the daylighting performance of membrane buildings together with prediction techniques, led this investigation to an analysis of three case studies. This investigation was intended to satisfy the following aims:

- To simplify this study using built examples of daylit sports buildings with fabric membranes
- To be able to compare the physical modelling and computer modelling studies with site measurements recorded in the real buildings to assess the accuracy of the prediction tools
- To gain an overall impression of the behaviour of daylight in existing buildings
- To clarify other parameters that could affect daylight availability and quality and are not normally taken into consideration at a design stage
- To carry out a post-occupancy evaluation study regarding users satisfaction towards the lighting performance of the buildings for their intended purpose

The selection of the case studies responded to the following criteria:

1. Location: all case studies are located in the UK so as to be able to visit them as many times as necessary.
2. Function: due to the importance that lighting signifies for the appropriate performance of sports halls, only this typology of buildings was chosen.
3. Lighting approach: for the purposes of this project it was necessary to include only daylit buildings.
4. Daylighting control: fabric membranes must be included in the design of these buildings, either as a major part of their external envelope or used as internal louvres. Both of these solutions are common in fabric architecture.
5. Availability: access to these spaces, contact to their occupants, and the possibility of having the electric lighting systems off were necessary to carry out this investigation.
6. Innovative design: for the selection of the case studies the innovation of their designs was also considered, particularly their lighting solution and their contribution to sustainable architecture.

After visiting and contacting the managers and designers of some buildings, three sports halls were selected and available for this study:

- The MCC Indoor Cricket School at Lord's Ground, London
- The ECB National Cricket Academy, Loughborough
- The Amenity Building of the Inland Revenue Centre, Nottingham

Although a larger number of case study buildings could provide more consistent data for validating computer and physical modelling approaches for the prediction of daylight, the selected buildings cover two very common use of fabric membranes: a tensile membrane roof structure and interior membrane louvres.

3.2.2 Method adopted and apparatus used for the measuring of daylight availability

In order to obtain an overall impression of the daylighting environment in the case studies, together with the correct lighting data that could be used to compare the lighting performance of these buildings with the physical and computer models, it was necessary to determine the aspects related to daylighting design that had to be measured on site. Since the quality of the lighting environment includes the assessment of average lighting levels, illuminance uniformity and overall visual environment; these have been the factors evaluated in this thesis.

Egan[1] has defined daylight as the illumination from the sky that is constantly changing due to the Earth's movement around the sun and conditions of the sky, which can be clear (<30% cloud cover); partly cloudy (30-70% cloud cover); and overcast (100% cloud cover).

The light that comes from the sky and reaches a particular point in a room is composed of three different components: light that comes directly from the sky is the sky component (SC), light that comes from external surfaces or buildings is the externally reflected component (ERC), and light that is reflected from internal surfaces is the internally reflected component (IRC) (Figure 3-1)[2].

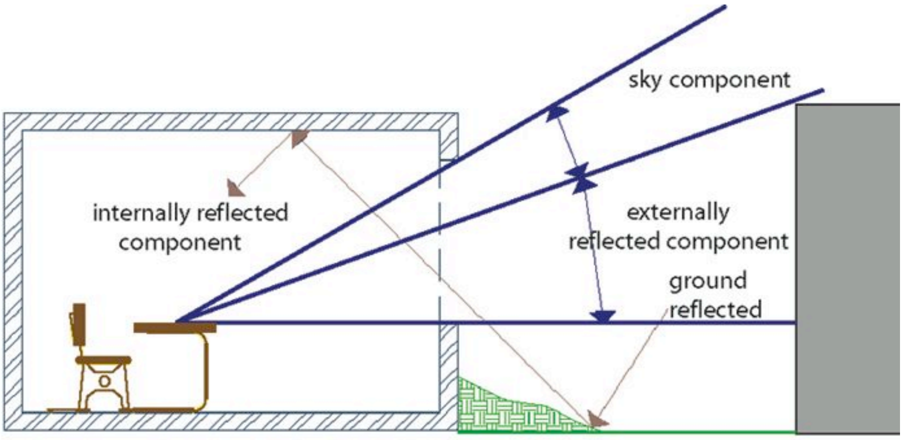


Fig. 3-1 Daylight components (reproduced from [2]).

According to Baker and Steemers[3] daylight illumination can be measured in lux, but the illuminance in a room has to be considered as a ratio and expressed as a percentage due to the changing conditions of the outdoor illuminance from the diffuse sky. This is called the Daylight Factor (Fig. 3-2), which is defined by:

$$DF = Ei / Eo \times 100\% \quad (3.1)$$

Where:

Ei = Internal illuminance on the horizontal plane

Eo = external unobstructed illuminance on the horizontal plane.

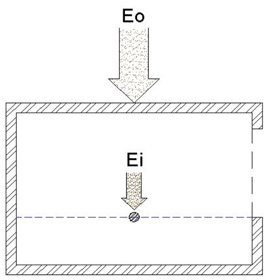


Fig. 3-2 Daylight Factor

Usually the DF varies between 1 to 5%, where 5% would be considered as a brightly daylit building, and between a range of 2 to 5% as partially daylit. With the purpose of obtaining this data a series of simultaneous illuminance[a] measurements were taken in the playing areas

[a] *Illuminance:* the density or concentration of luminous flux incident on a surface (luminous flux density). It is measured in lux (lumens per square metre)[4].

of each building, which are the areas covered by fabric membranes, and in the unobstructed exterior of the enclosures.

In sports buildings the main design area is where the playing and training take place. For some sports such as cricket and badminton the spatial variation of light is important due to the need to maintain a very uniform lighting, reducing the adaptation of the eye to continuous changing light levels. Therefore, the minimum maintained average illuminance (Em) values, and the uniformity ratio (ratio of the minimum illuminance in an area to the Em value)[5] were calculated from the recorded data.

Equipment

The lighting equipment used for this study included:

- Six single channel photometric sensors Skye SKL 310.
- A Data Hog 2 Skye Data logger (SDL 5000 series).
- A hand held Skye Illuminance meter recorded the exterior horizontal illuminance.
- A Hagner universal photometer model S3 was used to measure luminance levels.

3.2.3 Case Study 1: MCC Indoor Cricket School

The first cricket school built in England with fabric louvres integrated into its daylighting design approach is the Marylebone Cricket Club Indoor School located in London, England.

One specific part of the school will be studied in this research: the playing area (1,555.20 m^2) (Figures 3-3 and 3-4). In this area lighting control is very important for cricket training, and is here where the architects incorporated interior fabric blinds under the roof to regulate the access of daylight. With this method direct sunshine, glare and reflections are expected to be avoided; while keeping high levels of uniform light throughout the playing area.

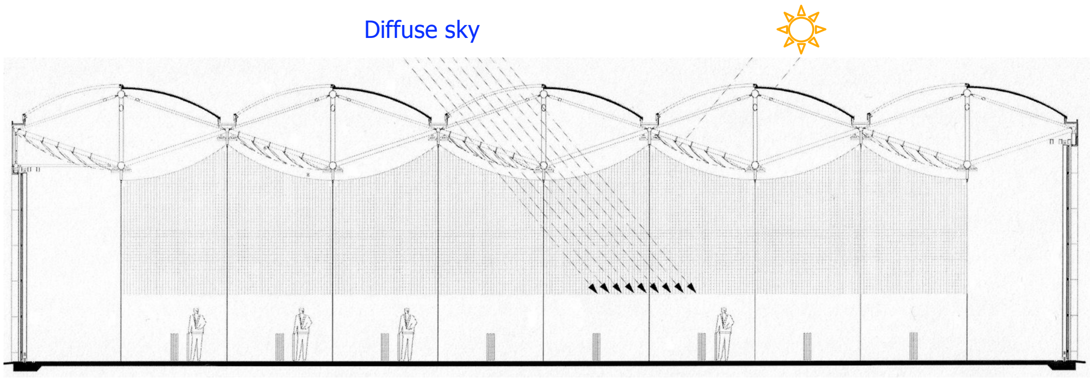
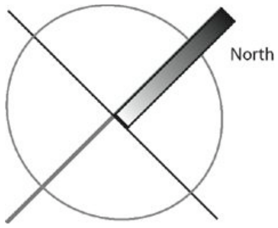
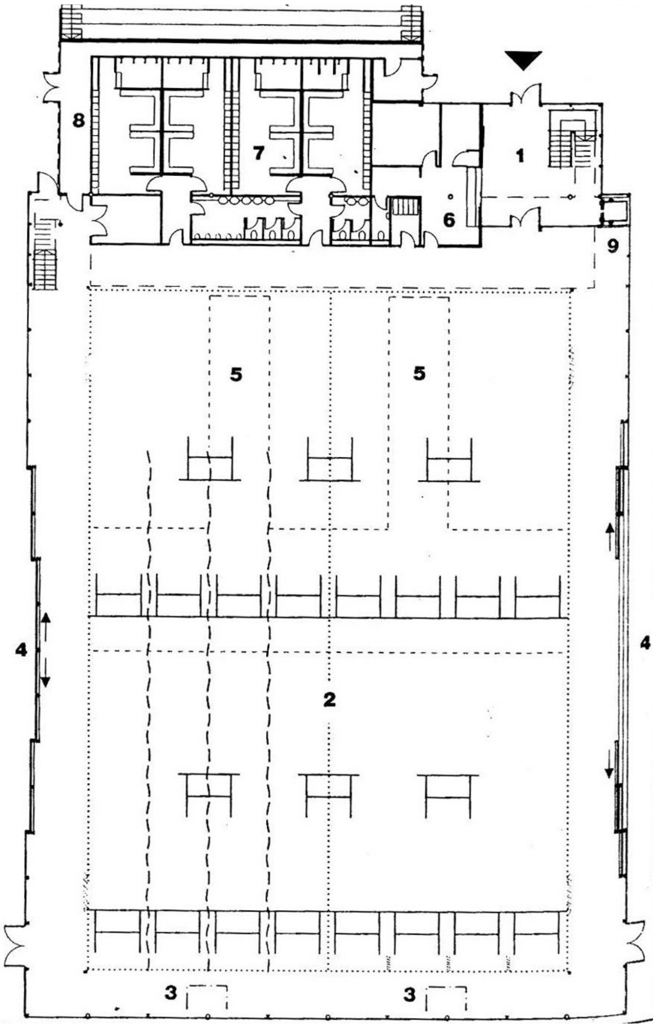


Fig. 3-3 Cross section through playing area.





Key to plan:
1 Entrance/reception
2 Playing area
3 Umpire's platform
4 Sliding doors
5 Shock pads for bowlers' run up
6 Offices
7 Changing rooms, showers, WCs
8 Plant room
9 Lift

Fig. 3-4 Ground floor plan.

3.2.3.1 Project Description

The MCC Indoor School was the first of five indoor cricket facilities designed by David Morley Architects. In general, sustainability and natural illumination have been major concerns in all these projects. The MCC

School was completed in July 1995 and is located at Lord's Ground in London. The project responded to the competition brief launched in 1993 by the MCC for the design of an indoor cricket facility to replace their existing indoor cricket school[6].

The site for the School is on the eastern corner of the Lord's Ground, having important views from the Wellington roundabout and Regents Park. The main access to the building is from the north gate of the complex (Figure 3-5).

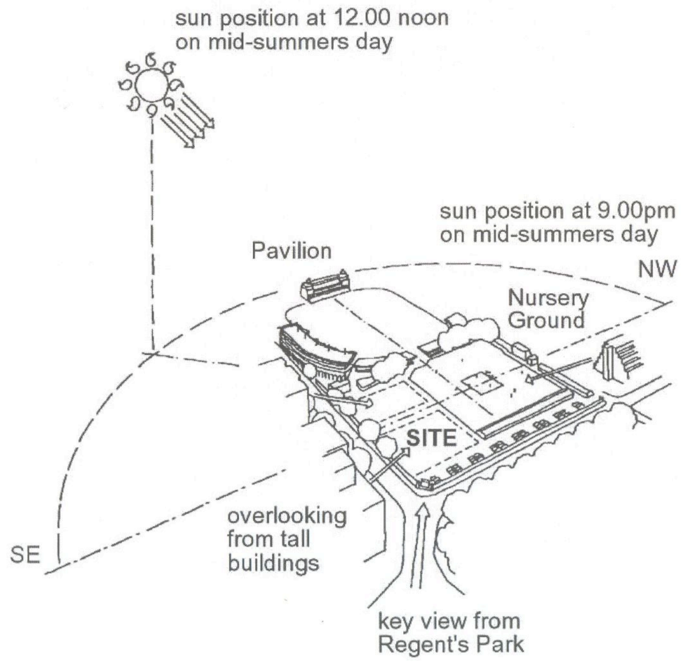


Fig. 3-5 Site Context

3.2.3.2 Design Concept

The innovative design of the MCC Indoor School includes the use of natural daylight achieving uniform lighting. The design proposals were based on an exhaustive analysis of the functional aspects and the context of the building. The building was oriented in a way that allowed glazed areas to take advantage of the lighting conditions from the northeast. This orientation avoids the evening sunlight available during the summertime.

The functional solution for the Indoor Cricket School was organised in a double sided pavilion which encloses eight batting nets and all supplementary accommodation for both facilities: the indoor school and the outdoor cricket of the existing practice ground. The location at one end of the pavilion of the following facilities: bar, training rooms, changing rooms and staff offices allowed the possibility of having spectators' galleries for both the indoor playing area and the outdoor ground. Moreover, the sides of the playing area are free of other accommodation and can be opened for natural ventilation in warm weather (Figure 3-6).

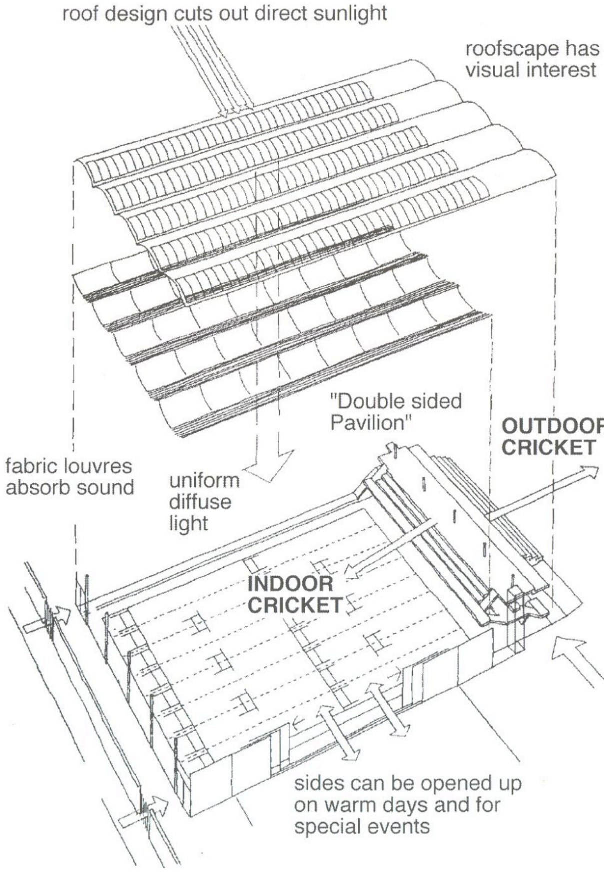


Fig. 3-6 Design concept.

3.2.3.3 Roof solution

The school at Lords was specifically designed to maximise the north daylight that penetrates the building from mid-morning to early evening, during the busiest operation period.

The designers suggested three different solutions (Figure 3-7). The first one included a traditional opaque closed building, which was rejected for the high energy consumption necessary to artificially illuminate such a building. The second option considered was a translucent roof with a translucency of around 12%, which was enough to naturally light the building for 70% of the year. This solution was also rejected due to the sudden changes in light levels that a cloud may cause. The third solution proposed was a north light roof similar to a sawtooth roof. This last approach only admits light from the diffuse part of the sky, where changes in light levels occur over a longer period of time. The designers considered 5,000 lux available from an overcast sky and 1,200 lux on the playing surface; therefore a 24% daylight factor was the initial design target[7].

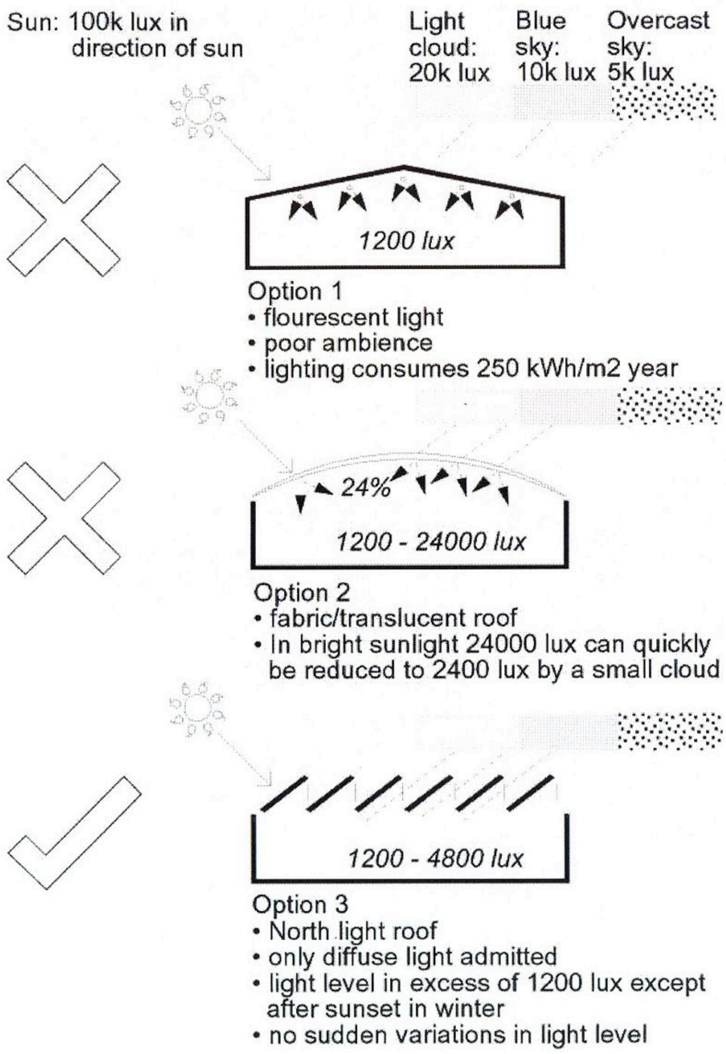


Fig. 3-7 Roof concept.

The main structure of the Indoor Cricket School is made of aluminium, which provided smooth inside and outside surfaces. Solid panels are made from 14g aluminium with a 70mm EHD polystyrene insulation. The roof is formed from a series of aluminium-clad vaults with half of them facing north and comprising a double-glazed transparent polycarbonate unit with a 70mm air gap. On the other half side of the vaults sunlight penetration is diffused by a series of curved fire-resistant fabric louvres located beneath the glazing and fixed to the main steel structure (Figure 3-8) [8].

Basically the fabric battens avoid the penetration of direct sunshine into the playing area. The fabric is placed at a specific fixed tilt angle and diffuses daylight coming in between a certain critical angle. There are inter-reflections of light between each fabric piece: daylight strikes on the fabric, it is reflected into the adjacent one and then diffused towards the interior of the building.

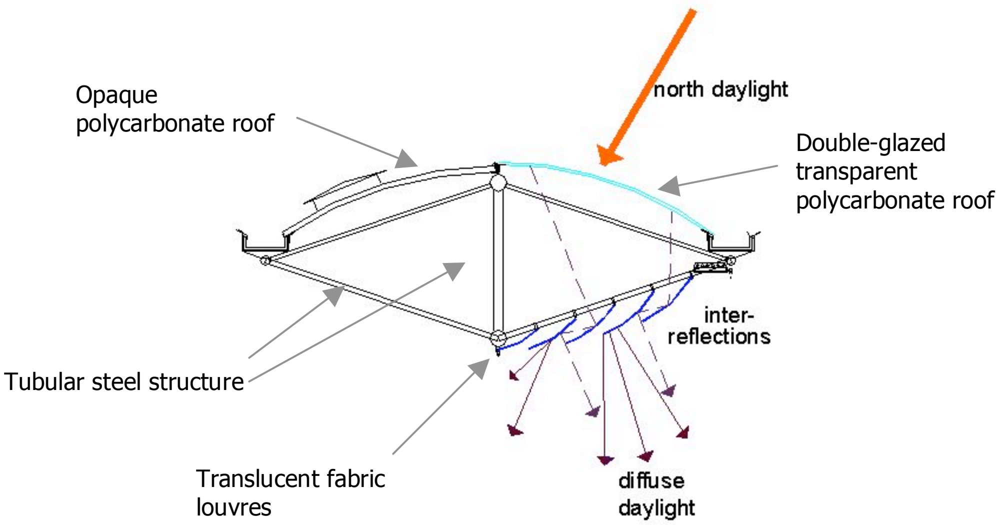


Fig. 3-8 Roof detail.

The fabric membrane used for this building was supplied by Lucas Sails and Kayospruce. The fabric is an acrylic canvas developed in America for boat covers and is registered as Sunbrella natural colour fire-resist FIR8604, with a weight of 314gm/m^2 and an average life span of 5 to 10 years[9]. It was not possible to obtain the optical properties of the fabric from the manufacturers; hence, the measurement of these characteristics was carried out in this research and is reported in chapter 4.

Fig. 3-9a, b & c Interior views of the Cricket School

3.2.4 Case Study 2: ECB National Cricket Academy

3.2.4.1 Project description

The National Cricket Academy located in the campus of the University of Loughborough is also a David Morley Architects' project finished in October 2003. The building includes in an area of 70m by 25m: six lanes of playing area, fitness centre, changing rooms, office accommodation for the National Academy staff, a 'performance analysis suite' which includes an editing suite and video library, seminar rooms, bar and viewing balcony (Figures 3-10a-c and 3-11).

The lighting objective in this construction was to achieve a minimum of 1500 lux in the playing area. The design has included a combination of both natural and artificial light. A series of light sensors were placed all across the building in order to automatically activate the electric lamps when the 1500 lux required in the playing area cannot be achieved with daylight only.

3.2.4.2 Roof solution

The fabric sails designed for the National Cricket Academy are made of 100% acrylic coated polyester and were tensioned with steel battens and brackets located at one end of each sail. The membrane was supplied also by Kayospruce. The fabric is registered[10] as Holiday ivory colour fire-resist HOL707, with a weight of 418.7gm/m^2. This solution is very similar to the fabric louvres of Lord's roof. However, the recent design at Loughborough seems to be more efficient because the fabric is highly tensioned and this characteristic makes the distance between each blind greater than when they are less tensioned (as in the Lord's School) allowing a more unrestricted penetration of diffuse daylight into the building (Figure 3-12).

Fig. 3-10a Main façade National Cricket Academy. **Fig. 3-10b** Interior view of playing area. **Fig. 3-10c** Fabric louvres.

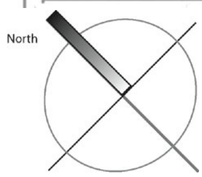


Fig. 3-11 Ground floor plan.

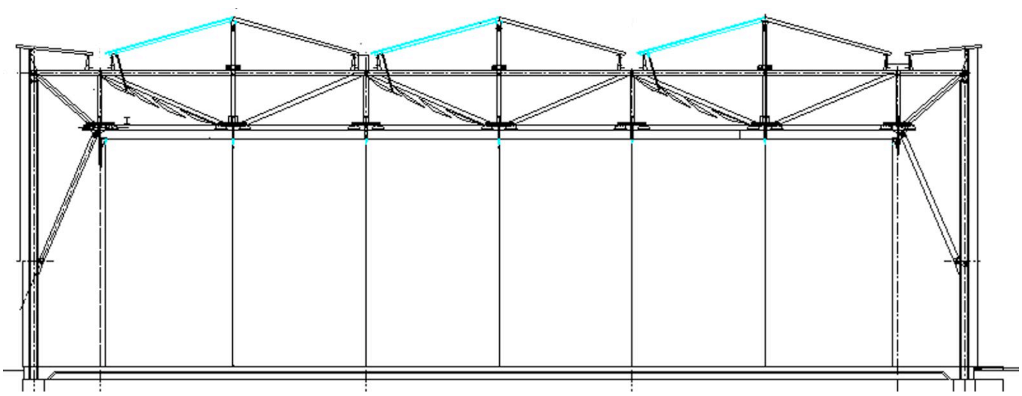


Fig. 3-12 Section across playing lanes.

3.2.5 Case Study 3: Amenity Building, IRC

3.2.5.1 Project description

The design of the Inland Revenue Centre in Nottingham (IRAB) was carried out by Michael Hopkins and Partners and Ove Arup & partners in 1994. The Amenity Building is approximately 3,000m^2 in area and is covered by a single PTFE/glass membrane, which is divided into three different segments; where the central membrane is the largest and covers the sports hall.

The sports practiced in this building include basketball, badminton and volleyball. Although all of these games are played at a recreational level and do not require such high levels of light, the architects decided to take maximum advantage of the daylight availability continuing with the design concept of the Inland Revenue Centre. Therefore, the architectural project aimed to be a green ecological design with maximum use of natural ventilation and light, suitable for construction in a short period of time. The view of the castle had to stay unobstructed[11].

3.2.5.2 Roof solution

The shape of the membrane roof provides a large interior space emphasising the lightness of the structure. The glazing areas integrated into the membrane roof act as joining points between the central and lateral membranes. Four elliptical glazed ladder trusses are located at the top of the membrane providing access to direct light into the playing area. Four masts pass across the glazed trusses holding them with steel rods (Figures 3-13 and 3-14).

The roof membrane is PTFE coated glass fibre fabric[12] and covers a surface of 2,700 m^2. The membrane is connected to the edge cables by means of aluminium clamping strips and metal straps. The cables under the membrane are used to join the tips of the ladder trusses with the membrane corners and with the edge cables; they are also connected with the A-frame and the substructure by a welded corner plate assembly[13]. The consulting engineers of this project were Ove Arup & Partners, the membrane material was supplied by Verseidag – Indutex GmbH and Skyspan Ltd. was in charge of the textile construction.

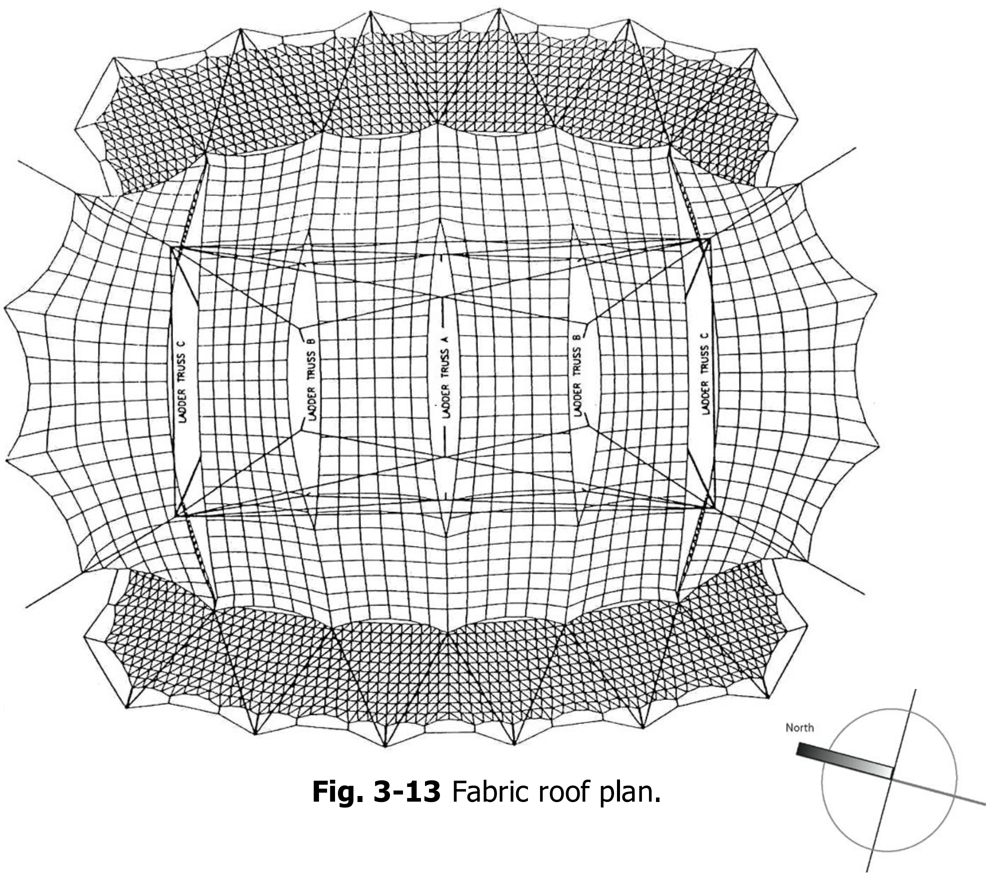


Fig. 3-13 Fabric roof plan.

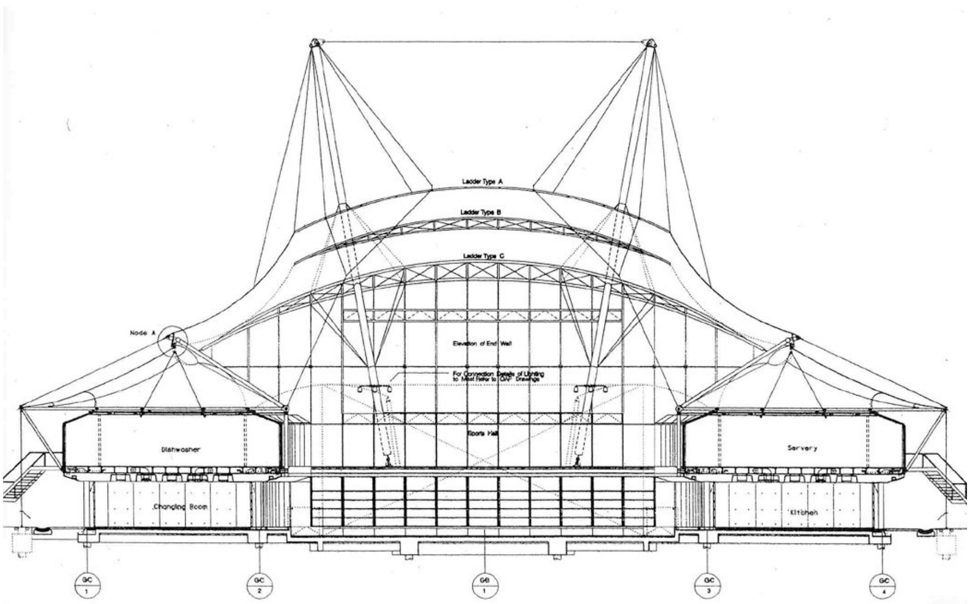


Fig. 3-14 Cross section of the Amenity Building.

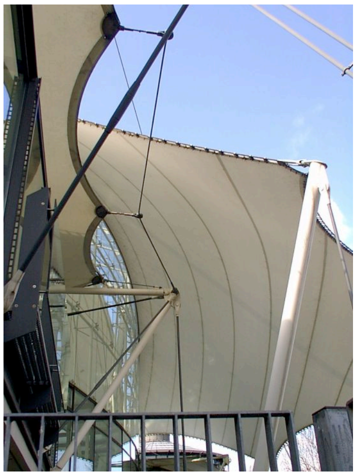
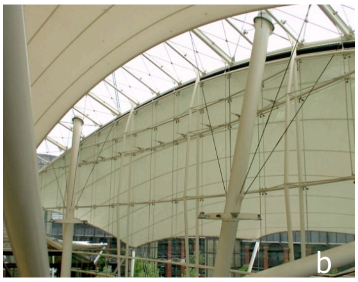


Fig. 3-15 left Exterior view of the Amenity Building.
Fig. 3-15 right Front membrane.



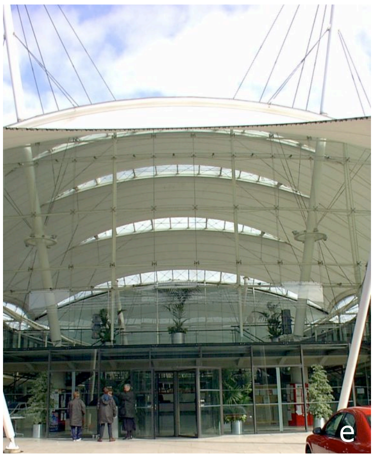


Fig. 3-16a-d Interior views of IRAB
Fig. 3-16e Main entrance of IRAB

3.3 THE GENERAL APPROACH ADOPTED FOR THIS RESEARCH

The development of building technology and new materials has allowed the advance and widespread application of fabric architecture. These structures can be used for different purposes, in different climatic conditions, both as new structures or as extension of existing buildings, either for temporary or for permanent enclosures. However, in order to take full advantage of their characteristics it is necessary to be able to understand, predict and control their environmental behaviour.

The analysis of the case study buildings has shown the importance that lighting represents for the adequate performance of sports buildings. In addition, the analysis suggested that it is appropriate to use fabrics for daylighting control if they are properly placed according to the general design of the building and the site characteristics. Although their use has increased considerably in the last years, there is not yet a defined or a verified methodology and simulation techniques for the daylighting design of fabric buildings in particular.

In order to assess different lighting simulation techniques while evaluating the daylighting performance of the buildings chosen as case studies this research has been divided into the following steps:

1. Analysis of the optical properties of fabric samples: transmittance and reflectance factors.
2. Field study of the daylighting performance of the case studies.
3. Computer simulation of the daylighting performance of the case studies.
4. Physical scale modelling of the case studies for their analysis under an artificial sky.
5. Assessment of the simulation tools through the comparison of computer simulation and scale modelling simulation against the lighting measurements taken in the real buildings.
6. Users' survey as a post occupancy evaluation study: questionnaires.

3.3.1 Analysis of the optical properties of fabric membranes

It was apparent from the review of the existing body of knowledge and the preliminary lighting monitoring of the case studies that the optical characteristics of the fabric membranes and the other interior materials have a very important role in the daylighting performance of the buildings, particularly their transmittance and reflectance properties.

It was vital to know these characteristics for the appropriate modelling of the case studies, but they were not available from the manufacturers of the fabrics used in the cricket schools. Therefore, it was necessary to test different samples of cloth to simulate the real fabric membrane of the Inland Revenue Amenity Building in the scale model. The transmittance of the fabrics used in the cricket schools was tested using samples of the real materials.

The reflectance factors of the surface of other materials used in the buildings were obtained from the luminance measurements taken in each building; this data was used for the modelling of the case studies. The method used to obtain reflectance factors is explained in chapter four of this thesis.

3.3.2 Assessment of daylighting computer simulation techniques against scale modelling

The development of computing technology has resulted in a great number of available computer software for architecture design, including: architectural drawing, structural analysis, furniture design, study of construction materials, and environmental analysis of buildings. There are some computer programs specifically developed for the design of tensile membrane structures, such as: EASY, ESI, ForTen32, Cadisi, PAM-LISA, etc.[14]. Nevertheless, most of them can simulate only the structural behaviour of membrane structures.

On the other hand, there are many computer programs that perform lighting calculations (Superlite, Adeline, Lightscape, Lumen Micro),[15] but only a few can accurately model daylight and they tend to be not user friendly or require exact input data (i.e. geometry, sky conditions, and materials characteristics). One of the methods for lighting calculations is the Ray Tracing method, which is the most sophisticated, accurate, and nowadays is becoming a viable option for regular use and not only for research purposes[16]. The method consists of tracing rays of light; forward (away from their source) or backwards where the rays are traced from the reference surface back towards their source (the rays originate at the destination and are traced back through a series of reflections until they reach a light source).

Due to the complex geometry of membrane structures it was decided to use a ray tracing software to perform the computer simulations of the case studies aiming at demonstrating the possibility of simulating the lighting behaviour of fabrics with a common lighting package. The reasons for this consist in the following factors:

- The method has no constraints on the detail or simplicity of the space to be modelled, can model complex or unusual spaces.
- Can consider the colour of sources and surfaces.
- Possible to obtain highly realistic images.

The ray tracing software selected for this study is ***Desktop Radiance***[17], which is a powerful lighting software able to calculate daylight, DFs, Illuminance, Luminance values. The program is able to model complex geometry and it is flexible enough to create new materials that can be translucent like the membranes used in the case studies. This software also allows one to import geometry from AutoCad or other CAD packages. It is a Windows release of the UNIX based Radiance program. Desktop Radiance can be downloaded for free and configured into the AutoCad environment. Initial experimentation with this program revealed the difficulty of obtaining accurate numerical output, mainly caused by the limitations that this program presents due to the lack of further development of Desktop Radiance, which has not been adapted to newer versions of AutoCad.

Finally, the method selected for this study was using the building analysis software Ecotect v5.20 [18] as a platform to access Desktop Radiance.

The following figure shows the simulation process adopted for this study.

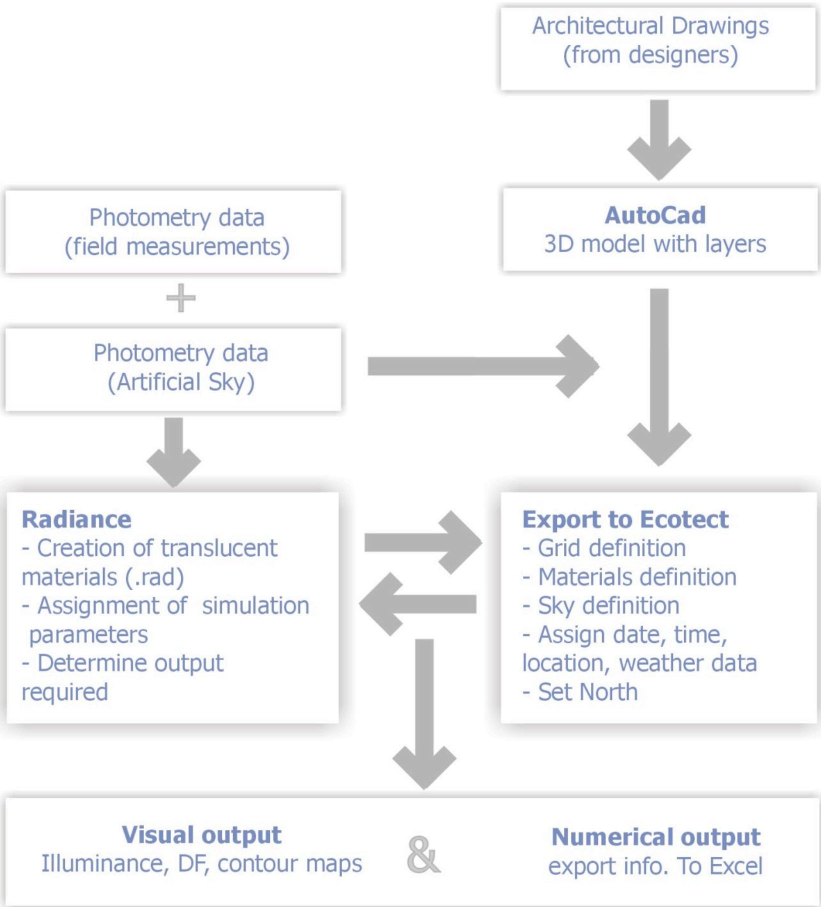


Fig. 3-17 Overview of the computer simulation process.

The results from the computer simulation of the three buildings were then compared with the DF and illuminance variation registered in the scale modelling tests. Physical models of each of the selected case studies were built with the main aim of carrying out a lighting study of the three models in the artificial sky (mirror box type) available at the School of the Built Environment at the University of Nottingham.

The following points were key features taken into consideration when making the models:

- The section of the building to be modelled.
- The influence of skylight windows and vertical windows in the lighting environment of the playing areas.
- The reflectance of the real interior materials (opaque roof, floors, walls, partitions). And the reflectance of paper and other materials that could simulate the real characteristics in the physical models.

- The reflectance and transmittance of the fabrics used in the real buildings, which in the case of the Cricket buildings were also used in the scale models.
- The transmittance factor of an elastic cloth that could simulate the characteristics of the fabric membrane used in the Amenity Building (3rd case study).
- The scale of the models considering the size of the artificial sky and the buildings' areas modelled in this study.

3.3.3 Comparison of simulation techniques vs. real building study

In order to validate the simulation techniques described above, it was necessary to compare the results obtained in the scale modelling and in the computer modelling of all three case study buildings, with the real buildings monitoring data.

The computer models were tested with the same parameters and sky and site conditions available during the site measurements. Illuminance values, Daylight Factor, and Illuminance variation throughout the playing areas were found and compared. Subsequently, these results were also compared against the data collected during the study of the scale models tested under the artificial sky.

3.3.4 Method adopted for the users' survey regarding lighting performance and visual perception

A questionnaire was designed specifically for this post occupancy evaluation study and distributed among the people who use the case study buildings. Baker and Steemers[19] have pointed out the kind of feedback that can be obtained from a lighting post-occupancy evaluation study:

1. Corrective actions that need to be taken.
2. Design features to be avoided.

3. Achievement of targets (design goals, environmental targets: energy).
4. Design aspects for future and long term research.

The same authors have also mentioned the need to consider in the questionnaire the physical environment as a whole, including noise and thermal conditions. This approach allows the user to rate the importance of daylight quality against other qualities of the building's environment and performance.

The decision to use a questionnaire to evaluate the lighting performance of the spaces was based on:

- The need to know the perception of the lighting environment from the users' point of view, taking into consideration their experience as sports players, frequency of visits to the buildings, age, etc.
- The questionnaire offered the possibility of obtaining responses from more people (including: students, instructors, visitors and staff), spending less time and money carrying out the survey.
- This qualitative study allowed the user to fill in the questionnaire without feeling any pressure from the researcher, and without trying to guess the 'right' answer according to the investigation objectives.
- Respondents could complete the questionnaire when best suited them.
- The possibility of keeping respondents' anonymity.
- Standardization of questions.
- Shows how the occupant responds to uncomfortable conditions in the space and their satisfaction regarding the architectural design of the sports building.

In addition to distributing the questionnaires in the three case study buildings, the survey was also conducted in the Sports Centre of the University of Nottingham. This building was selected because of easy accessibility and its architectural approach: completely enclosed and artificially lit. The questionnaire's design and results will be analysed and discussed in chapter 8.

The overall methodology proposed for this project is shown in the following scheme.

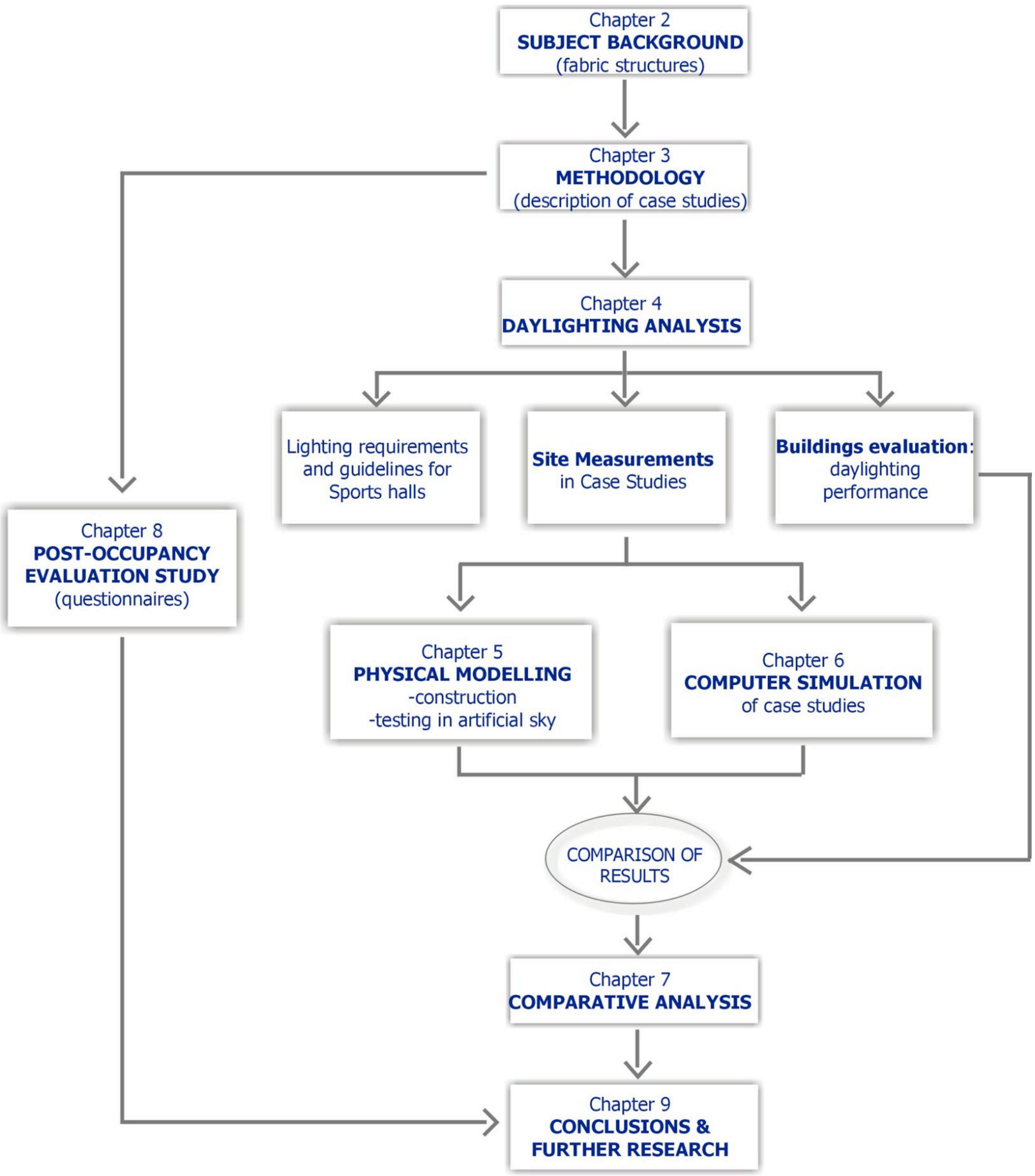


Fig. 3-18 Illustration of the methodology adopted for the research presented in this thesis.

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3.4.1 Figures and tables

Four

4. DAYLIGHT ANALYSIS OF SPORTS MEMBRANE BUILDINGS

4.1 INTRODUCTION: LIGHTING REQUIREMENTS FOR SPORTS HALLS

The selection of illuminance levels depends on the specific visual task to be performed inside a building. Lighting recommendations have changed since first being issued in 1899. These recommended illuminance levels have increased considerably in the United States and at a more controlled rate in Europe[1]. Some illuminance data for different tasks have been recommended by Tregenza and Loe[2] (Table 4-1).

The selection of these illuminance values depends on several factors, such as:

- Occupant age or eyesight condition
- Room or task background surface reflectance
- Accuracy requirements
- Length of periods to perform certain tasks

Task lighting involves not only ensuring a minimum level of illuminance, but also understanding the relationship between the task, the viewer and the sources of light, in order to avoid discomfort caused by glare or excessive brightness. Despite the fact that both daylighting and electric lighting come from different sources, they have to be considered together when designing the lighting approach to their distribution and control inside and outside the building.

Table 4-1 Typical recommended task illuminance in the UK

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

In the case of sports halls, lighting is a very important factor for playing and watching sports. Both, artificial and natural lighting must be designed to complement each other providing adequate light levels according to the sport performed. In multiple sports halls the lighting provided should be designed for the sport with the highest requirements.

The values of illuminance depend on the following considerations[3]:

1. The size of the objects to be seen
2. The direction and speed of movement
3. The luminance of the objects
4. The luminance and colour contrast between the objects (the ball, for instance) and the background

A potential reduction of the illuminance must be considered at the design stage; this could be caused by dust and the reduction of the reflection factors of walls and ceiling for ageing of materials. The uniformity of illuminance is also important in order to avoid seeing multiple images of moving objects and having the eye to adapt to constantly changing light levels within the playing hall.

The Commission Internationale de l'Eclairage (CIE) recommends certain reflection factors for major surfaces in sports halls:

- ceiling: 0.6
- walls: 0.3 - 0.6
- floor: 0.2

They have pointed out that the factors have to respond to the type of sport performed, where badminton for instance needs a reflection factor of the walls to be about 0.2 in order to increase the contrast between the shuttlecock and the background[4].

4.1.1 Daylighting design

The incorporation of windows and daylight in sports buildings respond to the need for exterior views reducing a feeling of being enclosed, and allowing the users to keep track of the time and weather conditions. In addition, daylight access can considerably help to reduce the use of electric lighting particularly with sports that demand high levels of light. The recommended horizontal illuminance must be met by daylighting (through windows or skylights) for a significant proportion of the time that the building is in use. When designing with daylight it is important to avoid the penetration of direct sunlight that can produce glare and overheating.

The CIE has mentioned some disadvantages of introducing large daylighting components in sport areas[5]:

- Possible glare for people facing the windows
- If the windows are located along one side, objects and people viewed against them are seen in silhouette
- At night, the lighting equipment and the bright surfaces of the room are reflected on the window
- Reflections in polished floors

- Solar heat gain and heat losses

Because of these problems, traditionally, sports halls have been built only with electric lighting in the main hall. Nonetheless, growing ecological awareness has pushed architects and clients to adopt new lighting approaches including the access of daylight in sports centres.

The illuminance required in a sport building depends on the type of sport and playing level, where higher playing levels demand higher lighting levels because the speed of action increases and the visual task becomes harder. The ultimate objective of a good lighting solution is to provide the players, officials and spectators with sufficient light to easily follow the action. According to the Lighting Guide for Sports published by CIBSE[6] light uniformity is important when designing sports halls: the playing surfaces should appear uniformly bright when viewed from different directions, and once this is acceptable the illuminance gradient should also be checked in the relevant points.

Table 4-2 shows the daylight factor required for different indoor sports facilities, together with the minimum maintained average illuminance (Em) values recommended by CIBSE and the Illuminating Engineering Society (IES)[7], and the uniformity ratio which is the ratio of the minimum illuminance in a given area to the Em value. These values shown in Table 4-2 have been selected as relevant to the case studies analysed in this thesis.

Table 4-2 Daylight factors, illuminance values, uniformity & reflectance [7].

Sport	**Em** (lux)	**Uniformity ratio**	**Average DF** (%)	**Min. DF**(%)	**Reflectance**
Badminton	300	0.8	5	3.5	Walls:0.2-0.6 Ceiling:0.6-0.9 Floor:0.2-0.4
Basketball	300	0.8	5	3.5	Walls:0.4-0.6 Ceiling:0.6-0.8
Cricket National/ International	1000	0.9	5	3.5	Side walls & walls behind wicket: 0.6-0.8 Ceiling & wall behind bowler:0.4-0.6
Volleyball	300	0.8	5	3.5	Back walls:0.2 Side walls:0.4-0.6 Ceiling:0.6-0.8

4.1.2 A daylit sports hall

As it was mentioned before, traditionally sports halls have been built including natural light in reception areas only. Controlling the lighting environment in playing areas is more difficult, often designers found easier to eliminate glare and direct solar radiation restricting the availability of daylight. Research developed regarding the use of daylight in sports halls and the analysis of case studies has contributed to broaden the knowledge about the advantages that incorporating daylight in buildings represent for reducing energy consumption for electric lighting and improvement of their visual environment.

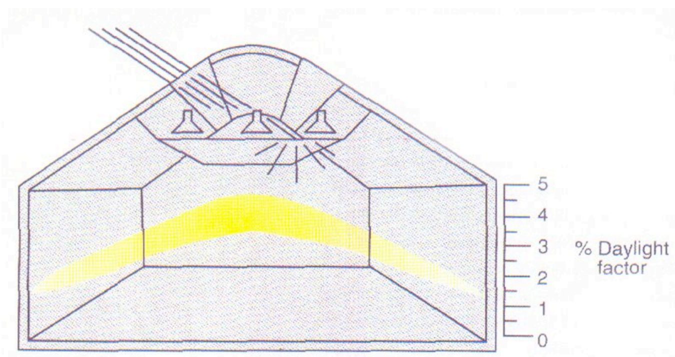
One of these examples is the sports hall of the Brune Park Secondary School; the analysis of this project was reported by the Building Research Establishment (BRECSU)[8]. The introduction of daylight in this building was required by the Hampshire County Council in 1986 with the idea of reducing glare caused by electric lighting systems. This project was selected as an example in this thesis because it is a daylit sports hall with fabric located under the rooflights, acting as a diffuser in a very similar way as the case studies analysed in this research.

The multipurpose hall includes a playing area (16 x 30 m), a viewing gallery, weight training room and changing rooms, all allocated in an area of 940 m^2. It was designed by Jackson Greenen Down and Partners.

This building allows daylight access through rooflights and is diffused by a sail cloth located over the playing area. The objective of this solution is to provide very good illuminance (300 lux on the horizontal plane) without excessive glare. The rooflights occupy about 9% of the sports hall, and are triple glazed with a light transmission of 60%. The fabric located below has a light transmission of 60%; hence, about 35% of the exterior light available is transmitted into the playing area.

The daylighting solution of the Brune Park School sports hall has proven to be very successful, with an average daylight factor of 3.5%, and a maximum of almost 5% at the centre of the playing area.

According to measurements taken in the building, during 60% of the time the hall was in use, no electric lighting was needed to reach the minimum illuminance required. Daylight reduced the annual electricity consumption by 32% or 18400 kWh. This is probably one of the first sports buildings where daylight has been diffused and controlled by a translucent fabric structure. Although the daylighting strategy was successful providing enough light in the playing area, overheating was recorded due to the lack of enough ventilation in the building and solar heat gain through the rooflights.



4-1b

Fig. 4-1a Interior view of the Brune Park School Sports Hall
Fig. 4-1b Section showing Daylight Factors

4.2 MEASURING THE OPTICAL PROPERTIES OF FABRICS

The lighting performance of fabric buildings is closely related with the characteristics of the fabric used, especially its light reflectance and transmittance factors, which are dependent of features such as the colour of the material, its thickness, type of base and coating materials, general condition of cleanness and damage due to ageing. Fabrics' optical characteristics together with the reflectance factors of the walls, ceiling and floor materials of the building greatly influence the visual and lighting performance of the space. This was the reason to carry out the measuring of reflectance and transmittance factors of the surfaces of the case study buildings.

4.2.1 The purpose of the study

The main purpose of this study was to measure the optical characteristics of the materials used in the three case study buildings in order to understand their influence on the lighting behaviour of the buildings. In addition, the information obtained was useful to simulate the materials' properties in the physical scale models made for the study reported in chapter five and also in the computer modelling study described in chapter six.

The reflectance and transmittance of the fabrics used in buildings 1 and 2 were obtained through this study since the manufacturer could not provide the optical properties of the materials.

Due to the scope of this research, of comparing the lighting behaviour of buildings under overcast skies, the determination of the optical properties of the interior materials of the case study buildings was carried out under a diffuse light source. In addition, overcast sky conditions offer the most standardised circumstances in which to perform the measurements. Therefore, no angular distributions of incident, transmitted and reflected light were taken into consideration.

4.2.2 Method adopted and apparatus used

The European Design Guide for Tensile Surface Structures[9] mentions some international and European standards that are used to evaluate properties of fabrics, such as fire resistance and light transmission. These standards include ISO, EN, NF, DIN, BS and ASTM. Moreover, for light transmission in particular they recommend to use the ASTM (American

Society for Testing and Materials) E 424-71 standard; which has been used by fabric manufacturers such as Taconic[10].

Although, the ASTM E 424-71 standard test method for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials was considered in this work; other methods were adopted since they are best suited for the needs of this project. These methods are the Standard Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight, ASTM E 972-96; and the Standard Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight, ASTM E 1084-86[11]. The last two methods provide guidance for measuring the solar photometric transmittance of sheet materials that are transparent, translucent, textured or patterned.

According to the ASTM methods, the photometric transmittance[a] is measured using a photometer (illuminance meter) in an enclosure with the sun and sky as the light source. The apparatus to be used in this method are:

- An illuminance meter consisting of a suitable radiation detector
- An enclosure. This is a box capable of holding a 0.60 m^2 sample; it must have a square aperture of no less than 0.50 m by 0.50 m. The box must allow removing and replacing the material sample easily during the measurement process. The inside of the box shall be opaque black (Figures 4-2a & b).
- Due to the objectives of this study it was decided to measure the light transmittance of the fabrics under the artificial sky which simulates a CIE overcast sky. The details of the artificial sky used are specified in chapter five.

The lux meter was placed inside the box and the fabric sample was held 6 cm above the sensor. A second sensor was located outside the box

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[a] Luminous Transmittance is the ratio of the transmitted illuminance to the incident illuminance [ASTM E972-96 Standard Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight, p. 497].

without obstructions to record the illuminance incident on the surface of the sample.

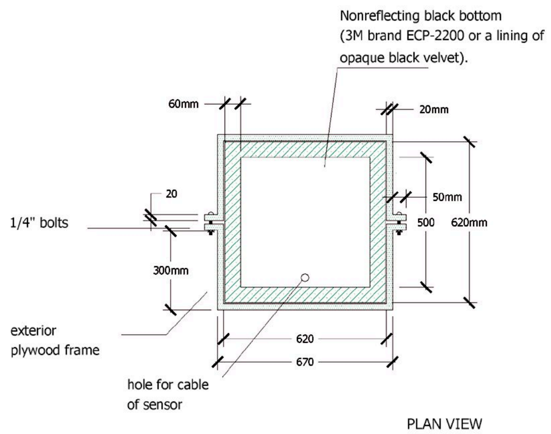


Fig. 4-2a Plan view of the test rig

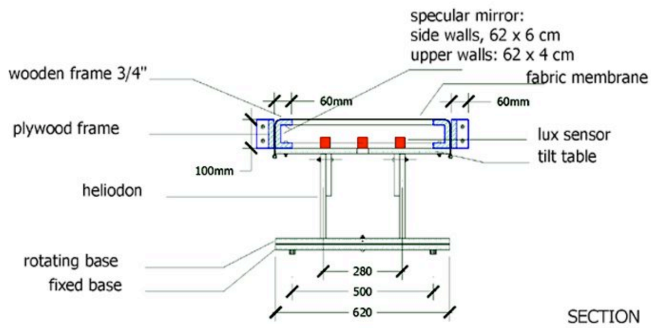


Fig. 4-2b Section of the test rig

The following figure illustrates the testing procedure followed to obtain the transmittance factors of three membrane samples (see Section 4.2.3). The test rig was placed inside the mirror sky of the School of the Built Environment that provided evenly diffused light. One light sensor was located inside the box underneath the membrane sample that was horizontally placed at the top of the box. On top of this box a second light sensor recorded the unobstructed horizontal illuminance incident on the membrane's surface. Both sensors were connected to a data logger, which recorded illuminance levels at one-minute intervals during one hour for each membrane sample. Then, the Transmittance (T_o) of the fabric is the ratio of the measured interior illuminance (E_2) and the exterior illuminance (E_1).

$$T_o = E_2 / E_1 \quad (4.1)$$

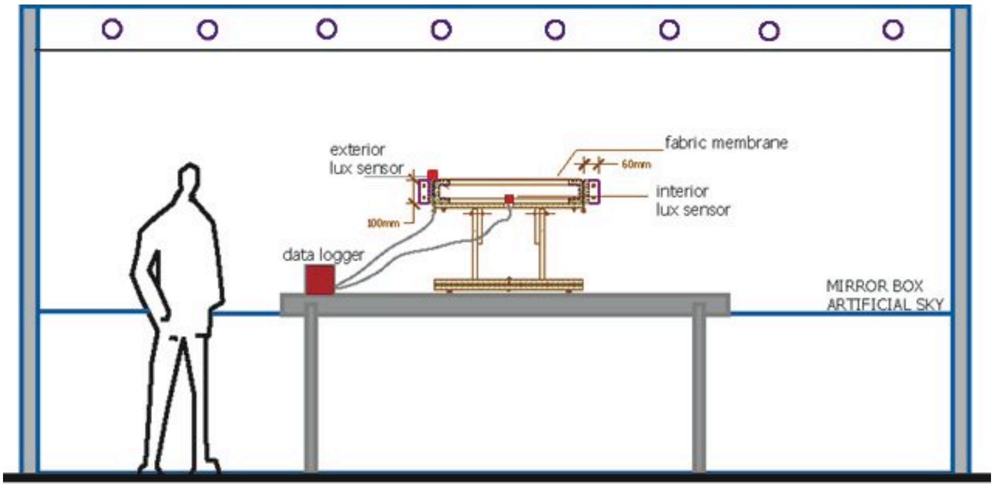


Fig. 4-2c Drawing of the testing procedure to obtain the light transmittance of fabric membranes.

People's lighting perception of a space depends more of the light that is reflected from surfaces than the light coming directly from the source. This reflected light greatly contributes to the illuminance levels in the building and to the penetration of light deep into the space. According to Baker and Steemers[12] reflectance is the ratio of the reflected energy to the incident energy, where perfect black would be 0 and perfect white would be 1. In order to record the reflection factors of the interior surface materials of the case studies, luminance measurements were taken on site using a Hagner photometer. This data was later used to accurately represent the optical properties of interior surfaces in the scale models.

The procedure (Fig. 4-3) included the selection of a reference sample with known reflectivity: Gore Tenara 3T40 100% fluoropolymer fabric woven with a reflection factor of 62% (ρ_{ref}), the material was provided by Architen Landrell. Under an overcast mirror sky, the reference sample was placed over the surface of interest; then, looking through the photometer the luminance was recorded (L_{ref}). After removing the reference sample, a record of the luminance on the surface of interest from the same distance and direction as before was recorded ($L_{surface}$). Then, the reflectance factor of the materials' surfaces in the buildings is obtained from the following Equation[13]:

$$\rho_{surface} = \rho_{ref} * L_{surface} / L_{ref} \qquad (4.2)$$

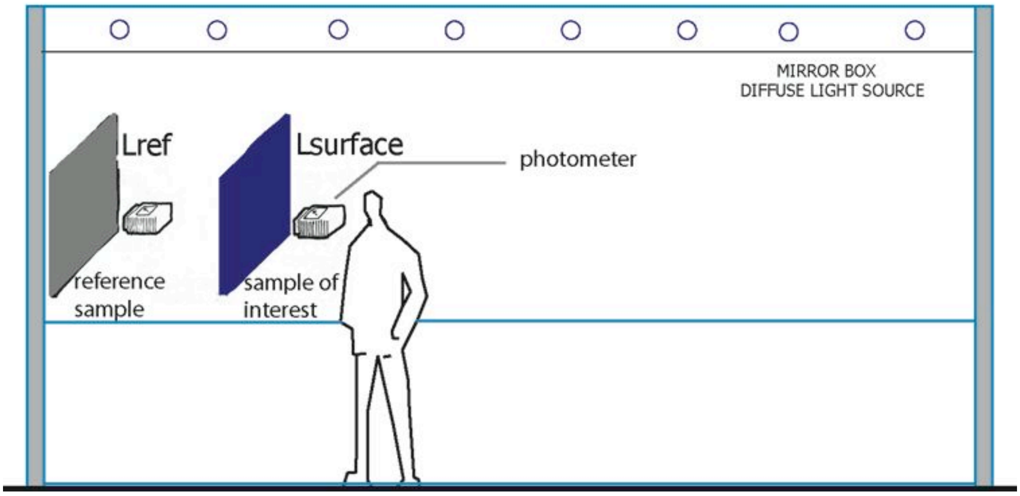


Fig. 4-3 Method for determining membranes' reflectance.

4.2.3 Selection of fabric samples

The fabric samples tested in the rig designed and built for this research included:

1. Sunbrella firesist 8604, modacrylic with a teflon finish
2. Holiday 707 flame retardant fabric, acrylic coated polyester (manufactured by Kayospruce Ltd.)
3. Lycra cotton fabric

The testing area of the fabric samples has a dimension of 0.60 x 0.60 m. The selection of these samples was based on the materials used in the case studies: fabric no. 1 was used in case study 1 (Lord's Cricket School) and fabric no. 2 was used in case study 2 (National Cricket Academy). The light transmittance of the fabric used in case study 3 (Amenity Building of the Inland Revenue Centre) was given by the manufacturer and the Lycra cotton fabric was tested in the rig to use it later to construct the physical scale model of this building, since it was impossible to use the real fabric at that scale.

4.2.4 Results

The nature of the fabric membranes analysed determines the optical properties of the materials, and therefore, their function in each building. The cricket centres have fabric membranes used as interior louvres aiming at diffusing daylight coming through the roof. Hence, the main features of these fabrics are their fire resistance and transmittance factors. The latter was increased with the fabric used in the National Cricket Academy (case study 2) with a 14.4% transmittance factor instead of the almost 7% of the fabric used in the Indoor School at Lord's. These fabrics require cleaning every three years and have a life span of five years.

On the other hand, the PTFE fibre glass fabric used in the Amenity building (case study 3) has been manufactured for outdoor use, with a life span of 25 years. The transmittance of this fabric is high (16%) and so is its reflectance factor (75%). This fabric is commonly used for permanent structures due to its high tensile strength, fire resistance, high durability and weather resistant properties.

The optical characteristics of these fabric membranes, whether used internally or externally, could be affected by the accumulation of dirt and weather exposure. This topic might be addressed in a further research.

The following Table presents the measured optical properties of the fabrics utilised in the case studies analysed in this thesis. This data was used for the buildings' computer and scale models developed for this research.

Table 4-3 Measured optical properties of fabric membranes

MATERIAL	WEIGHT (gm/m^2)	TRANSMITTANCE (%)	REFLECTANCE (%)	COLOUR
Sunbrella	314	6.7	46	Natural
Holiday	418.7	14.4	57.4	Ivory
Lycra	-	28.5	72.3	White
Lycra (2 layers)	-	15.8	72.3	White
PTFE fibreglass*		16	75	White

* This data was provided by the fabric manufacturer: Skyspan, web site available at http://www.skyspan.com

4.3 DAYLIGHT ANALYSIS OF CASE STUDY BUILDINGS

In order to understand the purpose and influence of fabric membranes in the lighting environment of sports halls, a series of on site lighting measurements were carried out in the three case study buildings. The main objectives, methodology, instruments used and sky conditions are described in the following sections.

4.3.1 Field measurements in case study buildings

On-site lighting monitoring is becoming a common practice among lighting professionals and researchers in order to investigate the lighting performance of existing buildings and the accuracy of computer lighting software to simulate the daylighting behaviour and the electrical lighting consumption of the buildings.

Galasiu and Atif[14] have pointed out the importance of validating daylighting and lighting software against real building measurements and monitoring. These authors have stated that it is essential to know the simulation capabilities and limitations of computer software when simulating real buildings with real occupancy.

4.3.1.1 Aims of the measuring programme

The main aim of this analysis and the daylight measurements taken on site in all three case study buildings is to obtain data that corresponds to the daylighting performance of the buildings and to compare it with the results of the computer modelling and the scale modelling. This comparison intends to validate the use of these two modelling techniques for their use as an effective prediction tool of daylight availability and control when using fabric membranes.

Other objectives are:

- To evaluate the performance of the buildings in terms of visual comfort only with daylight

- To assess the illuminance levels present in the playing areas and Daylight Factor
- To analyse daylight distribution and illuminance uniformity
- To study the effects of windows on the overall daylighting performance

4.3.1.2 Method adopted for the measuring programme

The areas selected for the field measurements are the main halls or playing areas, where higher light levels are required and the lighting environment is more important to perform the sports practised in each building. In addition, in these areas the roof solution becomes an essential part of the design of these buildings for both their lighting and visual performance.

A set of grid points were selected according to the dimensions and use of the space, for instance, in the cricket centres the training areas are divided into several playing lanes along the longitudinal sections of the buildings. Hence, the grid points were located to match the middle point of the width of each lane where the players usually stand.

The measurements took place under overcast sky conditions on different days of the year, according to the weather forecast and the availability of the space to carry out the measurements without causing too much trouble to the occupants. Measured parameters included simultaneous horizontal indoor illuminance collected every minute over each grid point at floor level (0.0 m high) and unobstructed horizontal exterior illuminance. However, in buildings 1 and 3 it was not possible to locate the exterior sensors on a complete unobstructed surface (i.e. the building's roof) and the estimate effect of placing the external sensor on a ground surrounded by obstructions will be discussed at the end of this chapter. In buildings one and three the exterior sensor was placed at floor level but in building two it was possible to place the sensor on a hill at 5.20 m high (Figures 4-4a, b and c).

In order to assure the simultaneity of the interior and exterior measurements, the clock of the data logger (used for interior readings) was set up matching the watch wore by the researcher located outside the buildings and also the watch wore by the researcher located inside the building. Specific times were established for moving the interior sensors around different measuring points (marked on a drawing plan) and for taking the exterior readings at the same time.

Finally, luminance from the surfaces of walls, floors and partitions were recorded to calculate the reflectance factors of the interior materials to use them to simulate these optical characteristics with the materials used in the physical models of the three buildings, as explained in section 4.2.2.

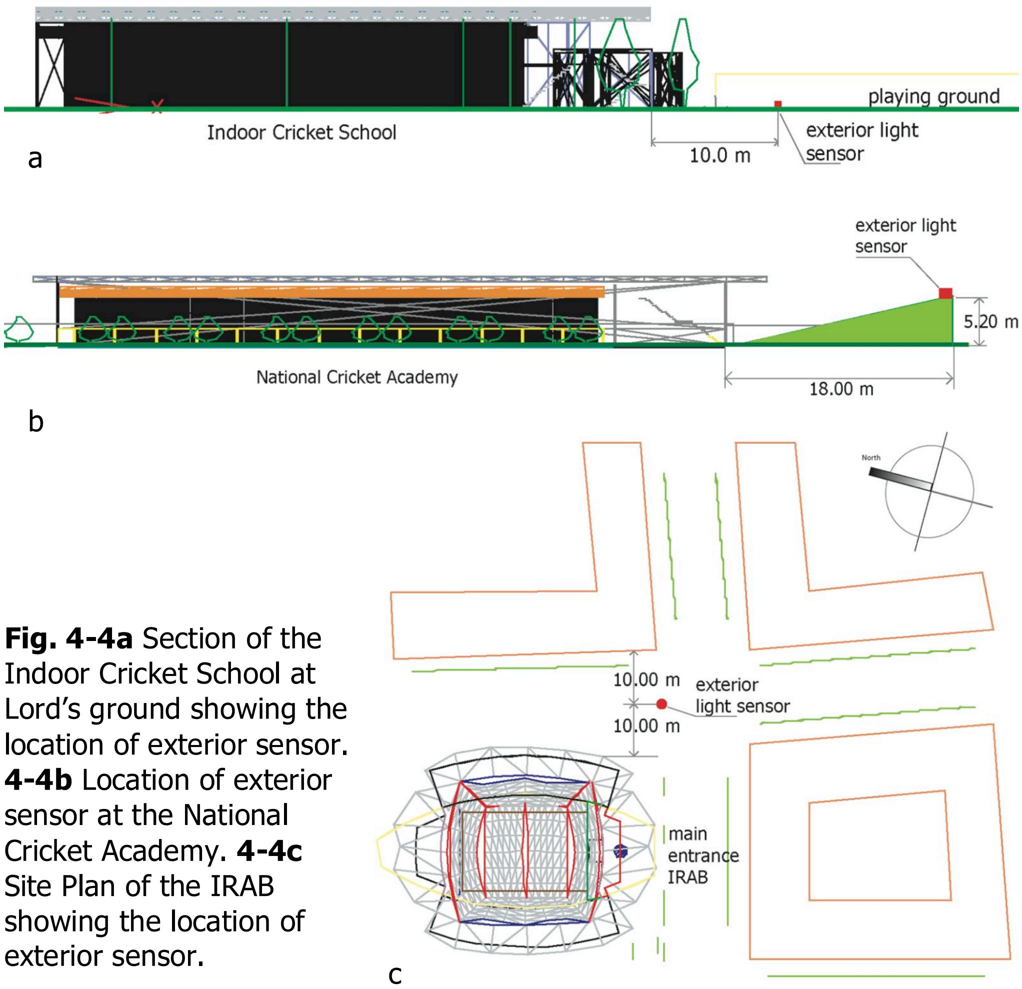


Fig. 4-4a Section of the Indoor Cricket School at Lord's ground showing the location of exterior sensor. **4-4b** Location of exterior sensor at the National Cricket Academy. **4-4c** Site Plan of the IRAB showing the location of exterior sensor.

4.3.1.3 Equipment used

The equipment used included the following:

- Six single channel photometric sensors Skye SKL 310. These sensors have cosine corrected heads, each containing a semi conductor diode and filter system that responds to light. The detector is a silicon photocell and the filters are glass type and/or metal interference[15]. These sensors were calibrated against a National Physical Laboratory UK reference standard lamp (Table 4-5). The sensors have a Data logger connector and one of them (sensor 00) can also be used with a hand-held Skye illuminance meter.

- A Data Hog 2 Skye Data logger (SDL 5000 series). The unit have a battery backed Random Access Memory (RAM), which stores all the logged data and also calibration factors. According to the manufacturers[16] the RAM may hold up to 11,001 records of data and time, in 121,020 bytes. A SkyeLynx Standard Communications Software version 2.6 is used to communicate and off-load data from the data logger to a PC.
- A Hagner universal photometer model S3 was used to measure the luminance levels. The instrument's output range is a min. of 10^{-2} lux or cd/m^2 and a maximum of 200,000 lux or cd/m^2.
- One tripod to lift the sensors
- A measuring tape was used to locate the grid points in the real buildings

Table 4-4 Calibration details of photometric sensors.

SOFTWARE CHANNEL	CALIBRATION CERTIFICATE No.	SERIAL No.	CALIBRATION FACTOR	DATE OF CALIB.
00	LUX/435/0103	SKL310/I120225423	0.1206 μAmps/kLux	Nov. 2002
01	LUX/432/0103	SKL310/I120225424	0.1117 μAmps/kLux	Nov. 2002
02	LUX/433/0103	SKL310/I120225425	0.1094 μAmps/kLux	Nov. 2002
03	LUX/434/0103	SKL310/I120225426	0.1205 μAmps/kLux	Nov. 2002
04	LUX/431/0103	SKL310/I120225427	0.1115 μAmps/kLux	Nov. 2002
05	LUX/436/0103	SKL310/I120225428	0.1027 μAmps/kLux	Jan. 2003

4.3.2 Analysis and results

4.3.2.1 Case study 1: MCC Indoor Cricket School

Measuring Grid

The field measurements in the cricket school at Lord's were taken in the training area, which consists of eight practice nets. This area is required to have a controlled lighting environment for an adequate cricket training. Roof-lights allow the access of daylight in this area; membrane louvres are located along four practice lanes under the roof of the hall. The general characteristics of the studied area are:

- Latitude: 51.4^{o} N
- Area: 1,548 m^2
- Height: 7.50 metres from the finished floor to the highest point of the membrane louvres.
- Minimum lighting level required: 1200 lux

With the purpose of determining the number of grid points and the distance between them, it was necessary to obtain first the Room Index (K), which is a measure of the proportions of the room[17]:

$$K = \frac{L \times W}{(L+W)h_m} \qquad (4.3)$$

Where L is the length of the room; W is the width of the room; and h_m is the height of the luminaires and fabric louvres plane above the horizontal reference plane.

The room index of the studied area is 2.79, and according to the relationship between room index and the minimum number of measurement points required to obtain an average illuminance with an error of less than 10% specified by the CIBSE Code for Interior Lighting[18], the minimum grid points required for this case study are 25 points. Though, because of the layout of the building it was decided to use a measuring grid of 56 points in order to take illuminance measurements in all the eight practice nets. The plan of the measuring grid is shown in Figure 4-5.

Sky conditions

The site measurements were taken on 20th June and 8th December 2005. The sky was predominantly overcast.

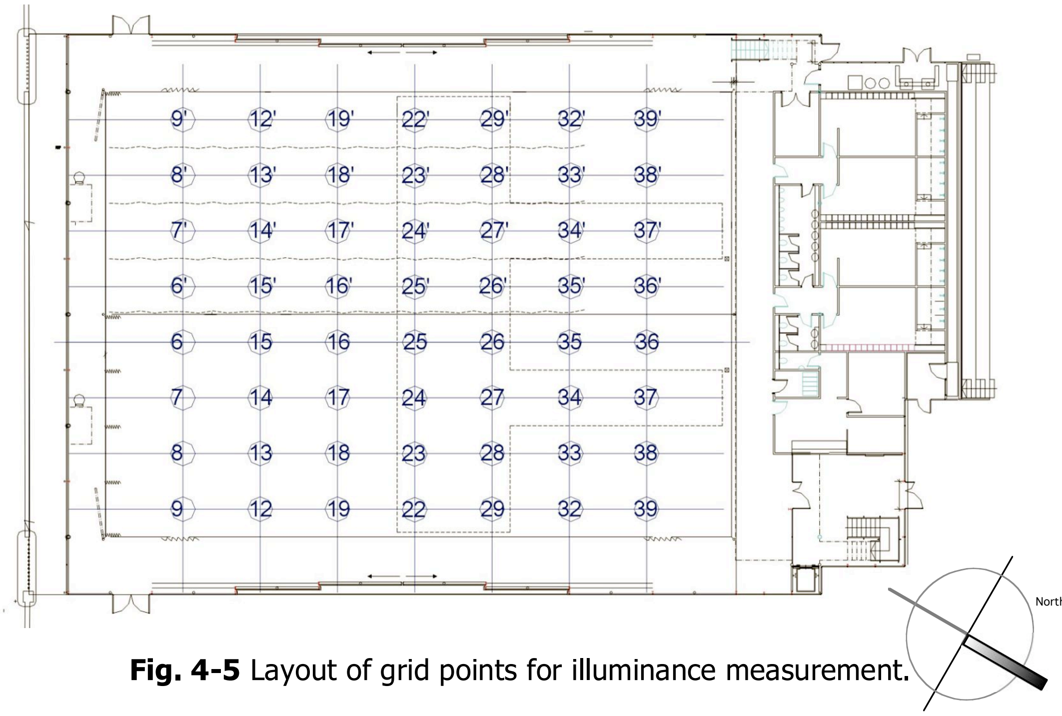


Fig. 4-5 Layout of grid points for illuminance measurement.

Results

The minimum interior horizontal illuminance recorded was 529 lux at 10:37 hrs; and a maximum of 2462 lux at 14:12 hrs. The minimum daylight factor registered was 2.95% and the maximum was 6.6%, with an average DF of 4.4%. Figure 4-6 illustrates the variation of daylight factors across the playing area.

The illuminance uniformity value obtained is 0.37, which shows quite an important variation of daylight in the interior space, considering that the CIBSE[19] recommends a value of 0.9 for cricket. This light uniformity allows the batsman and bowler to follow the movement of the ball without having to adapt their eyes to variations of light levels. According to Figure 4-6 the DFs variation corresponds to two factors:

- The opaque divisions located in each practicing lane in the wicket-keeping area (left of figure) reduce the amount of light reaching that section of the lanes.

- The areas with more daylight (yellow and light green) are found at both extremes of the building, and are probably influenced by the light that comes through the windowed areas of the main entrance (bottom right corner) and the emergency glass door and windows around the staircase (upper right corner of the drawing).

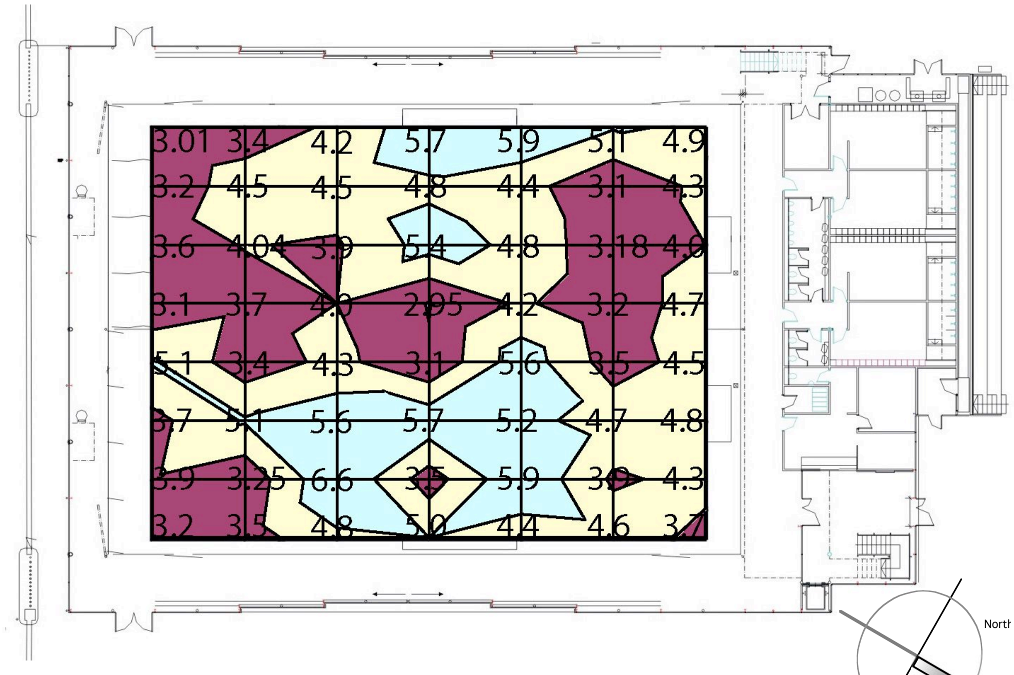


Fig. 4-6 DF (%) variation across playing hall

The long section of the building (Figure 4-7) shows the variation of DFs across one of the practicing nets located under an opaque section of the vaulted roof. Here, daylight availability is reduced by the opaque walls located at both ends of the lane (points 7 and 37); but in the middle points of the lane the variation of light is minimum, while maintaining a DF of around 5%. These figures demonstrate that this area is naturally lit.

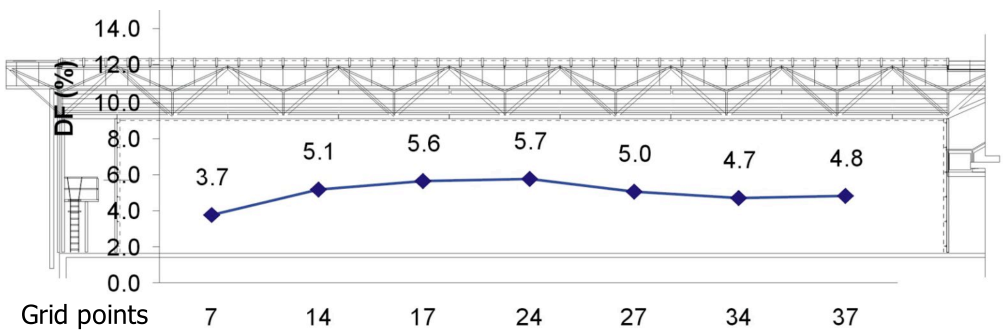


Fig. 4-7 DF (%) across a longitudinal section of the hall.

On the other hand, the long section across a playing lane located under a transparent section of the roof with fabric louvres has a different behaviour of daylight (Fig. 4-8). The variation of daylight factors is more evident from one point to the next one, following an undulating pattern. It seems that this behaviour repeats itself in all the practicing lanes located under the transparent sections of the roof. This is probably caused by the variation of the diffuse light of the sky, which occurs even under overcast conditions. Even though this daylight is diffused by the fabric louvres, if the intensity of light changes it will also change the amount of light that is diffused reaching the practice nets floor. This behaviour of course does not happen under the lanes covered by opaque roof, where the DFs are more constant.

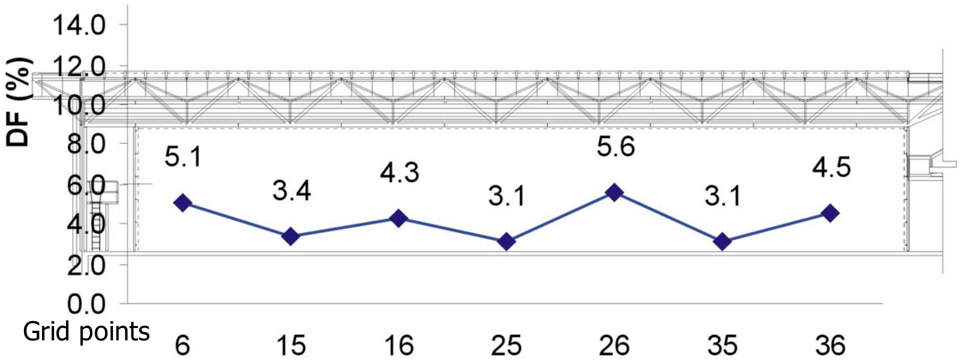


Fig. 4-8 DF (%) variation across a long section of the hall covered by membrane louvres

Figure 4-9 shows the variation of daylight factors across one section of the hall. This section passes through the area where the batsmen stand in each practice net. Opaque fabric encloses these spaces reducing the amount of light on the middle of each lane, hence the DF are quite low between 3% and 3.9%. It is notably higher the DF recorded over point six (5.1%), which may have been measured during a moment where the sky was brighter and since the point is located under a rooflight it was easily affected by this change on sky conditions.

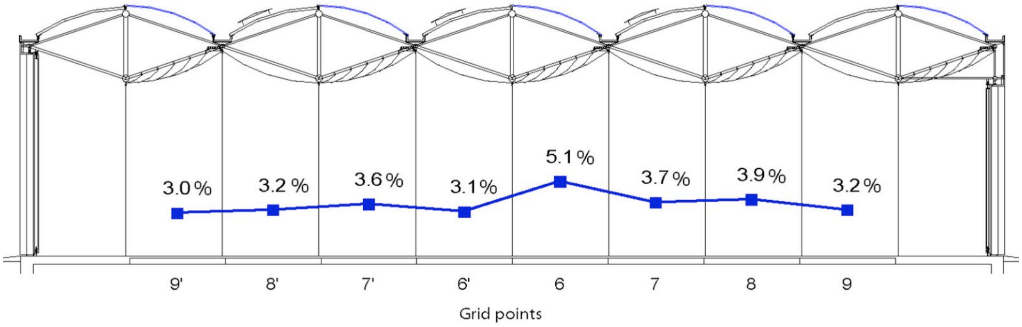


Fig. 4-9 Cross section through playing hall

A different cross section was cut through the grid points where the bowlers usually stand to start running and then throwing the ball to the batsman. Therefore, in this area of each lane is also essential to maintain constant light levels. The daylight factors obtained in this section are shown in Figure 4-10. Here, the minimum DF is 4.2% and the maximum DF is 5.9%; providing fairly uniform lighting. However, it can be noted that the values obtained on the lanes covered by fabric louvres are always higher than the DFs obtained under the opaque areas of the roof. It seems reasonable to think that the membranes diffuse daylight coming from the roof avoiding excessive light, but still there is more daylight available under these translucent sections than under the opaque roof.

The daylight factors in the section below are higher than the DFs presented in Figure 4-9 because in this area of the hall the practice lanes are not separated by the opaque vertical fabric, increasing the amount of light in the lanes.

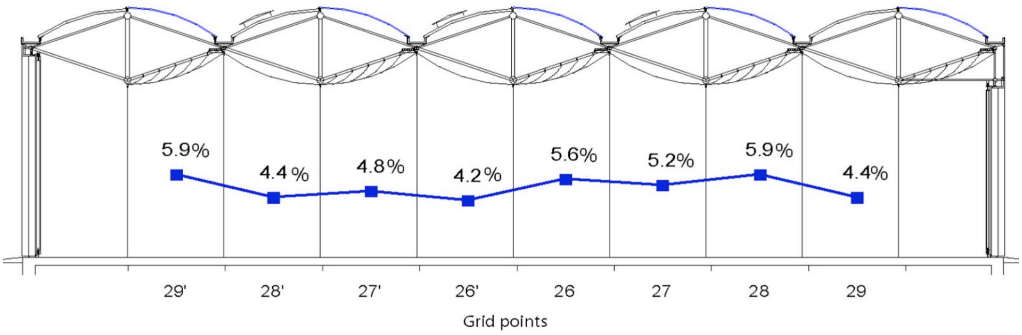


Fig. 4-10 Cross section through bowlers' area

The reflectance factors measured on site are shown in Table 4-5. Comparing this information with Table 4-2 in section 4.1.1, it can be noticed that the reflectance of the side walls and wall behind the wicket are almost in the lower level of the recommended range (60%), and the wall behind the bowler are in between the recommended range (40-60%). There is no specification for the reflectance factor of the floor, but the material has a low reflectance, it is opaque and it was also selected for its quality absorbing sound reducing the noise in the hall.

Table 4-5 Material properties assessed on site

SURFACE	COLOUR	REFLECTANCE FACTOR
Side walls	White aluminium	52%
Walls behind wicket and bowler	White cotton fabric	54%
Green Floor	Dark green synthetic grass	8.48%

Discussion

Although the average daylight factor obtained in the indoor cricket school at Lord's ground, 4.4%, does not indicate the building is completely naturally lit, it does provide important amounts of daylight in the playing area creating a pleasant environment.

The skylights in this building comprise 38% of the total roof area, providing daylight factors above 3% in the playing hall. This figure is lower than the minimum DF recommended by CIBSE of 3.5% (Table 4-2, section 4.1.1). In addition, during the winter illuminance measurements the interior horizontal illuminance recorded was always lower than the minimum recommended of 1,000 lux even with exterior illuminance of around 10,000 lux. However, this is the expected behaviour during winter when the sky is very cloudy and dull.

In order to achieve an interior illuminance of 1,000 lux with daylight considering a DF of 4.4%, it will be necessary to have an unobstructed sky illuminance of 23,000 lux. This occurs approximately 47% of the year in

London between 9 and 17.30 hrs[20]. During the winter months the daylight factor of the cricket school could provide around 400 lux on the playing hall with an exterior illuminance of at least 10,000 lux, which is likely to occur daily between 10 and 14 hrs in December, January and February[20].

The MCC indoor cricket school at Lord's Ground is the first attempt of building a daylighting cricket school, and although it is not a completely naturally lit building, the daylighting solution has reduced the use of artificial lighting.

Fig. 4-11 Interior view of Lord's

During the last decade David Morley Architects have designed and built a total of five indoor cricket centres with similar lighting strategies and solutions (Lord's, Edgbaston, Loughborough, Chester-le-Street and Gosforth)[21]. The following case study will demonstrate the improvements achieved with the experience of designing this type of daylighting cricket halls.

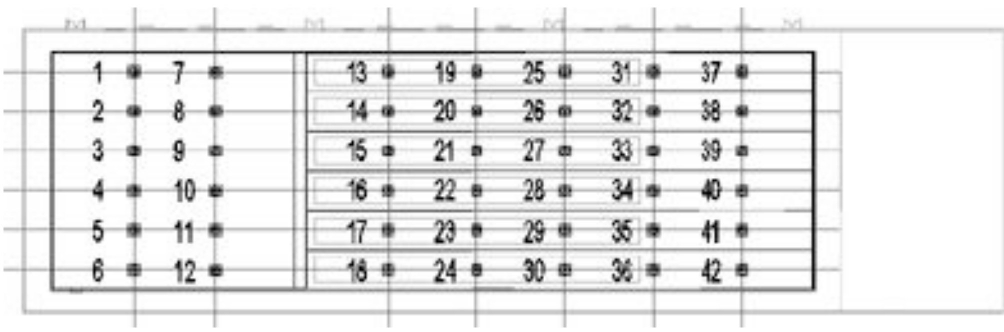
4.3.2.2 Case study 2: ECB National Cricket Academy

Measuring Grid

The specific part of the cricket academy chosen for this study is the training area, which is the main hall in the building and it is here where the light has to be controlled. This area is covered by fabric louvres located underneath the roof, and there are large windows situated at one side of the hall facing northeast. The general characteristics of the studied area are:

- Latitude: 52.83°N
- Area: 1914.36 m^2
- Height from the finished floor to the underside of the roof structure: 6.10 metres; height from floor to topside of the roof: 9.30 metres.
- Minimum lighting level required: 1500 lux; average DF=5%
- Number of practice lanes: 6; divided by a protective net and a cotton fabric in the wicket-keeping area.

The room index is 2.05, and according to the relationship between room index and the minimum number of measurement points to obtain an average illuminance value with an error of less than 10% specified by the CIBSE Code for interior lighting[18], the minimum points needed are 25. However, due to the spatial use of the Academy's main hall, a total number of 42 points were measured (Figure 4-12).



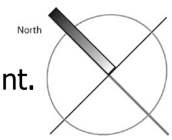


Fig. 4-12 Layout of grid points for illuminance measurement.

Sky conditions

The site measurements were taken on the 29th of June 2005, between 11:00 and 13:30 hrs. The sky was predominantly overcast.

Results

A minimum of 823 lux was recorded as interior horizontal illuminance at 11:08 hrs; and a maximum of 2155 lux was recorded at 11:49 hrs. The exterior horizontal illuminance varied between 16720 lux at 11:08 hrs and 29600 lux at 11:49 hrs. Figure 4-13 illustrates the daylight factor (DF) variation in the playing area at floor level; the minimum DF registered was 4.5%, the maximum was 7.3% and the average DF is 5.9%.

During the recording period the sky was very cloudy with light showers; while the unobstructed exterior average illuminance recorded between 11am and 1pm was 25526 lux.

Due to the limited number of lux sensors the illuminance measuring had to be taken during a morning session moving the sensors around the grid points. Illuminance values were recorded at every minute during periods of five minutes per grid point. The area with more daylight penetration is situated at the end of the playing zone (left of Figure 4-13); here lanes' partitions are rarely used allowing a more unobstructed penetration of daylight. This area is used by cricketers for warming up before training (Figure 4-15).

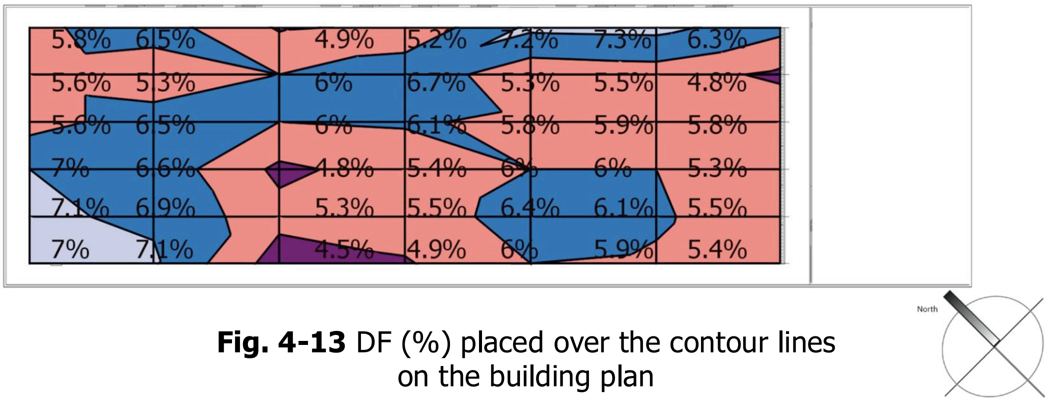


Fig. 4-13 DF (%) placed over the contour lines on the building plan

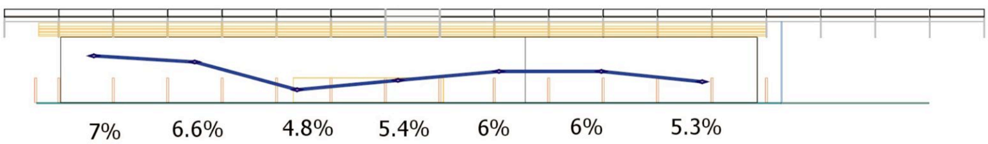


Fig. 4-14 DF (%) variation through the longitudinal section of lane 4

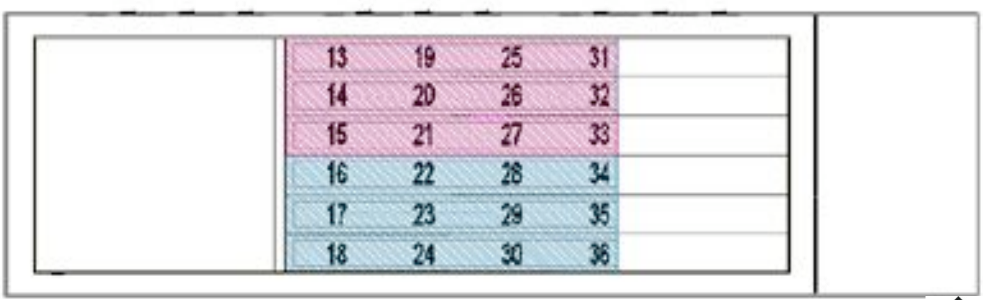
Fig. 4-15 Warming up area.

Fig. 4-16 Vertical fabric (blinkers)

The training area (points 13 to 42) has a variation of daylight factors of around 2.8% (absolute value). The greater DF (7.3%) occurred over points 25 and 31 which are located near the lateral window. The grid points located next to the vertical fabrics or blinkers that divide the lanes where the batsmen are situated (points 13, 16, 17 and 18) have low daylight factors compared to the first twelve grid points. Despite the high reflectivity of the fabric, the space becomes enclosed and is less influenced by the vertical window, restricting the access of daylight through the roof openings only (Figure 4-16).

The spatial variation of light has been defined as the uniformity or diversity of illuminance over the task and room surfaces in an interior space[22]. Illuminance uniformity is related to variation over the task area, and the term 'diversity' is used to show changes throughout the interior. According to Table 4-2 the illuminance uniformity recommended by CIBSE[19] is 0.9, in order to allow the batsman and bowler to follow the movement of the ball, which generally travels very fast. Excessive variations of illuminance over the task area and surroundings may affect the visual performance and comfort of the players.

For this analysis in particular, the studied area was reduced at only the training lanes, dividing it into two sub-sections. One of these sections is an area located close to the long window (red area); and the other one is located at the other side of the building (blue area) (see Figure 4-17). The purpose of this division is to facilitate the analysis of the illuminance variation and to assess the influence of the window over this variant. Each area includes the data collected from a total of twelve grid points per section.



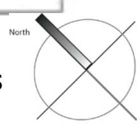


Fig. 4-17 Areas chosen for the Illuminance uniformity analysis

The Illuminance uniformity is 0.56 in the red area and 0.63 in the blue one. The illuminance uniformity of the whole building is 0.55. This information indicates that the illuminance variation is higher that the one recommended by CIBSE (0.9)[20]. However, these figures could still be considered acceptable being close to 0.66 or a ratio of minimum Illuminance : average illuminance = 1:1.5 recommended in the Lighting for Sports Halls published by the CIE in 1983[(3)]. Furthermore, the variation between the area close to the window and the area on the other side is insignificant; therefore, the window is not considerably affecting the illuminance uniformity of the chosen area.

The following sections show the Daylight Factor variation through the batting area (points 13 to 18), the bowlers' area (points 37 to 42) and the middle of the training zone (points 25 to 30).

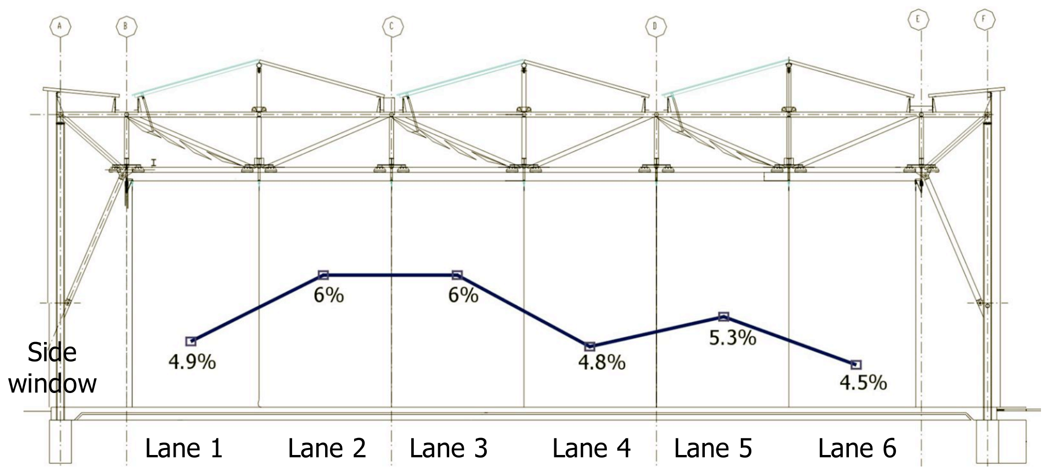


Fig. 4-18 Daylight Factors variation from point 13 to 18

The above figure represents the DF obtained in the points where the batsman is located in each one of the six lanes. Although the first point is located on the lane closer to the window, the DF is low (4.9%) compared to the DF of points 14 and 15. This could be caused by the fabric blinkers that surround point 13, which were removed from lanes 2 and 3, causing the daylight factors of points 14 and 15 to be higher and equal (6%). The fourth DF measured over point 16 is 4.8%, which represents a considerable reduction from point 15. Then the DF goes up again to 5.3%

and down to 4.5% in point 18 at the right side of the section. This behaviour responds to the geometry of the building roof and the location of the fabric louvres. These membranes are located underneath the transparent sections of the roof; therefore, more daylight access is permitted and diffused by the fabric towards different directions including the vertical fabric blinkers. From these partitions light is reflected to the playing lane bouncing several times while illuminating the space.

The grid points located under the opaque sections of the roof show a reduction of the daylight factors, 4.8% and 4.5% in lanes 4 and 6 respectively. This behaviour did not occur in lane 2 due to the removal of the fabric blinkers.

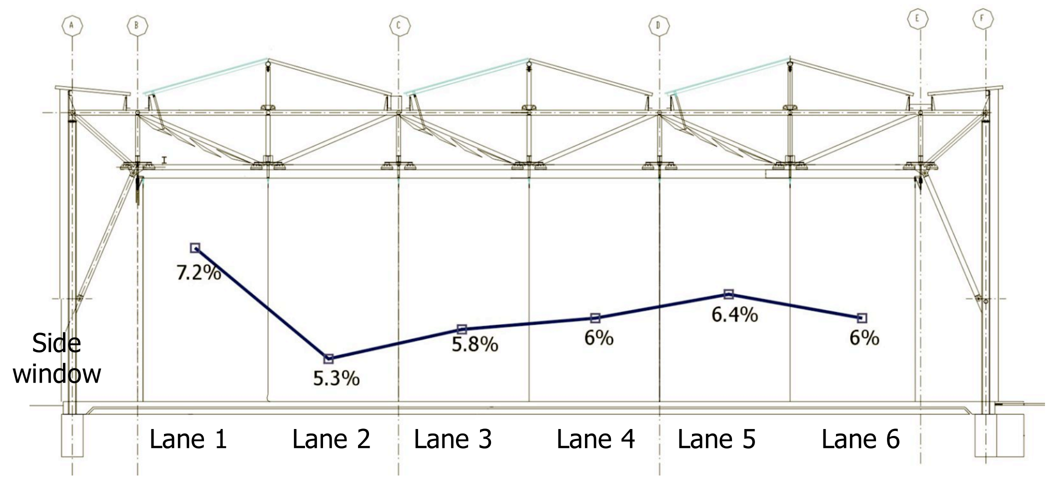


Fig. 4-19 Daylight Factor variation from point 25 to 30

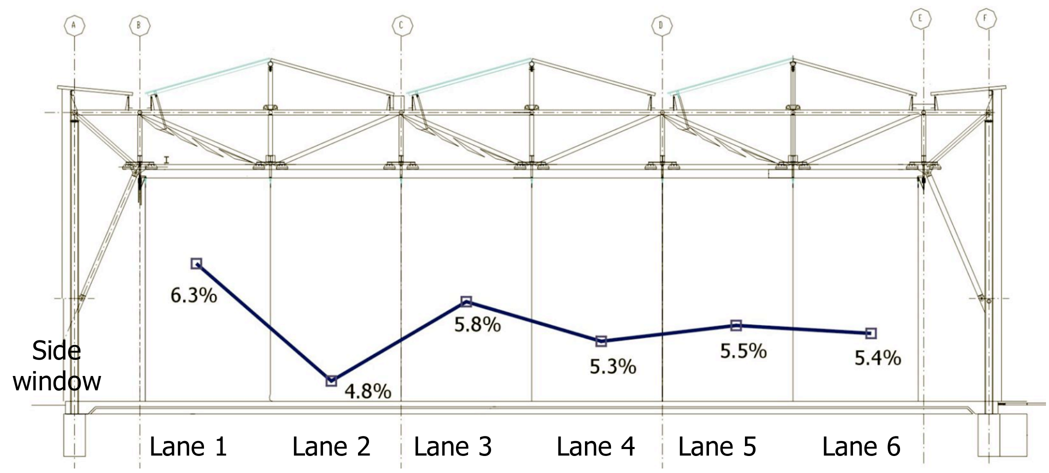


Fig. 4-20 Daylight Factor variation from point 37 to 42

Figures 4-19 and 4-20 illustrate the DF variation through two cross sections of the building. The results presented in both figures have a similar behaviour. Daylight availability responds to the geometry and layout of these areas. The peak daylight factors are found in lane 1 which is the nearer lane to the window. Then the DF drops down to 5.3% in Figure 4-19, and 4.8% in Figure 4-20; these points are located under the opaque section of the roof. It is important to take into consideration that points 25 to 30 and 37 to 42 are situated in a section of the training area with no fabric blinkers and no wing nets, which results in a more exposed area to daylight.

It can be concluded that in the last two figures daylight levels increased in the lanes located under the fabric louvres. However, DF variations were not very significant, except for the results obtained on the grid points of lane 1. In Figure 4-19 the DF varied between a minimum value of 5.3% and a maximum of 6.4% from lane 2 to 6. The DF in Figure 4-20 varied between 4.8% and 5.8%, among lanes 2 and 6.

The reflectance factors measured on site are shown in Table 4-6. Comparing this information with Table 4-2 section 4.1.1, it illustrates that the reflectance of the side walls and wall behind the wicket are almost in the lower level of the recommended range (60%), and the wall behind the bowler are in between the recommended range (40-60%). No specification is given for the reflectance factor of the floor, but the material has a very low diffuse reflectance and it is very rough and opaque.

Table 4-6 Material properties assessed on site

SURFACE	COLOUR	REFLECTANCE FACTOR
Side walls	White aluminium	53%
Walls behind wicket and bowler	White cotton fabric	54%
Green Floor	Dark green synthetic grass	6%

Discussion

The Daylight Factors obtained during the monitoring period did not fluctuate very much, the lowest one was 4.5% corresponding to grid point 18, and the highest was 7.3% on grid point 31. The average Daylight Factor is 5.9%, which indicates that the National Cricket Academy is a naturally light building. However, there were three moments registered between 11:08 and 11:20 am when the interior illuminance was below 1,000 lux (the minimum recommended to practice cricket in an indoor centre). This is significant because the points with illuminance lower than 1,000 lux are located in the batsman area (points 13, 16 and 19), exactly where more light is needed.

Despite the fact that the sky was very cloudy, the exterior illuminance increased with the morning sun path, at noon the higher exterior illuminance was recorded (32,900 lux). Nonetheless, the interior illuminance did not vary much maintaining approximately values of 1,900 lux. In order to maintain a minimum interior illuminance of 1,500 lux (design target) with the obtained DF of 5.9%, it will be necessary to have an exterior illuminance of 25,000 lux. This daylight availability occurs in the UK 46.9% of the year[20].

This situation is probably the result of many factors, such as:

- The orientation of the building. The lateral window that faces north-east was protected from direct sunshine since the sun was already at a low angle and on the opposite side of the building, where the building has no openings.
- The orientation and design of the roof. The transparent areas of the roof face north-east in order to let only the penetration of diffuse daylight into the building. The opaque sections of the roof block the afternoon sunlight.
- The fabric louvres. These fabric membranes are located underneath the roof structure exactly under the transparent sections of the roof. Their main function is to diffuse daylight providing a brighter and uniform interior environment, but avoiding the penetration of direct

sunlight that could cause glare. This fabric controls the illuminance levels of the interior space.

- The reflectance of the interior surfaces. The steel structure, the walls surfaces and the vertical fabrics that divide the playing lanes are all very reflective surfaces, causing several internal reflections of light.

Fig. 4-21a, b, c.
Interior of the National Cricket Academy.

4.3.2.3 Case study 3: Amenity Building, Inland Revenue Centre

The area studied during the field measurements was the main hall where people play basketball, badminton, volleyball and football. Sometimes children from the crèche are allowed to play in this area. This is the central area of the building and it is covered by a translucent membrane structure supported by four masts. The general characteristics of the studied area are:

- Latitude: 52.92° N
- Area: 536.50 m^2
- Highest point: 19 m (from finished floor to highest point of membrane roof)

- Minimum lighting level required: 300 lux; average DF= 5%

Following the method described in section 4.3.2.1, the room index was determined resulting in K=0.59; therefore a minimum number of 9 grid points had to be measured to obtain an average illuminance value with an error of less than 10%. It was decided to set a grid of 25 points to obtain a bigger picture of the illuminance distribution. The following figure shows the distribution of these points.

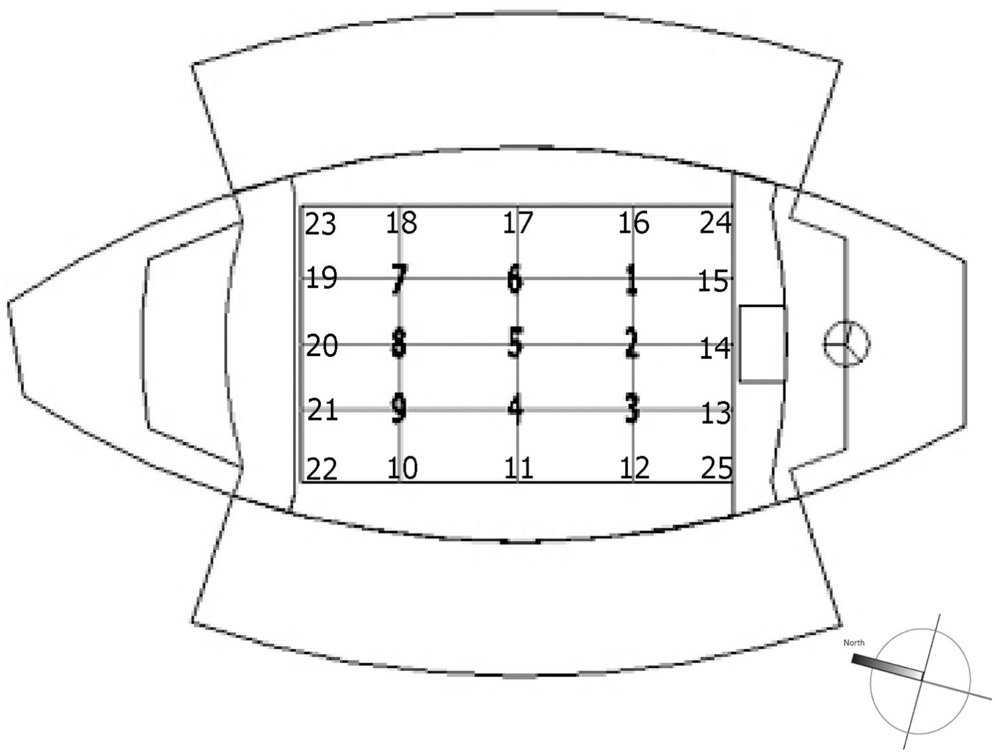


Fig. 4-22 Layout of grid points for illuminance measurements

Sky conditions

The field measurements were taken on the 2nd of February 2005, between 14:00 and 16:00 hrs. The sky on this winter day was overcast with an average exterior horizontal illuminance of 2031 lux. Furthermore, these measurements were complemented with readings taken on the 15th of September 2005, between 16:00 and 18:06 hrs. The sky was overcast with an average exterior horizontal illuminance of 4257 lux.

Results

The grid zone more exposed to daylight is the centre of the sports hall (between points 1 to 9), where the illuminance level registered was 2002 lux, which is the highest value recorded in the playing court. Illuminance levels dropped in the points located close to the walls of the other areas of the building, which have low surface reflectance factors. The minimum interior illuminance level is 216 lux in grid point number 24. Figure 4-23 illustrates the daylight factor variation in the playing area at floor level; the minimum DF registered was 16.4%, the maximum was 32.6% (over point 8) and the average DF is 24%.

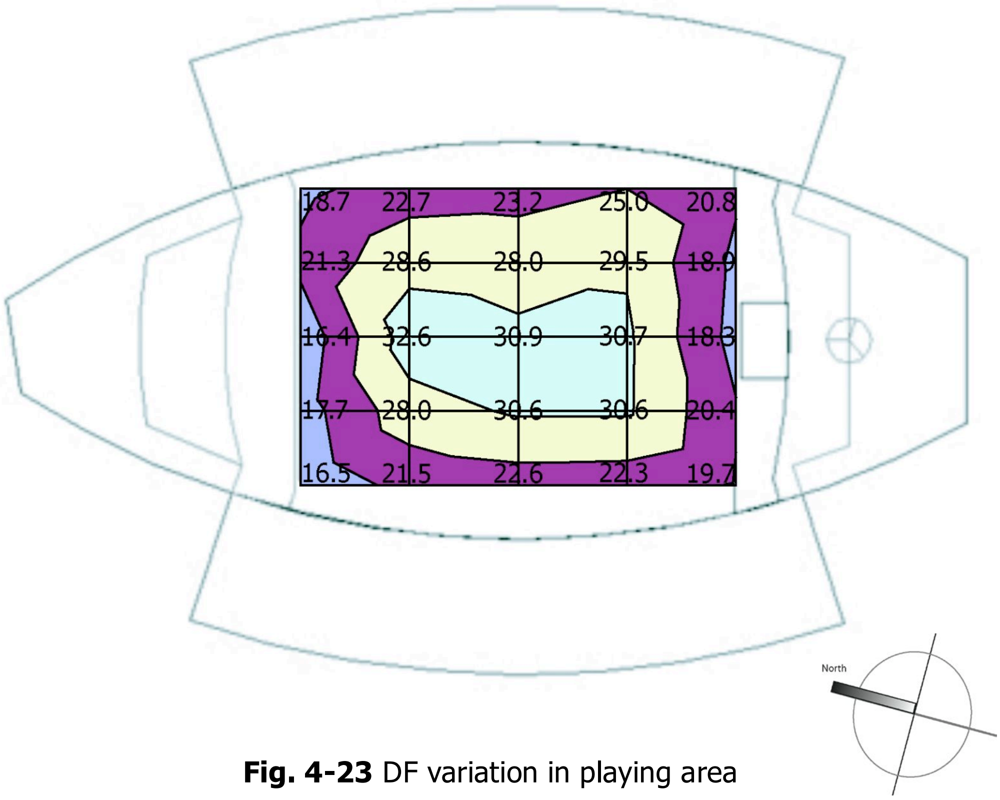


Fig. 4-23 DF variation in playing area

The average interior horizontal illuminance registered was 750 lux, which is more than the minimum required for the activities that take place in the space. According to Table 4-2 section 4.1.1 the average illuminance required to play badminton, basketball and volleyball at an amateur level is 300 lux. This building allows the penetration of an important amount of daylight even in a very dull day with an average exterior illuminance of 4257 lux. At the time when the field measurements were taken the building was in use and there was no need of artificial lighting, which contributes to reduce the energy consumption of the building. However, in a daylighting and very bright building like this one, it is important to take into consideration at a design stage, the probable presence of glare.

The following figure shows the daylight factor variation through the centre of the playing area in the longitudinal section of the building. The highest value is obtained over point eight (32.6%), which is caused by the shape and finishing materials of the main entrance façade situated on the south side of the building, and the north facing façade where the crèche is located. The latter has a bigger surface area where daylight can be reflected reaching the sensor located in point 8, elevating the daylight factor in that point.

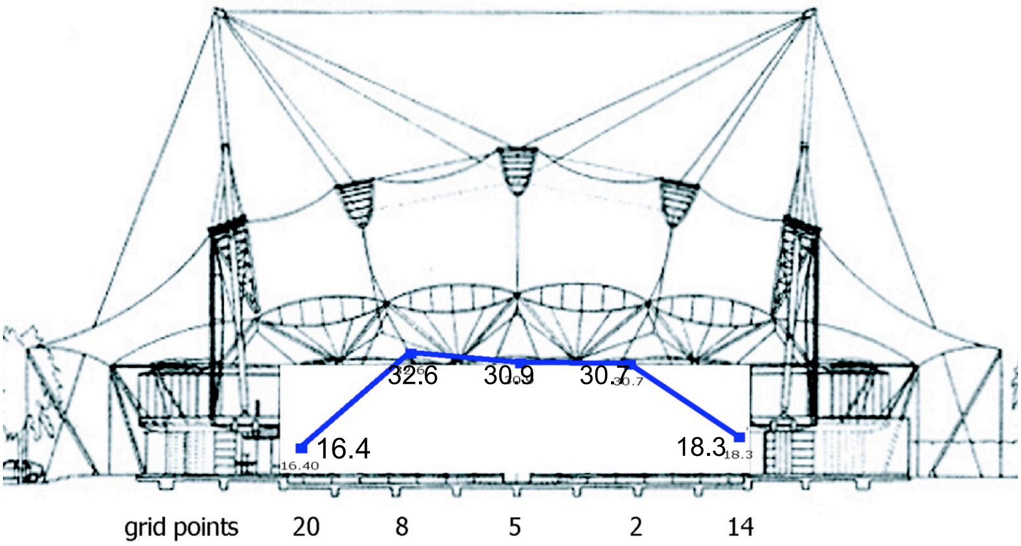


Fig. 4-24 DF (%) variation through longitudinal section

Figure 4-25 shows the behaviour of daylight through points 11, 4, 5, 6 and 17. As it was expected, while the height roof increases the DF and the exposure to daylight increase too. Furthermore, at the centre of the sports hall there is less influence of the lateral building blocks within the lighting behaviour of the space. However, the difference among the three measurement points is not very significant; daylighting availability in this building is high and relatively uniform throughout the interior space under an overcast sky.

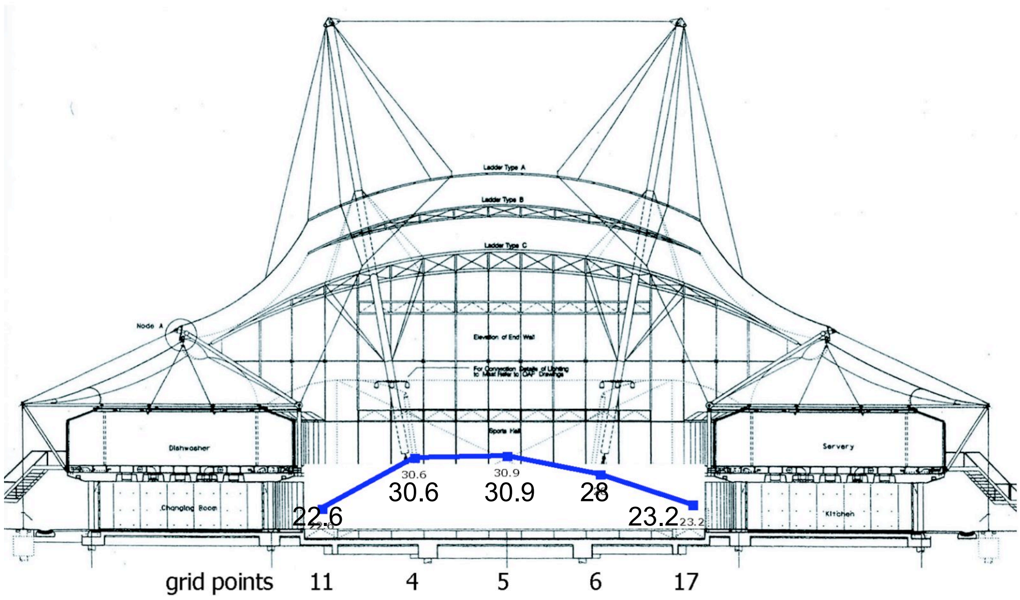


Fig. 4-25 DF (%) variation through section in points 11, 4, 5, 6 and 17

The illuminance uniformity calculated in the main hall from the readings taken on site in February 2005 is 0.89 (grid points 1 to 9). This figure indicates that the space is uniformly lit and that there is a negligible variation of illuminance levels over the task area. However, the readings taken in September 2005 showed the sensitivity of the building to exterior daylight variation. A maximum exterior horizontal illuminance of 9300 lux was recorded at 16:05 hrs; while a minimum exterior horizontal illuminance of 1040 lux was recorded at 18:00 hrs. This variation caused an illuminance uniformity of 0.29 within the 25 grid points.

The reflectance factors of the interior surfaces measured on site are included in Table 4-7. According to Table 4-2, the floor reflectance is on the upper limit of the range of reflectance factors recommended for badminton (0.2 to 0.4). Although the recommended walls reflectance factor for playing badminton is quite low (0.2) to be able to see the shuttlecock, the surrounding walls reflectance measured on site is 0.08; the difference between this dark surface and the bright roof and floors could cause visual problems while trying to constantly adapt the vision to different levels of light reflected from surfaces. For basketball and volleyball the recommended walls reflectance ranges between 0.4 and 0.6.

Table 4-7 Material properties assessed on site

SURFACE	COLOUR	REFLECTANCE FACTOR
Wooden floor	Brown	42.47%
Walls of side blocks	Dark grey	7.99%
Floor in corridors	White	47.29%
Membrane in roof*	White	75%

*Data obtained from Skyspan: www.skyspan.com

In order to maintain a minimum interior illuminance of 300 lux (minimum necessary to be able to play badminton, basketball, volleyball) with the obtained DF of 24%, it will be necessary to have an exterior illuminance of 1,300 lux. This daylight availability occurs in the UK 92% of the year[20].

Discussion

The high daylight factors found in the Amenity Building respond to the following aspects:

- The roof solution and materials. The translucent fabric membrane that covers the main hall, the 'eye' shape windows and the glazed north and south façades of the building produce a very environmentally sensitive building.
- The transmittance and reflectance properties of the fabric membranes that cover both sides of the building. These membranes are high reflective surfaces and contribute to the high lighting levels found in the main hall.
- The geometry of the roof and the combination of fabric membrane with glass allow the penetration almost unrestricted of daylight and sunlight through the glazing areas (Figures 4-26 and 4-27).
- The playing area has a polished wood floor with high reflectance: 42.47%; and the floor of the adjacent corridors is 47.29%.
- The height of the roof in the playing hall reaches 19 metres at the highest point. This characteristic together with the outside views provides a sensation of being outside barely protected by the fabric tent.

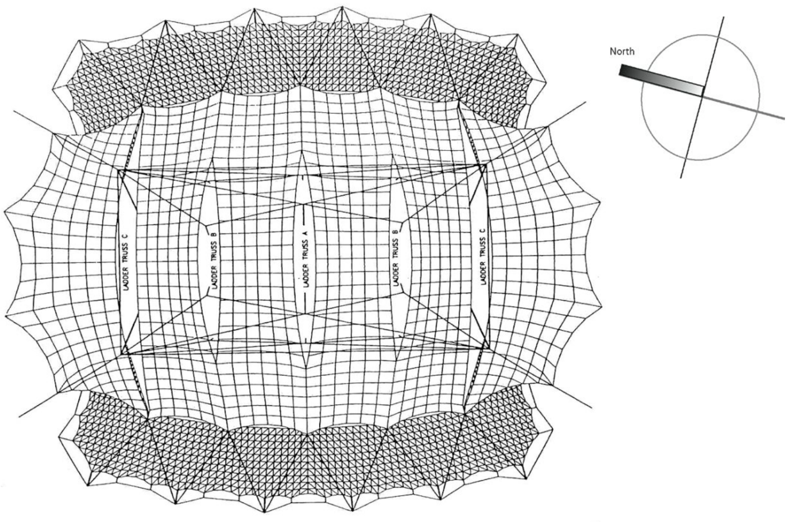


Fig. 4-26 Fabric roof plan (Hopkins).

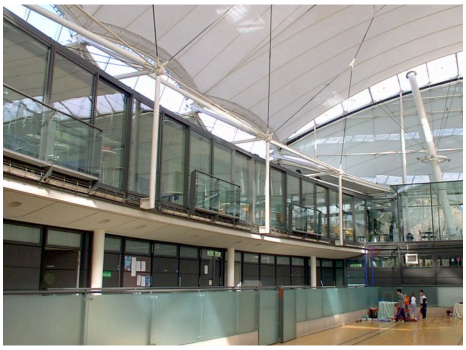


Fig. 4-27 Sunlight on the playing area coming from the glazing areas of the roof, IRAB.

Fig. 4-28a-d Interior views of the Amenity Building, Inland Revenue Centre, Nottingham

4.3.3 Effect of placing external sensor on ground with distant obstructions

In order to obtain daylight factors of an existing daylit building through field illuminance measurements, it is essential to simultaneously record the unobstructed sky illuminance with measurements taken inside the building. Sometimes due to technical, occupancy or maintenance problems it is not possible to place exterior sensors on the roof of the evaluated building to assure completely unobstructed sky illuminance readings. For instance, for this study the shape of the Amenity Building (IRAB) in Nottingham made unfeasible to place sensors on the roof and security restrictions made impossible the entrance to adjacent buildings.

The computer model of the IRAB and all its adjacent buildings was used to evaluate the effect of obstructions on the exterior sensor placed exactly where it was placed during the site measurements reported in this chapter (Fig. 4-4c).

Results show that the unobstructed sky illuminance (USI) considered by Radiance (11,632 lux) is slightly higher than the sky illuminance recorded by the external light sensor placed at ground level (10,303 lux). This difference caused slightly low average daylight factors in the field studies of buildings one and three. The divergence found between both studies, with a completely USI and with some obstructions, is around 11%. Table 4-8 shows the measured average daylight factors and results after correcting them for the USI divergence.

Table 4-8 Average daylight factors obtained with/without USI

BUILDING	FIELD DF without USI	DF WITH A CORRECTION FACTOR OF 11%
1. Lord's indoor cricket school	4.4%	4.88%
3. IRAB	24%	26.6%

4.4 CONCLUSIONS

The field study carried out in three case study sports buildings included the measurement of interior and exterior horizontal illuminance. These values provided the daylight factors of the buildings and their illuminance uniformity.

The findings indicate that the National Cricket Academy (Loughborough) is a daylight building with a DF of 5.9%. Daylight access the building through roof-lights facing northeast catching only the diffuse part of the sky. This daylight that comes into the playing area is controlled by membrane louvres located under the skylights. These structures avoid an uncontrolled penetration of light creating a steady lighting environment with enough light to practice cricket.

Even though the Indoor Cricket School at Lord's ground in London was designed with a very similar solution than the National Cricket Academy, its lighting performance is not as good. The average DF found is 4.4%, which indicates that a significant part of the interior lighting comes from the sky. However, the interior environment is not as bright as in Loughborough; this may be caused by the ageing of the interior surfaces since Lord's was built eight years before Loughborough, and the light transmittance of the membrane, which is considerably lower in Lord's (6.7%) than in Loughborough (14%).

The average DF obtained in the Amenity Building of the Inland Revenue Centre (IRAB) was very high: 24%. This produces a very bright environment where artificial lighting is rarely used in the playing area. The centre of this area is the most exposed to daylight having a very high roof (19 metres), a translucent PTFE membrane as roof with a light transmittance of 16%, and glass sections in between the membrane roof. It was observed that not only diffuse daylight penetrates the building, but also direct sunlight. This could produce a problem of overheating during the summer but could also cause discomfort glare to occupants.

The limitations of the field study include:

- The limited number of lux sensors available and the dimensions of the buildings made it impossible to take the interior illuminance measurements simultaneously in the whole playing areas.
- The location of the exterior sensor in buildings 1 and 3 was not completely unobstructed due to security restrictions to place exterior sensors on the roofs.
- The unpredictable weather conditions. Despite of having overcast skies most of the time, some days the sky conditions changed rapidly particularly during the afternoon making it difficult to use those measurements and having to obtain different sets of data.
- The occupancy and availability of the buildings. To carry out this type of study it is necessary to have full access to the area of interest. Even when only part of the building was in use at the time of the measuring process, balls hit by players were very fast making it dangerous to be around with the measuring equipment. Moreover, keeping artificial lights off was sometimes difficult because of the lack of sufficient daylight to illuminate the space while people were playing.

Nevertheless, the field study has shown the overall lighting performance of three daylighting buildings with high lighting demand. It is clear that daylight represents an important contribution to the lighting environment of these buildings.

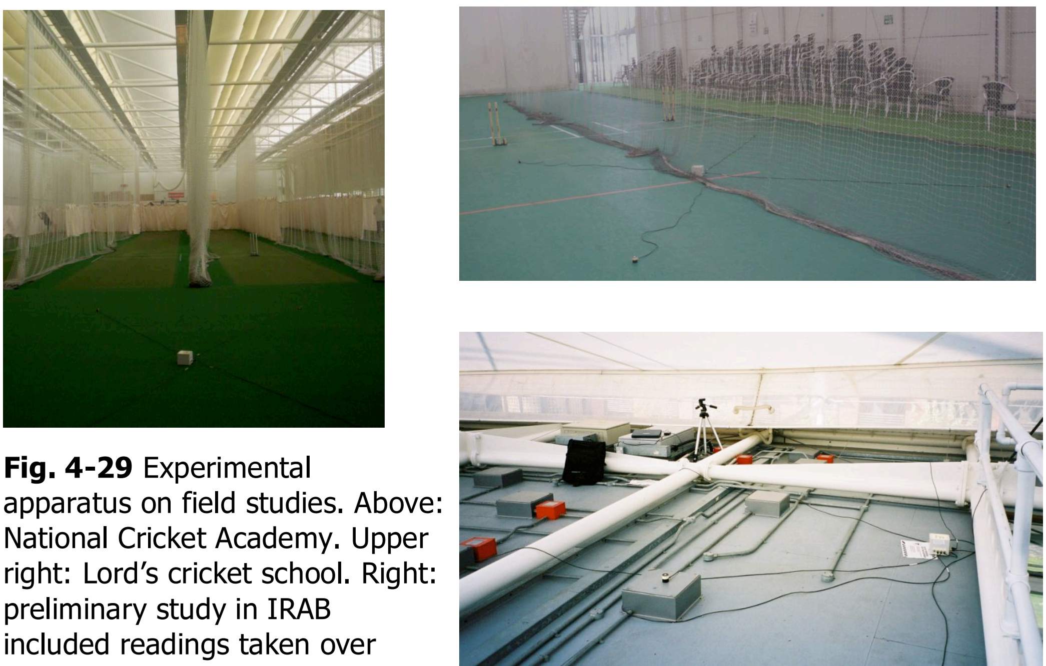


Fig. 4-29 Experimental apparatus on field studies. Above: National Cricket Academy. Upper right: Lord's cricket school. Right: preliminary study in IRAB included readings taken over interior roof at 6m high.

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4.5.1 Figures and tables

Five

5. PHYSICAL MODELLING

One of the traditional techniques to evaluate the performance of a daylighting system at the design stage has been scale modelling. However, recently, some companies and universities have developed computer software, which aim to simulate daylighting in buildings reducing the cost and time spent in making physical models.

Nonetheless, scale model studies still represent a flexible and accurate method to carry out lighting analysis. The small size of light wavelengths allows the use of scale models for daylighting studies since the physical behaviour of light is the same for a full-size room as for a properly constructed scale model.

This chapter includes an evaluation of the existing body of knowledge regarding scale modelling, and results from the lighting study of the scale models of the three case studies selected for this research (see sections 3.2.3, 3.2.4 and 3.2.5) are presented and analysed.

The main objective of this study is to evaluate scale modelling as a tool to simulate and study daylight in tensile fabric membrane buildings. This aim is achieved through an assessment of the daylighting performance of the case studies in terms of Illuminance variation and Daylight Factor measurements. The results presented in this chapter are then compared with the field measurements and computer modelling of the same buildings in chapter 7 of this thesis.

5.1 PHYSICAL MODELLING IN ARCHITECTURE

5.1.1 Artificial sky

Probably one of the most traditionally used methods for prediction and evaluation of interior daylight illumination in buildings is physical modelling. Advances in this matter and lighting simulation allow for daylighting systems' evaluation under realistic sky and sun conditions. In addition, scale models can be used to simulate complex geometries and allow quick changes to the geometry and materials employed.

The testing stage of daylight scale models can be carried out under a real or artificial sky. The cheapest way is the real sky option but it also presents some risks such as unpredictable weather conditions, which change considerably the interior illuminance levels. For daylight factor measurements it is necessary to make the study under a close approximation to the CIE overcast sky.

There are two types of artificial sky[1]: the hemispherical dome and a mirror box (Fig. 5-1a & b).

a

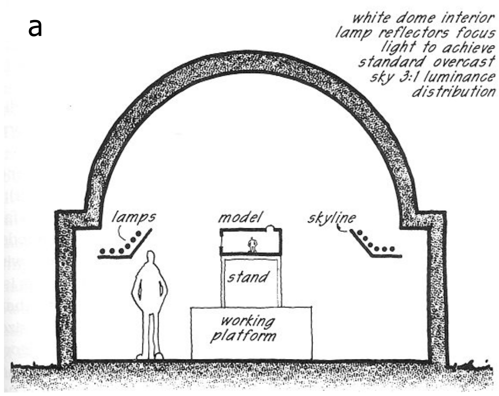
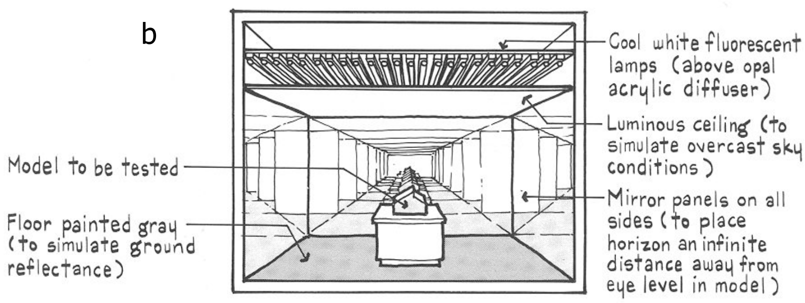


Fig. 5-1a Sky dome (left) [1].

Fig. 5-1b mirror box (below) [from Egan, 1983].

b



In a sky dome the required luminance distribution is projected onto a reflective hemisphere, which acts as the sky vault; and it is possible to install an artificial sun[2]. This artificial sky presents some disadvantages, such as:

- The dome needs to be at least five times the width of the model, so the luminance is uniformly distributed.
- With a tall model different parts of it can experience horizon error caused by light from below the horizon reaching points at the top of the model.
- The size and shape of a dome-type sky make expensive to build one and to locate it in a room.

Mirror box skies have been used for many years; Hopkinson et al.[3] have mentioned Pleijel as one of the first persons that used a mirror box in 1949 and himself together with Longmore and Petty in 1951. Mirror skies are square rooms with a luminous ceiling and mirrored walls. The mirrors reproduce an infinite horizon and the sky is a good approximation to the CIE overcast sky. A mirror box is easier to set up than dome skies and can be placed in a conventional square room. However, this type of artificial sky presents some disadvantages pointed out by Littlefair[4]:

- The CIE overcast sky is the only possible sky luminance distribution
- An artificial sun cannot be used
- Large models with no external obstructions can have multiple reflections of the model in the mirrors and this can affect the lighting measurements inside the model.

When using a mirror box the dimensions of the model should not exceed 30-40% of the sky dimensions for a rooflit building; and around 20% for models with vertical windows on two opposite sides[5].

It is always advisable, for reference purposes, to measure sky illuminance outside the model before or while recording data from the model itself. Artificial skies in the United Kingdom can be found at The University College London (UCL), which comprises 270 light sources; Cardiff University (UWCC) (Fig. 5-2 a & b) with 640 individual luminaries[6], The University of Liverpool, The University of Bath, The University of Cambridge, The Sheffield Hallam University and The University of Nottingham.

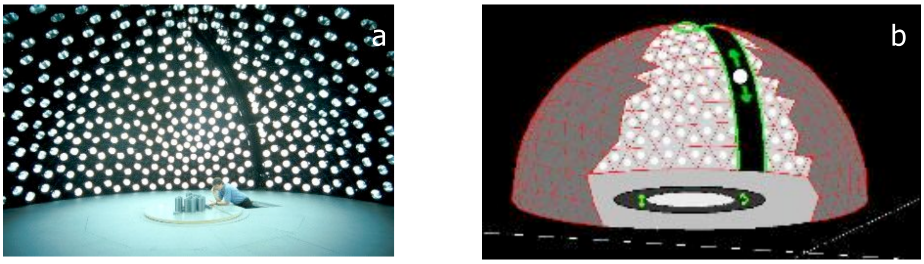


Fig. 5-2a & b Artificial sky and heliodon structure at Cardiff University [6].

5.1.2 The model and equipment

Some authors and institutions have pointed out the general characteristics that a scale model for lighting studies must have[2,3,5,7,8,9,10]. The main purpose of physical modelling is to accurately represent the behaviour of daylight in a building, and to achieve this it is necessary to follow some guidelines:

The geometry must be as similar as possible to the real building including interior partitions, staircases, apertures and fenestration that could influence the behaviour of daylight in the space. If possible, it is advisable to include all room surfaces. Windows details and rooflights must be modelled because they can significantly affect the distribution of daylight within the space.

- Surface reflectance (walls, ceiling and floor) must be modelled correctly and as close as possible to those of the proposed or real building. The walls should be absolutely opaque.
- The researcher must be able to gain access to the interior of the model for positioning the sensors and for visualisation purposes. Solutions could be: movable walls, roofs or holes in the floors just big enough to pass a photometer head or a light sensor.
- All joints in the model should be lightproof. Tape, paper or paint can be used to cover cardboard, foamboard or other model materials in

order to avoid light penetration and to represent the real surfaces' reflectance.

- The scale of the model depends on the size of the photocells used in the study, the size of the building to be modelled and the type of sky and dimensions of the artificial sky. Under real skies there is no maximum size of the model. Littlefair[11] suggests a minimum model size of 1:40 scale for a standard working plane of 0.8 m above the floor. However, Baker and Steemers[12] argue that the choice of scale is directly related to the particular purpose of the study (Table 5-1).
- External obstructions should be modelled especially when the building is side lit. The dimensions and reflectance of the obstructions must be accurately modelled. Trees, near buildings or lawns are some of the most common external obstructions that had to be included in the study.
- The location and number of measuring points must be defined in advance. The light sensors will preferably be placed in areas where main activities are developed, areas with major occupation levels or where light levels and quality are essential to carry out certain activities.
- Space contents such as sensor holders can influence the light levels by an increment of internal reflections. It is advisable to paint matte black all holders or cables placed inside the model.

Table 5-1 Scale choice in relation to purpose of study (reproduced from [12])

SCALE	PURPOSE
1:500 – 1:100	For preliminary design and concept development To provide an overall sense of the massing of the project. To study the shadows cast by the future building or by neighbouring buildings
1:200 – 1:10	To determine unwanted reflections on a glass façade To study direct sunlight penetration into a building (e.g. efficiency of solar protection) To study diffuse daylight in a very large space (e.g. atria)
1:100 – 1:10	To consider detailed refinement of spatial components To obtain highly detailed inside views (e.g. for video or photographs) To study accurate diffuse and direct daylight penetration

The equipment required to carry out daylight factor measurements include illuminance sensors placed inside and outside the model. Under real skies interior and exterior measurements should be taken simultaneously and under unobstructed sky since daylight levels vary constantly. In an artificial sky, the external illuminance can have slightly variations and therefore, it must be recorded at least after ten internal measurements.

The illuminance sensor used to measure the interior illuminance must be a photocell on a long lead, so the researcher can stand as far away as possible from the model avoiding obstruction when taking readings. Appropriate colour and cosine corrected photocells should be used.

Photographs inside the model can be taken placing the camera outside the model and taking the photograph through an opening or trapdoor using a wide angle lens.

5.2 EXISTING BODY OF KNOWLEDGE

5.2.1 Physical modelling for daylighting studies

Scale models are commonly used for daylighting studies despite the rapid development of computer programs for daylighting simulation. Designers use scale models during the design stage of a project and researchers use them as a tool to investigate daylighting behaviour in daylit buildings with complex geometry, such as atrium buildings or rooflit spaces.

In 1993 Love[13] published the findings of a study regarding the understanding of over-estimates of the internally reflected component obtained by scale model photometry under clear and overcast skies.

Workplace illuminance measurements in two scale models (1:12 and 1:3 scales) were compared with corresponding illuminance measurements in full-scale spaces (2.7m high x 2.7m width x 7.3m depth) with one typical office window (0.90 x 1.2 m). One space had very low reflectance interiors while the other had very high reflectance materials. The first one provided estimates of the sky component and direct sunlight, then, the internally reflected component was determined by subtracting those readings from illuminance values taken simultaneously in the higher reflectance space. Same interior materials were used in the full-scale spaces and the scale models. Photocells were located along the central axis of the space in five different positions; and illuminance was recorded at ten seconds intervals.

Love used the following equation to compare values obtained with scale models with full-scale values:

$$\text{Relative Difference} = ((Val_{FS} - Val_{M}) / Val_{FS}) * 100 \qquad (5.1)$$

Where Val_{FS} is the illuminance measured at a point in the full-scale space, and Val_{M} is the illuminance measured at a corresponding point in the model space.

The results of this experiment showed that under ideal conditions (simple spaces and windows, correct placement of sensors and holders with low reflectivity) without direct sunlight striking the fenestration under overcast skies or clear skies with no sun, values estimated in the scale model can be within 10 to 15% of values from the full-scale spaces. Moreover, it was also noticeable that large models do not necessarily provide greater accuracy, and can be more difficult to handle.

Cannon-Brookes[14] carried out a study of the performance of physical lighting models, comparing illuminance measurements taken in an existing museum building and in a scale model under identical sky conditions. External shading was modelled and the physical model (1:20 scale) was placed on the roof of a building adjacent to the museum to ensure that it experienced the same sky conditions.

Lux sensors were placed vertically on the walls of both the scale model and the real building, and simultaneous measurements at five minutes intervals were recorded when the gallery was empty between exhibitions. Results showed that under overcast sky the scale model out-performed the gallery by about 60%. These results were higher than expected and therefore, the model was modified. Adjustment to fenestration and reflectance of materials were made, and the scale model was tested under the mirror box sky of the Welsh School of Architecture. At the end of the comparison study the divergence of the model's performance was between 10% and 25%.

The following table presents the divergence obtained by different authors from illuminance studies made with scale models that have been compared with full-size buildings. It clearly shows that in these studies scale models significantly over estimated the performance of the modelled buildings.

Table 5-2 Relative divergence from previous studies with scale models vs. real buildings (all values are positive).

Reed & Nowak (1955)[14]	**Kim et al. (1985)**[14]	**Love & Navvab (1991)**[15]	**Love (1993)**[13]	**McDowell et al. (1994)**[14]	**Cannon-Brookes (1997)**[14]	**Thanachareonkit et al. (2005)**[16]
10-30%	30%	SC 15%	10-15%	22% (V) 55% (H)	10-25%	SR 50%
		IRC 30-50%				PS 30-35%

(SC: sky component; IRC: internally reflected component; SR: surface reflectances; PS: photometric sensors).

Cannon-Brokes[14] has pointed out the main causes of the scale model's divergent performance:

1. Dimensional accuracy; e.g. poor detailing of window frames and glazing bars
2. Correct simulation of photometric properties

He has also mentioned dirt and maintenance as possible causes of inaccuracy. Usually scale models have clean smooth surfaces with higher reflectance, and windows have a higher overall transmittance. Table 5-3 provides correction factors for glazing and dirt recommended by different authors. Finally, the same author has proposed to give an error band of around 20% to the performance of small scale models used for lighting studies.

Table 5-3 Correction factors for glazing and dirt.

Type of correction	Robbins[17]	Littlefair[18]	Moore[19]	Cannon-Brookes[17]
Glazing transmittance	0.9	0.75	0.9	0.81 (combined with dirt)
Dirt	0.9	Vertical glazing: 0.9 Sloping: 0.8 Horizontal: 0.7*	0.9	-

*These factors can be applied to buildings situated in a 'clean' location, distant from industrial areas.

Recently, Samant and Medjdoub[20] used scale modelling to carry out a parametric assessment of the effects of different reflectance distributions on the daylight factor at the base of a four sided atrium measured under overcast sky in a mirror box artificial sky.

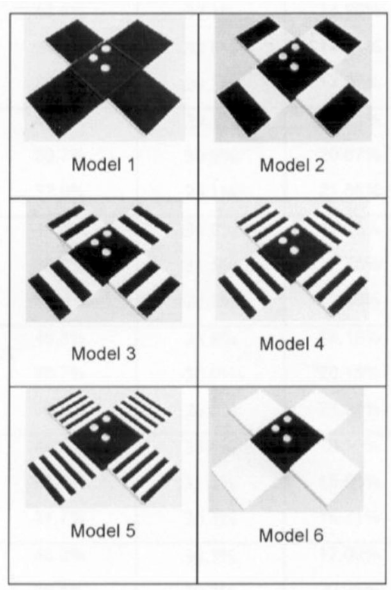


Fig. 5-3 Models used in Samant's and Medjdoub's study [20].

Six models were constructed to a scale of 1:100 to represent an atrium of 24x24 x 24 m high. Medium density fibreboard was used for the walls and floors painted with various configurations of white and black bands with 0.85 and 0.02 reflectance factors respectively. Horizontal daylight factors were measured in three different points at floor level: the centre, the edge and one corner of the atrium.

The authors concluded that the distribution of the walls reflectances did affect the average daylight factor values. The results from the scale model study were then compared with an Ecotect model and Radiance daylighting analysis. The daylight levels obtained through both simulation tools followed the same pattern; however, the illuminance values were underestimated by Radiance in comparison with the physical model study. Therefore, the authors suggest multiplying the Radiance results by a factor of 1.2 but without any explanation for using this figure. This study shows the potential of scale modelling as a research tool in the area of daylighting, although, no investigation was made to evaluate the physical models' performance and representation accuracy. In addition, the six models investigated were very simple and perhaps not close to a real building's geometry and fenestration; though, it shows the importance that surface reflectances have in the lighting behaviour of buildings.

Comparisons and validation studies between scale modelling and computer modelling need to be further investigated following a precise methodology in order to simulate identical sky conditions, fenestration, geometry and photometric properties of materials with both tools.

5.2.2 Physical modelling of tensile fabric membrane buildings

The double curvature of membranes and their complex geometry make impossible to design them with the same tools as conventional buildings. Scale modelling represents an important design tool to study the appearance, shape and geometry of fabric architecture helping designers to make decisions about the three dimensional shape of the membrane structure and cutting patterns.

Monjo-Carrio and Gamez-Guardiola[21] have pointed out three different types of processes that have to be followed when designing a tensile membrane enclosure:

1. Geometric calculation
2. Physical modelling
3. Computer modelling

According to the authors, the geometric method is only good for simple problems and for more complicated problems physical modelling becomes very effective. Computational methods are improving constantly and have become also a useful tool for the analysis of difficult structures.

In addition, Forster and Mollaert[22] consider that both physical and numerical methods are important when designing tensile fabric buildings.

Each method offers particular qualities for the development of a design concept. Physical modelling is probably the best method to understand the behaviour of the material, their double curvature and the tension forces applied to it. Furthermore, the visual appearance of a space enclosed by a membrane structure is more evident if simulated with a scale model.

Physical models of textile buildings are usually made with elastic materials of different thickness and elasticity coefficients such as: spandex clothe, elastic nets, lycra fabric, etc. Advantages of using these materials consist of being able to easily modify the models, and to visualise large and complex roofs as a whole which helps in the form-finding stage.

There are no precedent studies in the author's literature search where physical models of fabric buildings have been especially constructed for daylighting analysis. Probably the only exception is David Morley Architects who designed the Lord's Cricket Indoor School and constructed a physical model of a section of the building for lighting studies (1:20 scale model). The analysis was developed in the artificial sky of the Bartlett School of Architecture in 1995 and the results obtained helped to decide the roof solution and the client's acceptance of the daylighting approach. Unfortunately the results were not available to be included in this thesis. Even in this case the model makers did not use a fabric material to simulate the fabric louvres; instead, plastic with a matte white paint was utilised.

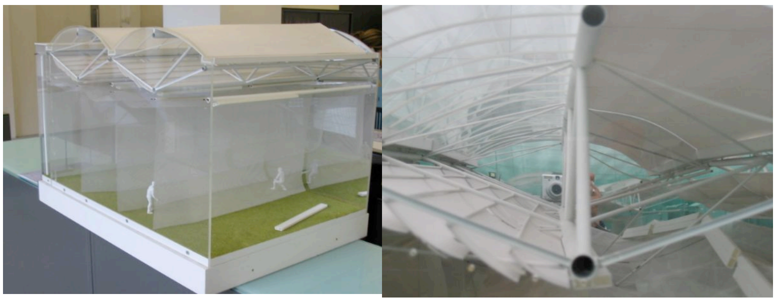


Fig. 5-4 David Morley Architects' scale model

5.3 SCALE MODELS OF CASE STUDY BUILDINGS

This section includes results of the study carried out under the artificial sky of the School of the Built Environment at the University of Nottingham.

Scale models of the three buildings evaluated in this thesis were constructed especially for these lighting experiments. The main objective of this study is to evaluate the accuracy of scale modelling as a design tool for simulating daylight behaviour in tensile fabric membrane buildings. In order to achieve this aim, Daylight Factors and uniformity ratios were measured.

Two physical models of the Indoor Cricket School at Lord's Ground were modelled. One model of the National Cricket Academy and one of the Inland Revenue Amenity Building (IRAB) were constructed and later on studied under the artificial sky.

The recommended ratios of scale models compared to size of artificial sky should not exceed 30-40% in rooflit buildings, and 20% in buildings with vertical windows on two opposite sides[5]. The research models' ratios follow the recommendation:

- Case study 1: represents 6.5% of the artificial sky dimension.
- Case study 2: represents 6% of the artificial sky dimension.
- Case study 3: represents 17% of the artificial sky dimension.

5.3.1 Instrumentation

The artificial sky used for this project is located in the School of the Built Environment (SBE) at the University of Nottingham. It is a mirror sky with sixteen 12-950 Osram Lumilux de Luxe 'daylight' 40 watts lamps with a colour temperature of 5400 K.

Fig. 5-5 Artificial sky at the SBE

The dimensions of the artificial sky are 2.50m x 2.50m x 1.20 m high up to diffusing cloth, and 400mm more up to lamps. The table height is 950mm. The diffusing cloth is a woven glass-fibre fabric with 50% light transmittance. The glass on the walls has a reflectance of 0.83, and the table reflectance factor is 0.18[23].

The measuring equipment used for the study of all scale models included:

- Six single channel photometric sensors Skye SKL 310, with cosine corrected heads, each containing a semi conductor diode and filter system that responds to light. The detector is a silicon photocell and the filters are glass type and/or metal interference[24]. These sensors were calibrated against a National Physical Laboratory UK reference standard lamp.
- A Data Hog 2 Skye Data logger (SDL 5000 series). SkyeLynx Standard Communications Software version 2.6 is used to communicate and off-load data from the data logger to a PC.
- A Hagner universal photometer model S3 was used to measure the luminance values of the scale model materials, which later were used to obtain their reflectance.

5.3.2 Case study 1: MCC Indoor Cricket School at Lord's Ground, London.

This section includes the results obtained from the testing of the model's accuracy to simulate daylight in one case study building: the Indoor Cricket School located at Lord's Ground in London.

The designers considered 5,000 lux available from an overcast sky and a minimum of 1,000 lux on the playing surface, therefore a 20% daylight factor was established as the initial design target.

5.3.2.1 Testing method

An initial scale model was constructed to a scale of 1:50 reproducing two playing lanes and side corridors modelled with the full length of the building's playing area. This model will be referred as **A**. It was later modified in order to obtain a lower divergence between the results from the scale model and the real building using a rough model of the fabric louvres. The second stage of the model will be referred as model **B**. A third stage (model **C**) included the construction of more detailed fabric louvres, which are similar to the real roof solution.

A quantitative analysis was planned which consisted in measuring the illuminance levels at a floor level inside the physical models. In addition, the illuminance variation throughout the building was also recorded. The models were placed in a mirror box or artificial sky. A series of lux meters were positioned over 36 grid points in models A, B and C, which were marked on the floor surface of the physical models. These points were determined by calculating the Room Index K (explained in chapter 4). The resulted Room Index for the models is 1.23, which according to a table published in the CIBSE Code for Interior Lighting[25] indicates that a minimum of 16 measuring points are needed. However, in order to obtain a more accurate representation of the lighting behaviour inside the space 36 grid points were measured including points over the side corridors (Figure 5-6).

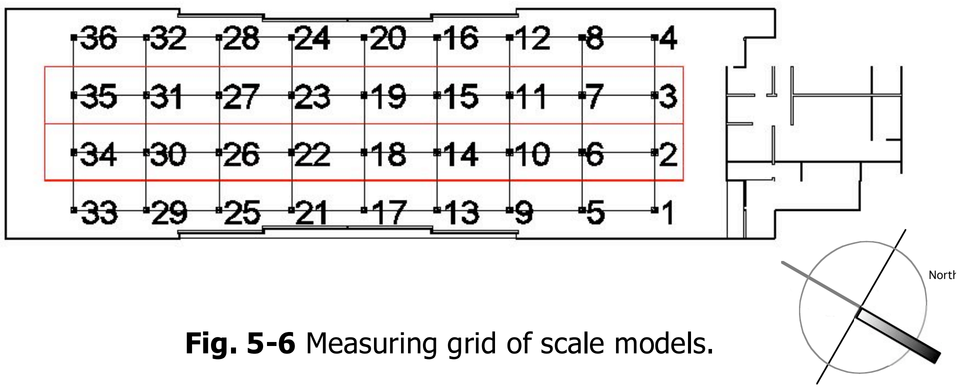


Fig. 5-6 Measuring grid of scale models.

Due to the limited number of lux meters it was not possible to take the readings in all 36 points at once; the sensors had to be moved along the model grid points leaving each of them around a period of twenty minutes in the same point recording at one minute intervals. One lux meter simultaneously recorded the external horizontal illuminance.

The tests carried out with the scale models were also intended to be analysed in a qualitative method making use of the photographs taken from both models including the modifications made to models A and B.

It is important to bear in mind that the models do not represent the exact geometry of the real building due to the difficulty of modelling big buildings at an appropriate scale for lighting studies. Therefore, it is not possible to make a like to like comparison with these physical models and the real building. Nevertheless, it is possible to compare the lighting behaviour throughout one of the playing lanes, which is the area where light is required to be uniform and high. This study will show the performance of the three models, A, B and C, and the influence that possible experimental errors may have on the simulation of daylighting levels and behaviour in the Cricket School.

5.3.2.2 Description of scale model A

This model was made by the researcher at the School of the Built Environment to a scale of 1:50. It was constructed with foamboard covered by paper to give similar photometric properties to the real building.

Probably the most difficult part when modelling this building has been the reproduction of the vaulted roof, especially the fabric louvers located underneath the roof structure. The real fabric was used, and tensioning it represented a hard job. First of all, it is important to mention that each vault has five louvers all along the length of the building; and for this scale model only three vaults were modelled. The long section (42m) of each vault was divided into three subsections which were held by two longitudinal and four small transversal supports.

The reflectance of the walls and floor materials used in this model are intended to be very similar to the characteristics of the real materials. The windows and roof openings were left open. The offices, reception and changing rooms were not included in the model; only the playing area was simulated.

Table 5-4 Photometric properties of materials used in model A and properties of real materials

Surface	Reflect.	(%)	Absorpt.	(%)	Transmitt.	(%)
	Real	scale mod.	Real	scale mod.	Real	scale mod.
-Green floor	8.48	8.26	-	-	-	-
-Walls and roof cladding	52	41.33	-	-	-	-
-Fabric used in louvres	46	46	47.3	47.3	6.7	6.7

Fig. 5-7a-d Scale model A constructed for this study.

5.3.2.3 Description of Scale model B

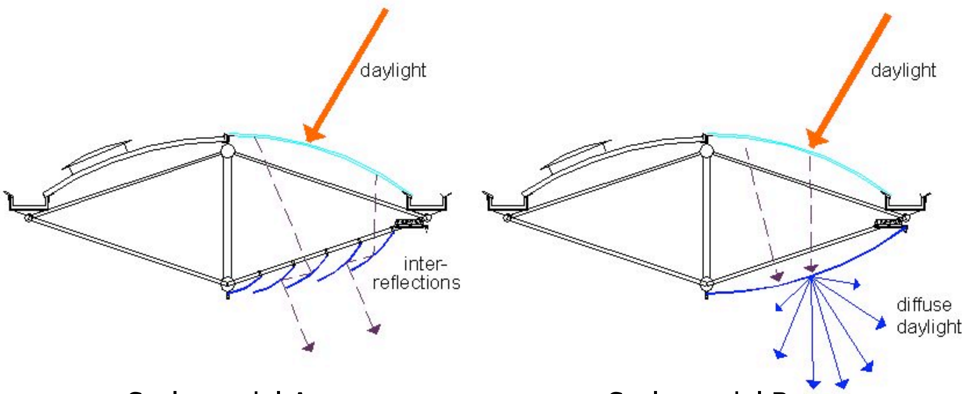
Due to the results obtained in the artificial sky with model A, where daylight levels inside the building were overestimated when comparing the resulted DF with the design target of 20%, some modifications have been made in order to improve the model performance:

1. The fabric used to divide the playing lanes was placed in the model.
2. The fabric louvres were modelled with a different approach.

The main purpose of the interior net like fabric is to protect the players and the roof structure from the balls which are hit very strongly reaching a speed of 90MPH, whilst dividing the playing lanes. The dimension of the nets openings (10x10cm) was simulated with polyester net like fabric having to scale down the real size openings to the model's scale.

In addition, a different approach for modelling the fabric louvers was adopted. A single fabric piece was placed under every vault with a longitude of 42 meters and a width of 3 meters. The same fabric type as in model A was used. Having only one piece of fabric instead of five pieces per lane (modelled in A) produces the following effects on the lighting simulation of the space (Figure 5-8):

- Reduces the space between fabric louvres decreasing daylight penetration area. The large spaces between fabric pieces were mainly caused by the lack of tension applied to them in model A
- Provides larger diffusing area
- Avoids inter-reflections of light between fabric pieces reducing the amount of daylight reaching the interior space



Scale model A   Scale model B

Fig. 5-8 Comparison between fabric louvres' configuration and lighting effect in models A and B

Fig. 5-9 Roof of scale model with three fabric pieces

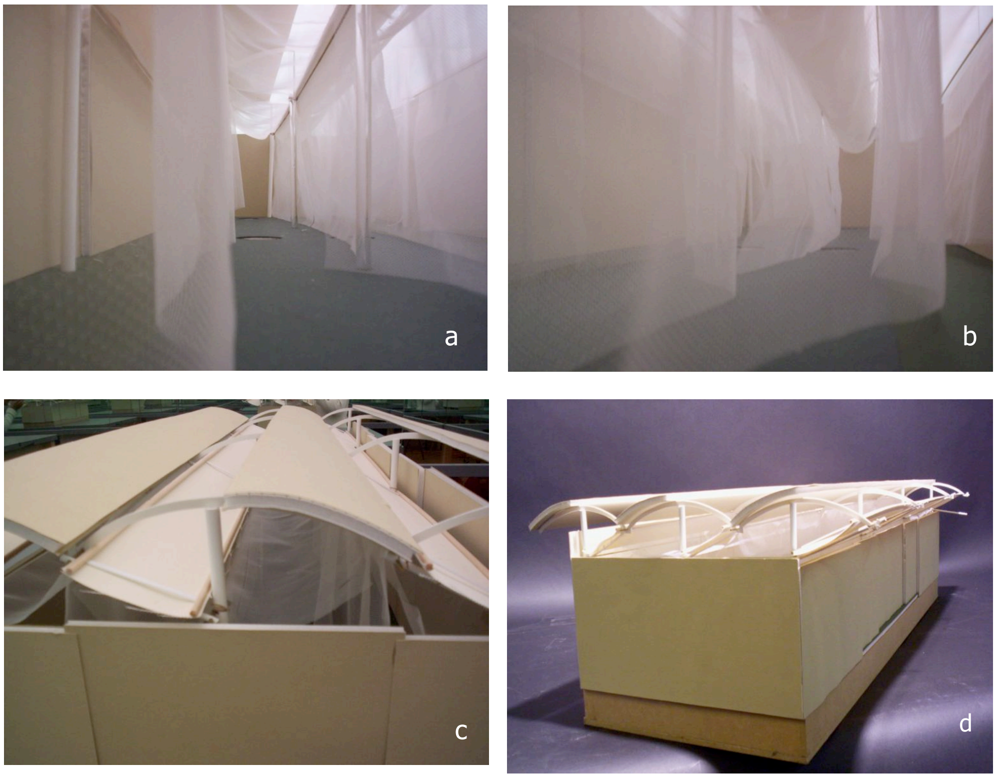


Fig. 5-10a-d Model B made for this study with modifications.

5.3.2.4 Description of Scale model C

Although model B could be useful to obtain preliminary results, still the geometry of the fabric louvres does not correspond to the real solution. Therefore, a third scale model was constructed in order to verify the results obtained with model B. Five fabric sections situated under each vault replaced the three pieces of fabric used in Model B. Each of them has the whole length of the building and is tilted according to their position under the roof. The fabric membrane used is the same as in the other models but this time it was tensioned using wooden sticks.

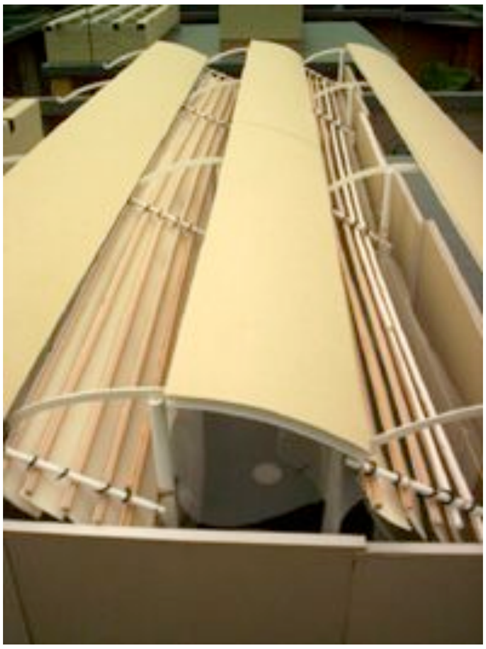


Fig. 5-11 Fabric louvres in Model C

5.3.2.5 Results

Model A

The physical model made specifically for this study was tested in the artificial sky or mirror box at the SBE. It has been previously explained that this model represented to a scale of 1:50 the whole length of the playing area including two playing lanes and a corridor at each side of these lanes. Due to the lack of tension applied to the fabric louvres it was decided to carry out a preliminary test in order to assess the influence that this factor could have in the lighting performance of the model. The measuring grid points were a total number of 36 and a lux sensor recorded the exterior horizontal illuminance.

The average daylight factor obtained is 26.76% and the average

Uniformity ratio is 0.53.

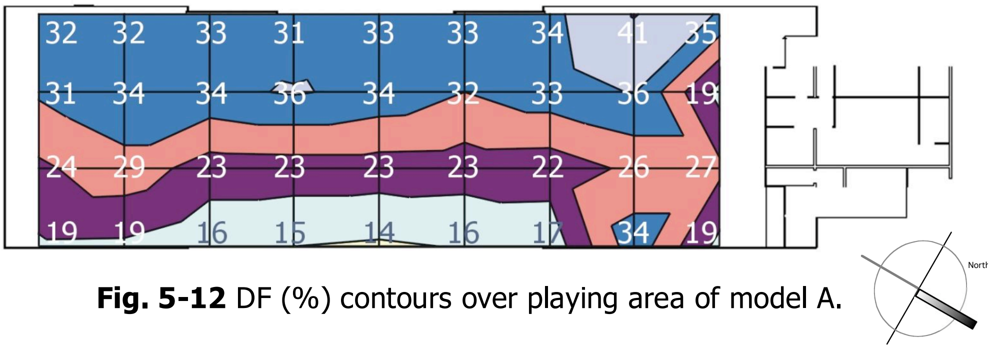


Fig. 5-12 DF (%) contours over playing area of model A.

Figure 5-13 shows the location of sections A-A′ and B-B′. These were chosen to illustrate the daylight factor variation through the playing area. The longitudinal section (A-A′) has been placed at the centre of the whole length of a playing lane. Section B-B′ is located at the middle of the training area.

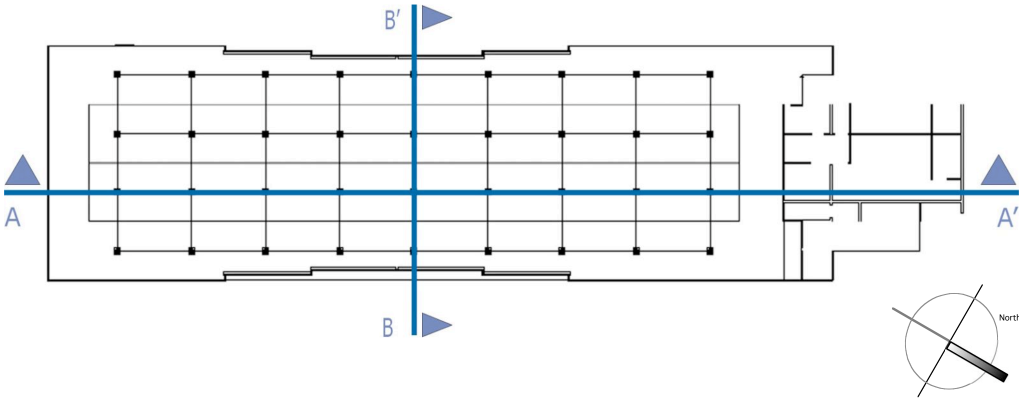


Fig. 5-13 Location of sections A-A′ and B-B′ over floor plan

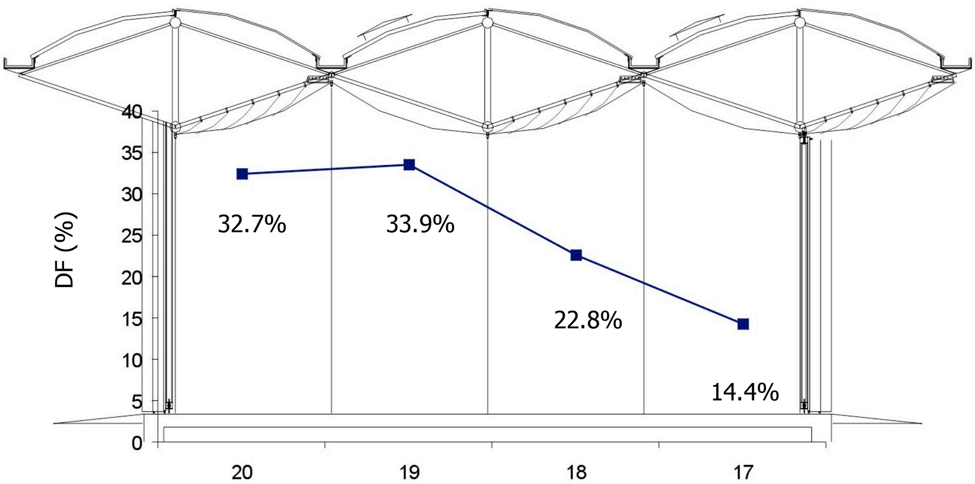


Fig. 5-14 DF through section across points 20, 19, 18 and 17.

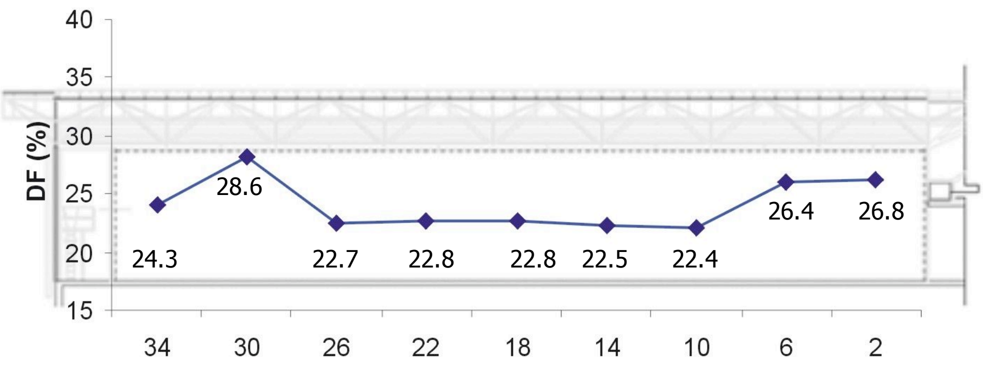


Fig. 5-15 DF variation through longitudinal section of model A

Figures 5-12 and 5-14 demonstrate the importance that geometry and tension applied to the fabric membrane of the roof have on the interior daylight availability. The difference between the DF obtained in one side of the model, over point 20 for instance, and the other side over point 17 is approximately 18.3%. This variation resulted from the loose fabric louvres that were placed in the model with different tension stress, causing diverse opening angles between layers of fabric. Therefore, daylight penetrated the building following a different pattern in each playing lane and causing such a large average DF variation along the transversal section of the model.

Furthermore, the roof geometry and the location of the light sensors are also producing the disparity between the registered DF over point 20 and the DF over point 17. The latter has a more restricted sky view angle. The sensor placed on point 20 has in total an angle of incidence of the sky component of 34 degrees; point 19 has an angle of 41°, point 18 has an angle of 26° and finally, the point that receives lower light incidence is point 17 with a sky view angle of 13° (Figure 5-16).

In order to prove the influence of the geometry and tension applied to the fabric on the daylight availability in the building, it was decided to continue with a second stage of testing, making some probably crucial changes to the model.

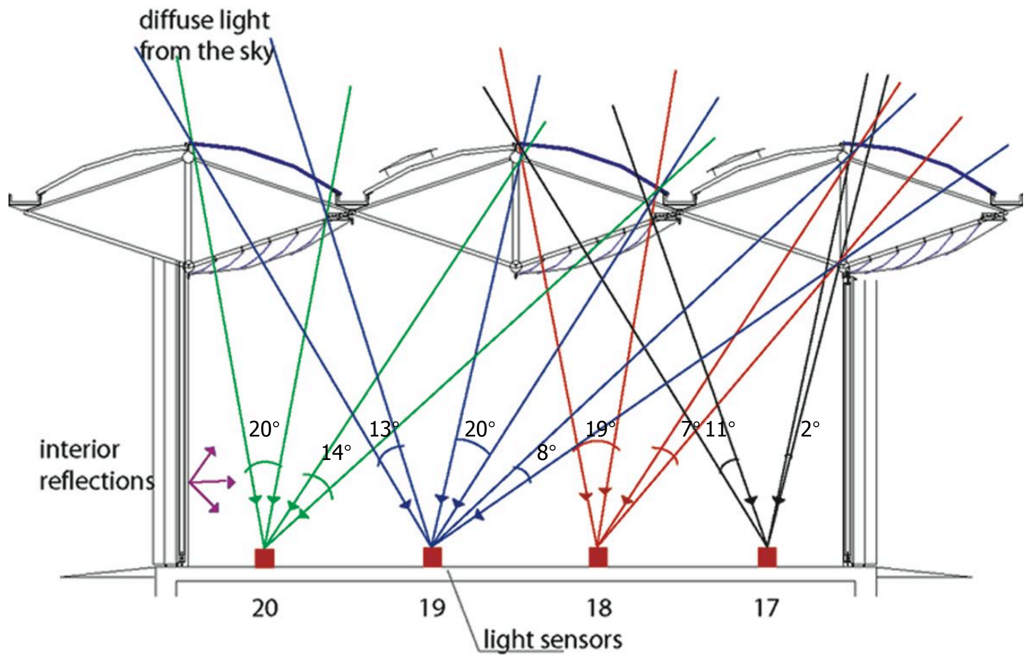


Fig. 5-16 Sky view angles of four light sensors

Model B

Once the fabric louvres of model A were replaced for three single pieces scaled dimensions of 42m long and 3m wide placed one in each roof vault, the scale model was tested again in the artificial sky. The results obtained in the second testing stage are as follows:

- Average Daylight Factor: 16.65%
- Uniformity ratio: 0.8

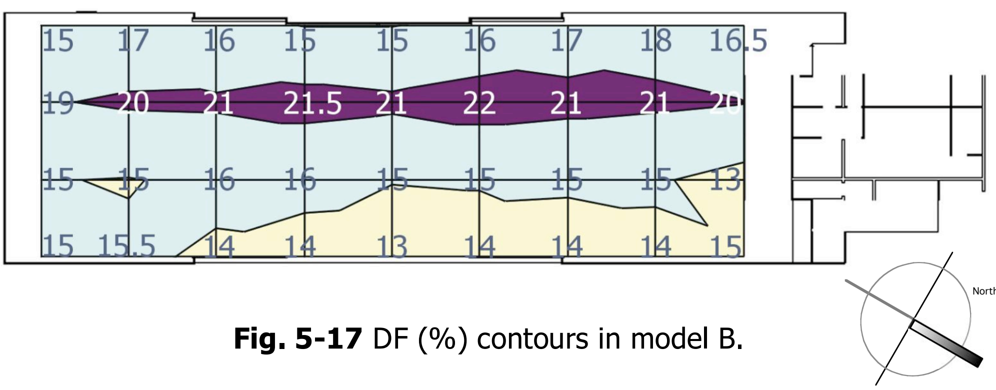


Fig. 5-17 DF (%) contours in model B.

In this testing stage scale model B provided a more even illumination than model A. The total average Daylight Factor decreased to 16.65%, which is closer to the initial design target of the building (20%) even though the real performance of the School measured on site is DF=4.4%.

The average uniformity ratio obtained roughly illustrates the behaviour of the light throughout the playing area, and in this case, the light levels appear to be very uniform.

The reduction of the DF from model A (26.76%) to model B (16.65%) is the result of the better representation of the interior space of the cricket school. The addition of the fabric that divides the playing lanes reduced the amount of light reaching the sensors. Moreover, the replacement of the fabric louvres for a single piece of fabric caused a more restricted penetration of light into the space. This last change is the result of a limitation when using scale models for lighting studies, where sometimes the modelling of the exact geometry and photometric characteristics of the materials is not possible. Hence, a geometry simplification could be the response when modelling complex buildings; it is also important to consider available materials, modelling skills, time and budget allocated for a specific lighting study. The results could still represent the lighting behaviour of a building where scale modelling is an evaluation tool that helps to make design decisions.

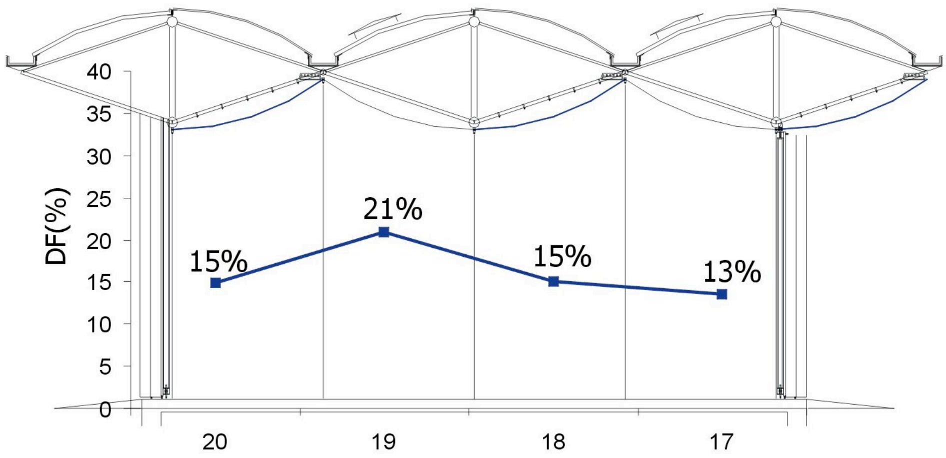


Fig. 5-18 DF (%) variation through section in model B

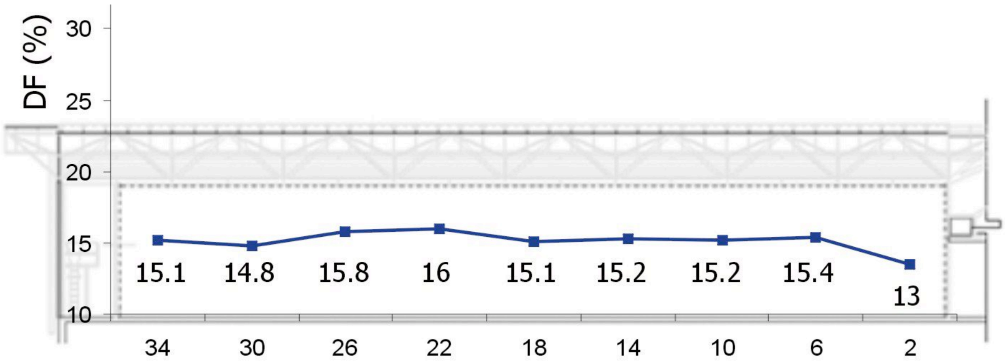


Fig. 5-19 DF (%) variation through longitudinal section, model B.

The DF difference through the longitudinal section of the model is fairly small with daylight factors varying between 13% and 16%.

A correction factor for windows and dirt based on Table 5-3 was applied to the average daylight factor obtained in model B. A correction factor of 0.80 was used for the double layer of clear Lexan Exell D sheet polycarbonate (6mm outer layer + 70mm air gap + 4mm inner layer) used in the rooflights of the cricket school. In addition, a correction factor of 0.80 was applied for dirt following Littlefair's recommendation for sloping glazing in 'clean' locations (Table 5-3). Therefore, the previous DF of 16.65% was multiplied by 0.64 and a final average DF of **10.66%** was obtained.

Model C

A better representation of the fabric louvres was achieved in model C. The geometry of the louvres was the real one with the fabric properly tensioned. However, the resulted average daylight factor does not differ very much from the DF obtained with model B. The resulted DF in model C is **10.96%** and the uniformity ratio is 0.42. This indicates that a simple representation of the geometry can be used as a rough way to quickly understand the lighting performance of the building in order to make preliminary design decisions.

5.3.2.6 Initial conclusions

The resulted longitudinal sections have shown that daylight is very uniform all along the playing lanes. This behaviour results from the interior characteristics of the space, including:

- Roof design. It is regular all the way through the length of the building; half a vault covers one playing lane.
- Symmetry of the space. The playing area has no vertical windows and the partition nets are located symmetrically in each lane.
- Constant reflectance factors. The finishing material used for floors is the same in the whole training area and the same happens with the materials used in walls, roof and fabric louvres.

This daylighting behaviour responds to the cricket requirement of having uniform light levels along the space between the ball man and the batsman.

Regarding scale modelling as a daylighting prediction tool, a series of points can be obtained from this analysis, especially concerning the limitations of scale models to accurately predict the lighting behaviour in a space, and possible errors when carrying out a lighting study using physical models of real buildings.

Daylit buildings generally have side windows combined with rooflights, atriums or other daylighting control systems such as louvres or venetian blinds of different materials and geometry. These complex daylighting devices are difficult to simulate in a scale model but at the same time are essential for the lighting analysis of such buildings.

One of the problems encountered during this study was the size of the area to be simulated where a 38% of the total roof was skylight. To represent such a large area at a big scale would have resulted in a very large model difficult to handle and to use within the artificial sky. Therefore, it was decided to simulate only a section of the building to a scale of 1:50. Despite the fact that this model was suitable to be used in the artificial sky, the rooflights details were still small and difficult to model with the real fabric material (model A).

Scale modelling could be an expensive tool in terms of materials' cost and working time. For the Indoor Cricket School's scale model approximately £200 were spent, and it took one person working during a week to construct this model. The modifications made to model A that transformed it into model B and C required three extra days person's work.

Modelling an existing building constructed ten years ago made difficult to obtain information from the designers regarding the architectural drawings and materials' characteristics. Hence, a series of visits to the School were needed to integrate a complete set of information, including measurements of the surface reflectance of the interior finishes.

In the case of this case study, daylight penetrates mainly through the skylights. The fabric louvres' geometry and photometric characteristics influence the availability of daylight, as it was proved in this study changing their geometry in model B to facilitate their modelling. In addition, maintenance of the fabric is also important as dirt can also influence the access of daylight. In a physical model the lack of dirt on surfaces and windows can be a potential source of error[16].

Even when applying the glazing and dirt correction factors, the relative divergence between average daylight factors is +60% in favour of the scale model against the real building measurements. Two possible errors have produced this divergence:

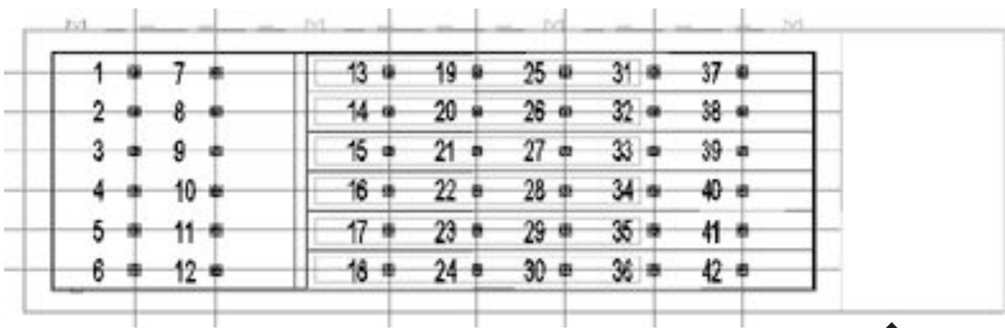
- Different geometrical modelling. In order to obtain accurate results it is important to represent the exact geometry of the building, especially windows and roof openings. This will allow an exact daylighting performance comparative assessment to take place between a real building and its scale model.
- Surface reflectance. It is extremely important to represent the real surfaces' reflectance in the scale model. Then, the model will probably not be useful for visual perception analysis or for marketing purposes, because the colours will not match the real ones. According to Thanachareonkit et al.[16] the impact of surface reflectance on daylight factors could be around +50% compared to a real building.

5.3.3 Case study 2: ECB National Cricket Academy, Loughborough.

5.3.3.1 Testing method

The playing area of the National Cricket Academy was modelled for carrying out a daylighting analysis. In order to obtain the Average Daylight Factor of the building and the illuminance uniformity it was necessary to measure the horizontal illuminance levels at floor plane. Simultaneously, exterior illuminance measurements were taken at one minute interval.

Lux sensors were located over a series of grid points whose location responded to the middle of each playing lane at different distances. Here is where the players stand to practice cricket. The Room Index of this area is 2.05, which corresponds to a minimum number of 25 measurement points to obtain a value of average illuminance with an error of less than 10%[25]. In order to place grid points in all playing lanes and following the structural geometry of the skylights a number of 42 points were selected (Figure 5-20).



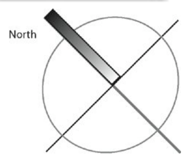


Fig. 5-20 Grid of measurement points

5.3.3.2 Description of scale model

The scale model of the National Cricket Academy included all six playing lanes, warming up area at the rear of the building and lateral corridors. The north-east façade has a vertical window facing the outdoor training pitch; this was also modelled since the window could be an important light source due to its dimensions (73.70m x 2.80m high).

The size of the building and the dimensions of the artificial sky restricted the scale of the model to a 1:75. The model represented 6% of the mirror box dimension.

The scale model was made with foam-board covered by card paper of different reflectance factors for walls, floor and roof. The real fabric cloth was used for the louvres located under the roof, which in an initial test were modelled as a single piece of fabric through the length of each playing lane (model A). Changes in the representation of the fabric louvres leaded to a second model (B). The fabric louvres were modelled following the real geometry; four pieces of fabric were placed under each transparent roof section. The window and the transparent sections of the roof were left open. The exterior ground reflectance was modelled.

The photometric properties of the materials used in scale model A and B are shown in Table 5-5.

Table 5-5 Photometric properties of materials used in scale model compared to real materials

Surface	Reflect. Real building	(%) Scale model	Absorpt. Real building	(%) Scale model	Transmitt. Real building	(%) Scale model
-Green floor surface	5.8	7.8	-	-	-	-
-walls and roof cladding	53	46.5	-	-	-	-
-Fabric used in louvres	57	57	29	29	14	14

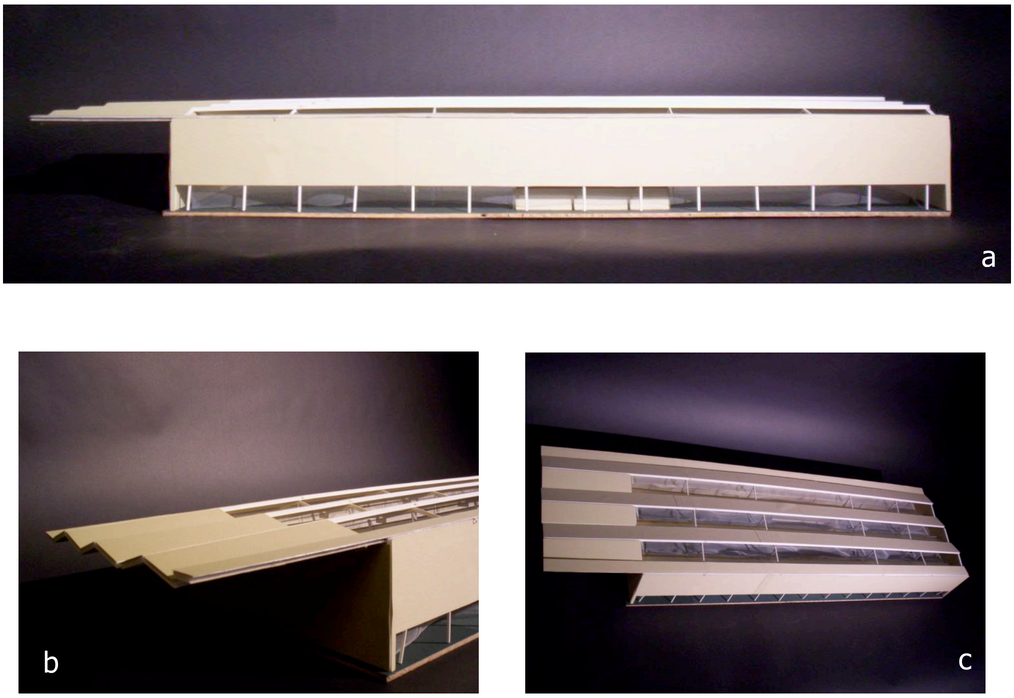


Fig. 5-21a, b, c Photos of scale model, National Cricket Academy

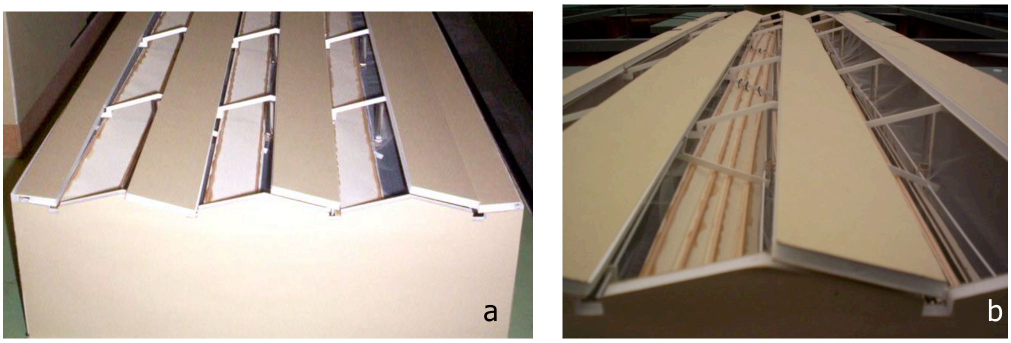


Fig. 5-22a Model A with single pieces of fabric.
5-22b Model B with four pieces of fabric under each vault.

5.3.3.3 Results

The resulted Average DF is 22.39% (Figure 5-24) and the Uniformity ratio is 0.56. The design target of this building was to reach 1,500 lux on the playing surface. Considering an exterior illuminance of 5,000 lux under an overcast sky it would be necessary to have a 30% DF. But this figure is considerably higher than the one recommended by CIBSE (average DF=5%)[26].

Hence, it seems that the scale model overestimated the availability of daylight in the building where the DF measured on site is 5.9%. Although the 22.39% is not a final result because it will still be adjusted for glazing transmission and dirt losses. The following figure shows the location of the sections through the Academy that were selected to illustrate the daylighting behaviour of the space.

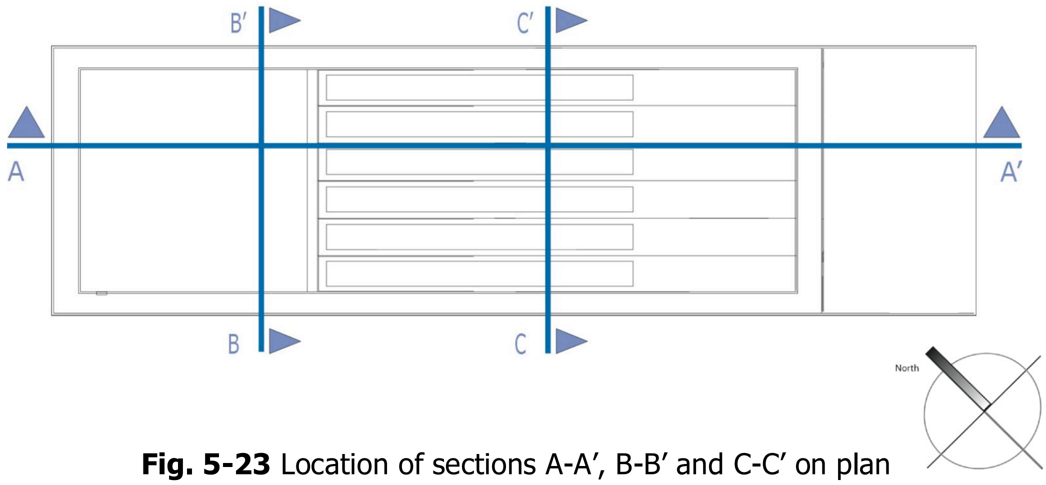


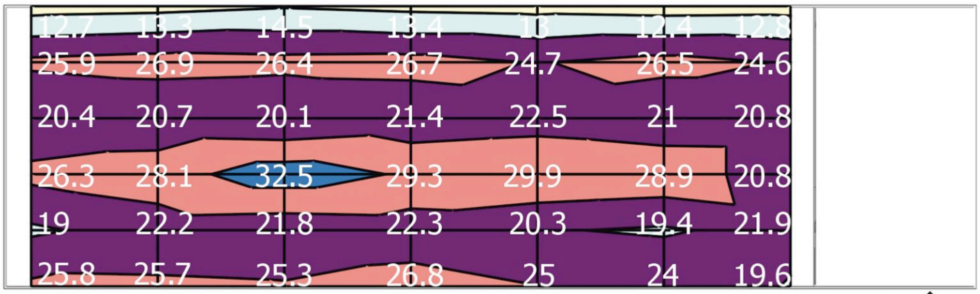
Fig. 5-23 Location of sections A-A′, B-B′ and C-C′ on plan

Figure 5-24 illustrates the daylight factor variation in the playing area. The maximum DF is 32.5% and it is located over playing lane four (blue colour).

Surprisingly, the minimum DFs are found in the first lane regardless the corridor and the vertical window besides it. Due to the scale of the model and the size of the sensors, the window did not have much effect on the internal lighting environment. The height of the sensors almost reached the highest point of the window frame. This demonstrates that there must be a compromise between modelling a complete building to have a full idea of the lighting behaviour of the space as a whole, and having the adequate equipment (sensors and artificial sky) for studying a big size scale model.

In addition, a dark green paper (reflectance=0.078) was placed outside the window simulating the ground reflectance of the outdoor pitch. This paper reflected less light than the surface of the table (reflectance=0.18) causing, together with the opaque roof over the corridor, a reduction of the DF values.

Daylight factors varied alternatively between lanes. For instance, higher values are found over lanes 2, 4 and 6. These DF are rather constant all along the lanes.



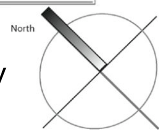


Fig. 5-24 DF (%) contours obtained in scale model study

The Illuminance Uniformity ratio is 0.56, which is quite low for the cricket requirements (0.9). The low illuminance levels recorded in the grid points located near the side window are causing this lack of uniformity. It seems that the reflectance of the interior surfaces produce high interior light reflectances and a consequent increment on illuminance levels.

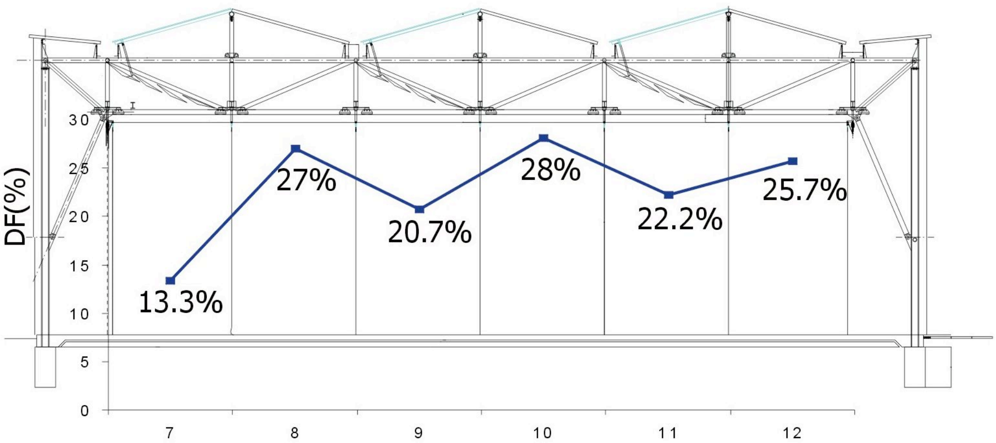


Fig. 5-25 DF variation through Section B-B’

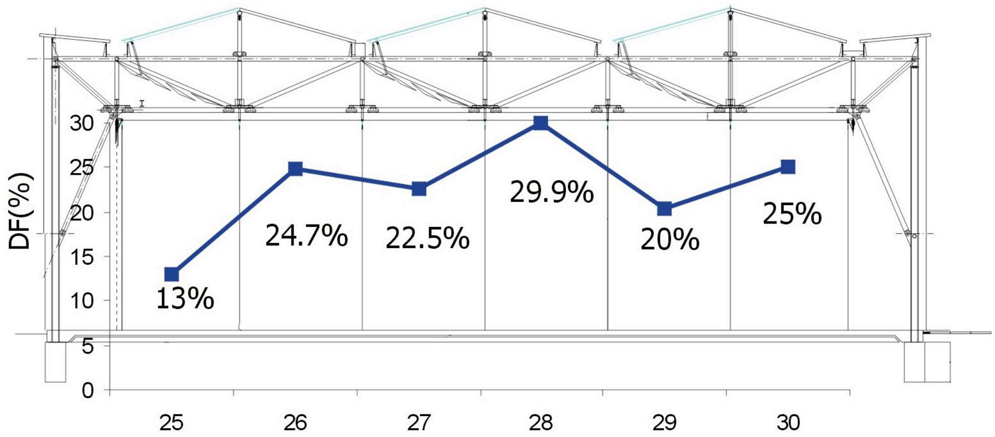


Fig. 5-26 DF variation through Section C-C′

Sections B-B′ and C-C′ illustrate the daylight behaviour through the transversal sections of the building. In both figures the DF increased in playing lanes that are under the opaque area of the roof, and decreased under the fabric louvres (Figures 5-25 & 5-26), which are located below the rooflights representing 29.3% of the roof area. This could demonstrate the role of the fabric which diffuses the light that penetrates the transparent roof avoiding the access of direct sunlight. However, these results do not correspond to the data from the real building where daylight patterns were no dependent on the location of fabric louvres.

Probably the light that strikes the transparent section of the roof is not totally diffused by the fabric louvres; part of it could penetrate reaching the lanes with no louvres and causing an increment in DF. Light inter-reflections within the structure of the building may also produce the increasing of daylight availability in the internal space.

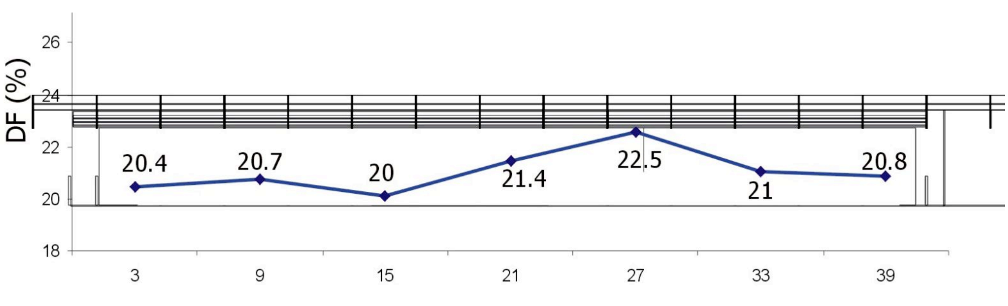


Fig. 5-27 DF variation through longitudinal Section A-A′

Figure 5-27 shows the DF variation through section A-A', which looks quite uniform. The DF varies between 20% in point 15 and 22.5% in point 27, which indicates a rather uniform lighting environment through the whole playing lane. Point 15 is located just behind the wicket and it is surrounded by a vertical fabric (natural colour); which reduces the amount of light reaching that point. Though, this decrement is not very significant.

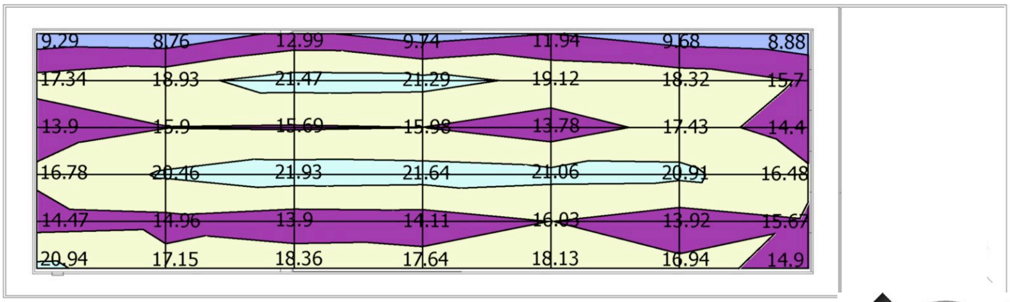
A correction factor of 0.8 for the transmittance of the double skin polycarbonate of the rooflights together with a dirt correction of 0.8 was applied to 80.98% of the total glazing. And correction factors of 0.87 for the 10mm toughened Pilkington glass of the side window with 0.9 for dirt were applied to 19.02% of the total glazing. The addition of both corrections was multiplied by the average daylight factor obtained (22.39%) resulting a **14.94% DF**.

Model B

The resulted daylight factor from the testing of model B is higher than the DF obtained with model A. In this second test the building's DF is **16%** including the correction factors for glass transmittance and dirt. This increment of 1.06% could be caused by inter-reflections of light generated in between the fabric louvres. This seems to be a more accurate representation of the real behaviour of such daylighting control system.

The following figures illustrate the light distribution throughout the playing area. Lighting behaviour is similar to model A where lower DFs are found in grid points located near the side window. Then, they clearly increase under the opaque sections of the roof and decrease in the playing lanes located under the fabric louvres. Apparently, the fabric membranes are efficient in terms of diffusing daylight and controlling its penetration into the interior space. However, the increment of daylight factor values under opaque areas could be caused by light penetrating through the transparent sections but outside the boundaries of the fabric membranes.

That behaviour is constant throughout the long section of the building with some decrement found in grid points located next to both extremes of the playing area, SE and NW walls.



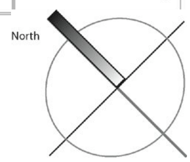


Fig. 5-28 DF (%) over grid plan.

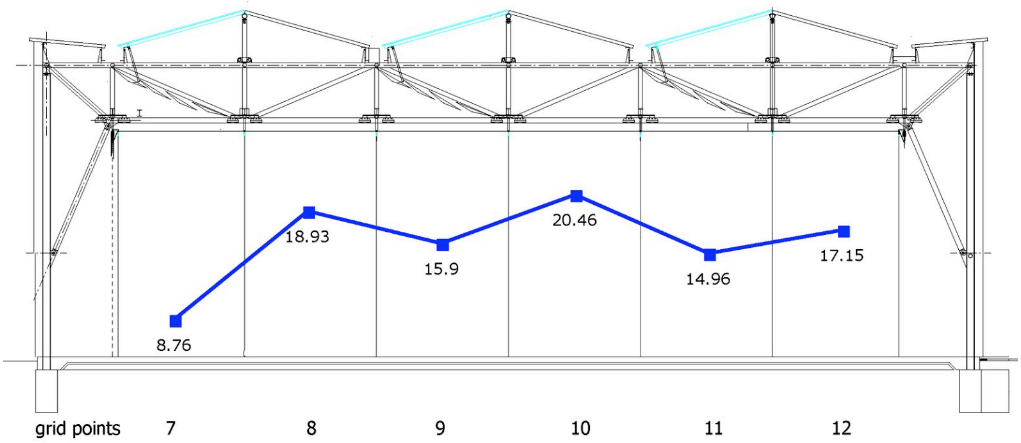


Fig. 5-29 DF (%) variation through section B-B’

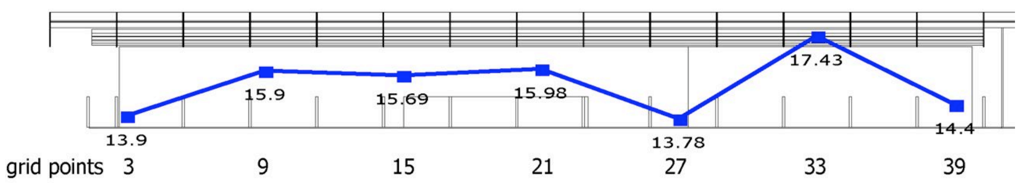


Fig. 5-30 DF (%) variation through section A-A’

Although the Indoor Cricket School at Lord’s Ground (Section 5.3.2) has a larger roof light area (38.08%) compared with the roof light area of the Academy at Loughborough (29.3%), the latter is a brighter building with a 5.9% daylight factor measured on site, against a 4.4% daylight factor measured in the School at Lord’s Ground. The side window of the

Loughborough building contributes to the daylight availability in the interior space; but a more significant influence has the different photometric properties of the fabric membranes used in these buildings. Lord's fabric has a reflectance of 46% and a transmittance of 6.7%; while Loughborough's fabric has a reflectance of 57% and a transmittance of 14%. It is therefore reasonable to think that these characteristics contribute to the greater availability of daylight in the Loughborough building.

A sensitivity study was carried out using Radiance lighting simulation software to test the influence of the photometric properties of fabric membranes and the impact of dirt on the daylighting performance of the building. The results are included in chapter six.

5.3.4 Case study 3: Inland Revenue Amenity Building, Nottingham.

5.3.4.1 Testing method

The playing area of this case study is smaller but considerably taller than the previous buildings. The resulted Room Index is 0.59, which indicates that a minimum of nine measurement points had to be chosen. However, in order to obtain a clearer and more accurate impression of the lighting performance of this building, 25 measurement points were selected (Figure 5-31).

The equipment used for this experiment is described in section 5.3.1. Five lux sensors recorded the interior horizontal illuminance simultaneously, and a sixth one recorded the exterior horizontal illuminance. These sensors recorded on the same grid point during a period of ten minutes at one minute intervals; then, they were relocated over other grid points.

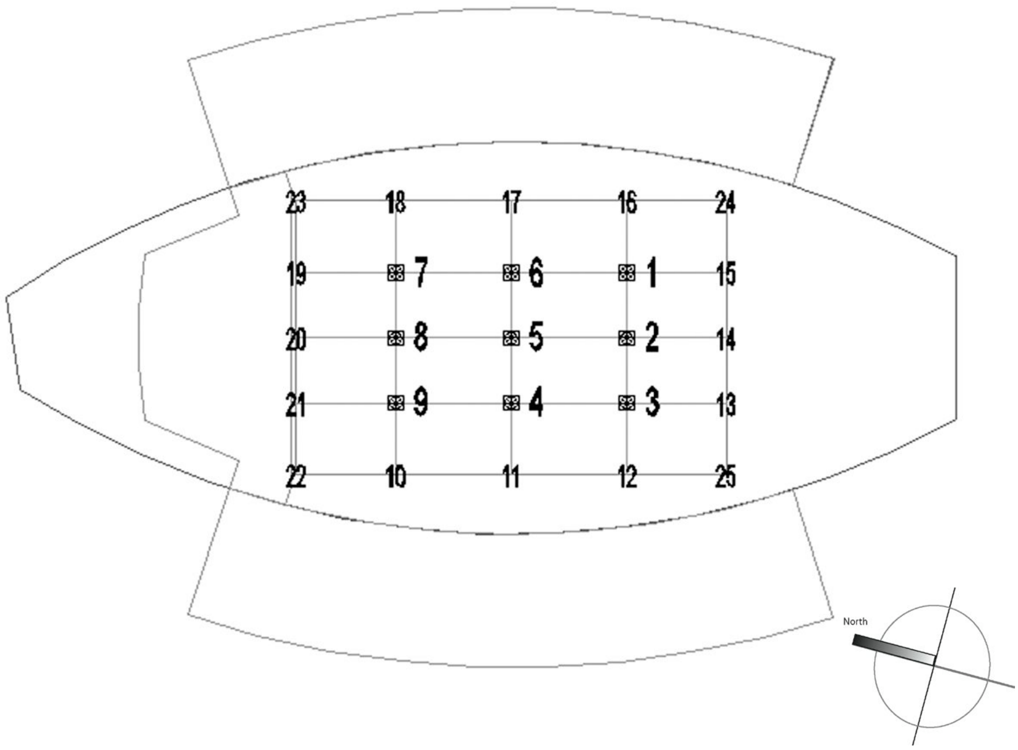


Fig. 5-31 Measuring grid and location of sensors

5.3.4.2 Description of scale model

The physical model of the Amenity Building was made to a 1:75 scale, using card paper of different colours according to their reflectivity, lycra fabric, white thread, a transparent plastic sheet and wooden sticks.

The central fabric membrane and the lateral membranes were modelled. The buildings located at the long sides of the playing area (cafeteria, gym, toilets, changing rooms), the crèche and the reception were also modelled using card paper. Window areas were left open, with the exception of the glass ladder trusses located in the main membrane. The membrane structure was tensioned with thread pulling the ends towards the floor of the physical model. Four masts support the central membrane.

Table 5-6 Photometric properties of materials used in scale model and measured in the real building

Surface	Reflect. Real building	(%) scale model	Absorpt. Real building	(%) scale model	Transmitt. Real building	(%) scale model
-Fabric membrane (2 layers of lycra cotton fabric)	75	72.33	9.0	11.87	16	15.8
-Wooden floor (pale pink paper)	42.47	39.26	-	-	-	-
-Corridors (beige paper)	47.29	46.5	-	<1	-	52.5
-Lateral buildings (dark green card paper)	8.0	7.8	-	-	-	-

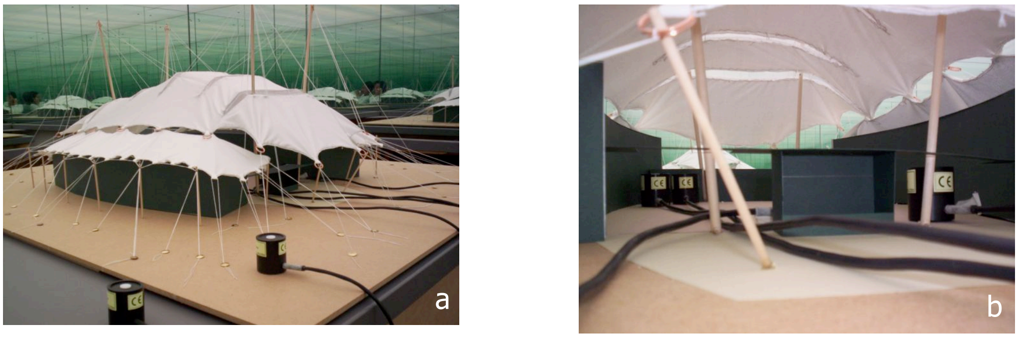


Fig. 5-32a & b Scale model under artificial sky.

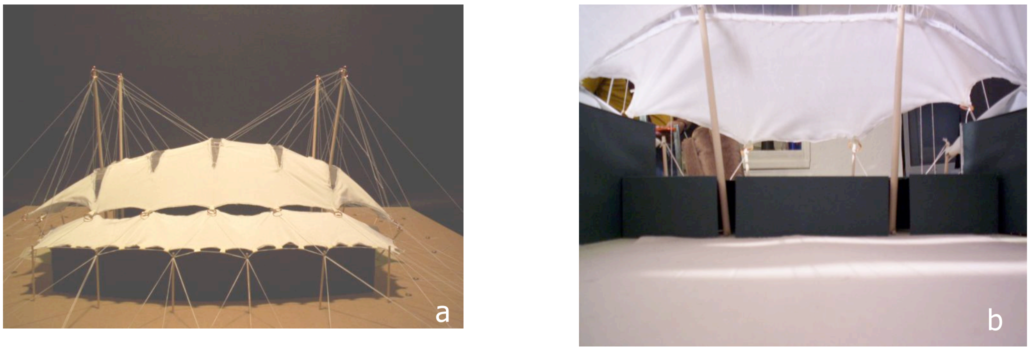


Fig. 5-33a & b Exterior and interior of scale model of the IRAB.

5.3.4.3 Results

The resulted average DF is 32.97%. This figure has not been adjusted for glazing transmittance losses and dirt. Though, indicates the playing area of the building is daylit. The Uniformity ratio obtained is 0.79, which means the ratio between the minimum illuminance value within the space and the average illuminance level is minimum. Therefore, the interior lighting is relatively uniform. The daylight factor measured in the real building is 24% with a DF uniformity of 0.69.

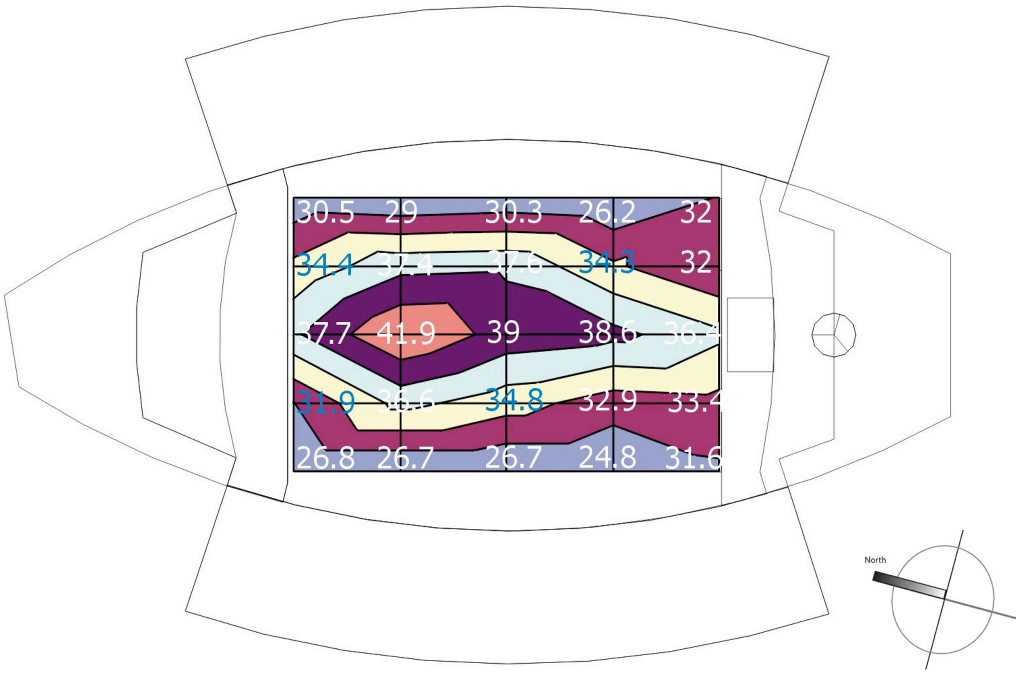


Fig. 5-34 DF (%) contours over plan of Amenity Building's scale model.

The above plan contains the DF contours in the playing area. The highest DF is 41.9% and is located over point 8 in the centre-left of the court. The DF decreases progressively towards the edge of the area, where the lateral buildings stand causing shade over this region. Lighting behaviour near the long sides of the grid area is almost symmetrical corresponding to the geometry of the Amenity building.

The south (main entrance) and north (crèche block) facades are not symmetrical and the DF contours follow this characteristic as it was expected. The block volume of the crèche represents a bigger obstruction to light than the reception desk and first floor corridor.

On the other hand, point 5 was expected to have the highest DF but instead the highest DF is located over point 8. This performance might correspond to different causes:

- More lighting reflections from the wall on the north side of the court;

- The geometry of the building: north and south façades are not identical;
- The non symmetrical geometry of the scale model;
- A non uniform or asymmetrical representation of a CIE overcast sky produced by the artificial sky used in this study.

The first assumption is based on the dimensions of the surface area of the wall which is bigger than the wall located at the opposite side of the court. However, the wall surface is opaque and dark and the reflectance factor is quite small (0.08).

In order to validate whether the artificial sky or the scale model construction influenced the lighting performance of the physical model, a further test was developed with the scale model under the artificial sky. The results from this second study will be included at the end of this section.

Figure 5-35 illustrates sections A-A′ and B-B′ situated over the plan of the building. Then the resulted DFs through these sections are shown.

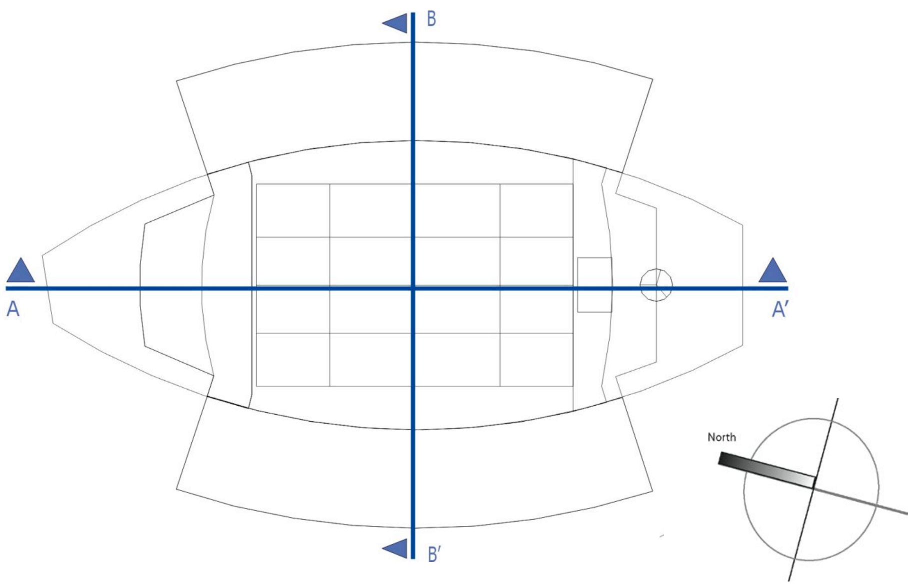


Fig. 5-35 Location of selected sections: A-A′ and B′-B

The curve through section B′-B (Figure 5-36) shows the highest point located over point 5, which is the centre of the court and the most exposed area to daylight. The tensile membrane structure reaches its highest point over the centre of the sports hall. Then, daylight factors decreased towards both sides of the curve mainly by the shade provided by the adjacent blocks and the lateral membranes placed over these two blocks.

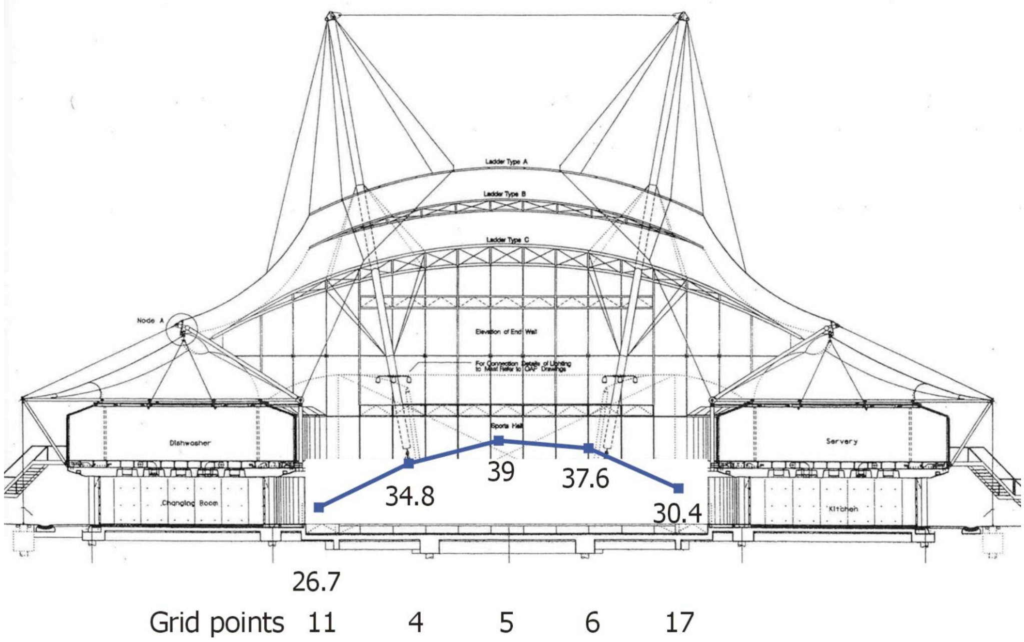


Fig. 5-36 DF (%) variation through section B'-B.

A completely symmetrical curve was expected but making a physical model of this type where tension applied to the membrane determines the shape of the enclosure it is not an easy task. For this reason, it seems that the final shape of the scale model could affect the lighting availability in the playing area, although the light performance through the section can yet be representative.

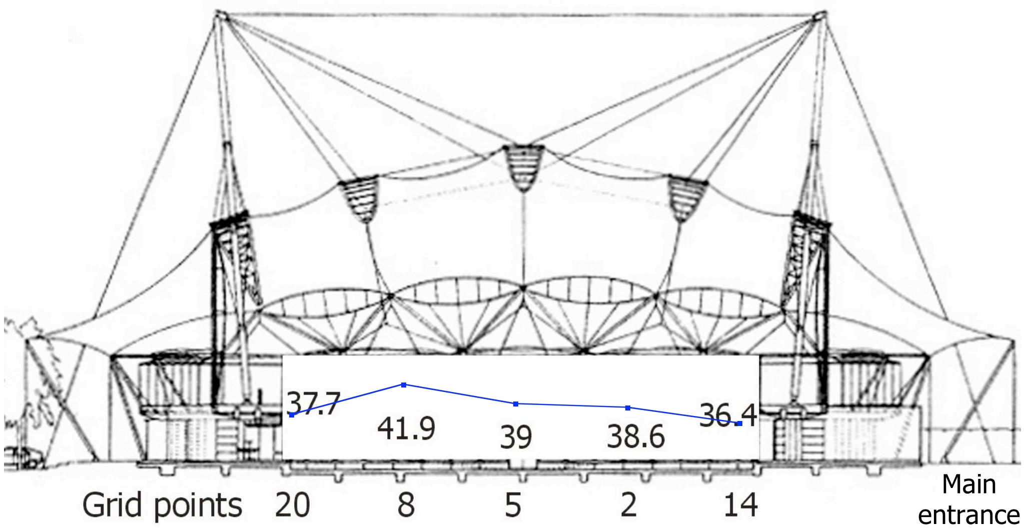


Fig. 5-37 DF (%) variation through section A-A'

The above section clearly shows how the curve reaches its highest point in point 8. The rest of the curve represents the expected behaviour, decreasing DFs in the direction of the edges of the studied area (points 20 and 14).

Results from test 2

In order to confirm whether the final shape of the scale model or the construction of the artificial sky influenced the results obtained in the lighting study, a further test was carried out.

This time the scale model was placed under the same artificial sky exactly on the opposite direction as in the study presented previously. Illuminance measurements were taken with the same equipment and in the same grid points. The result is presented in the comparative Figure 5-38.

In general, the daylighting contours in both figures have a similar pattern with the highest daylight factors around the centre of the scale model and the peak level situated on the left side of the artificial sky towards wall 4 (W4). However, the results would have been expected to be mirrored once the scale model was turned.

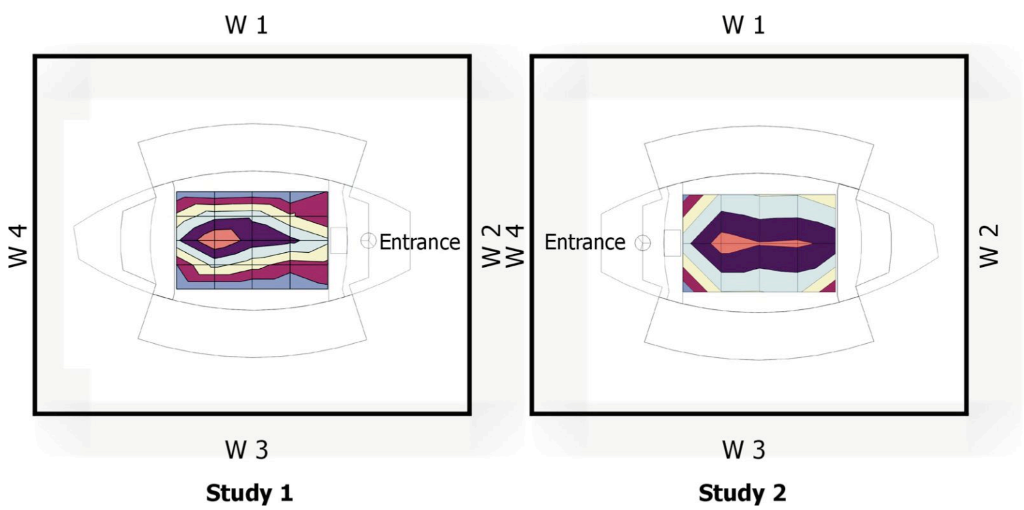


Fig. 5-38 Comparison between DF contours of IRAB scale model measured in study 1 with the main entrance facing wall 2 of the artificial sky, and in study 2 facing wall 4.

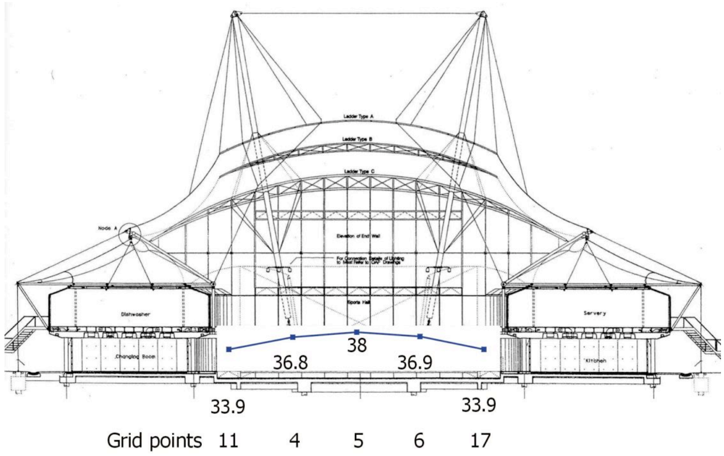


Fig. 5-39 DF (%) variation across Section B'-B

The curve through section B'-B is very similar to the one obtained in the first study. The highest DF is at the centre of the playing area in point five, and the values decrease almost symmetrically to both sides of the building. On the other hand, section A-A' shows a similar behaviour than Figure 5-37 of the first study but in opposite directions (Figure 5-40).

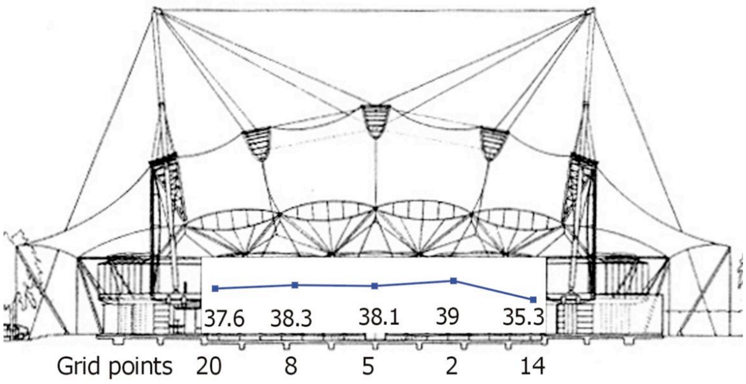


Fig. 5-40 DF (%) variation through Section A-A'

Since the artificial sky simulates overcast sky, ideally the diffused light must be uniform and affected only by the geometry of the model if the illuminance from the lamps is uniform. But this was not completely true with this model. A test was developed to measure the illuminance variation and uniformity of the light that reaches the table located inside the artificial sky. The table (1.20m x 1.20m) was divided into a 100mm by 100mm grid. Illuminance readings were taken with one lux sensor over 121 points.

Results show that illuminance uniformity in the artificial sky is 0.98, which is a fairly uniform figure. The lowest illuminance value is 1934 lux and the average is 1972 lux. The illuminance contours are presented in the following figure, where a difference of 10 lux was selected to plot the lines.

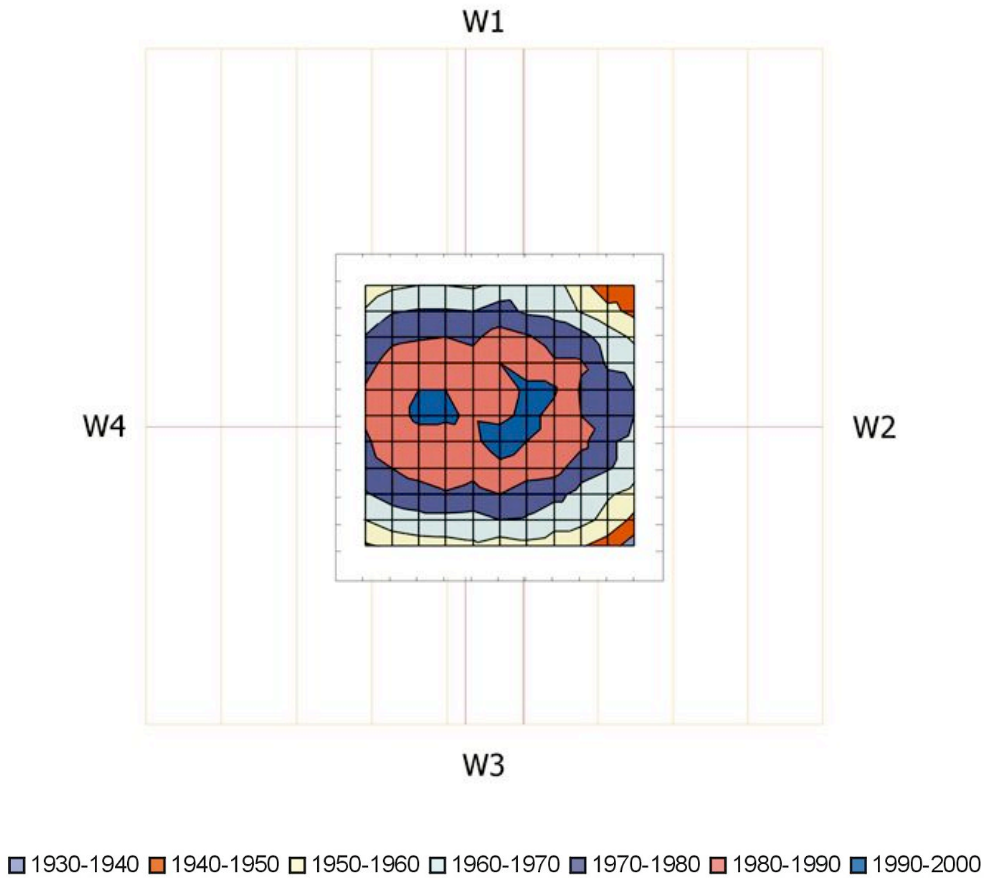


Fig. 5-41 Illuminance contours on table inside artificial sky.

The blue areas at the centre of the plot are the highest illuminance points over the table (with values between 1990 and 2000 lux). Light levels decrease towards the edges of the table due to the reduction of the table area and the light reflected from it. The orange area in the centre represents values between 1980 and 1990 lux. Therefore, the illuminance variation between the grid points of these two areas corresponds to a 10 or 20 lux difference.

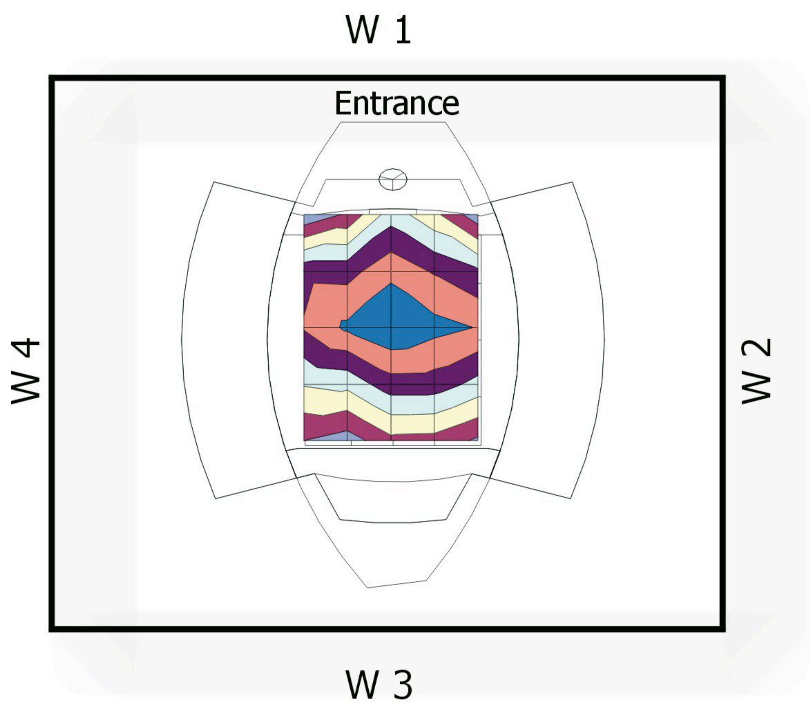
Although the illuminance variation under the artificial sky is not completely uniform, the areas where the highest values are found do not exactly correspond to the scale model grid points with higher DF. Therefore, there are two possible explanations:

1. The geometry of the building is causing the DF peak value to be 7.8 meters away from the centre of the sports hall in point eight. The crèche block that closes the playing area on its north side reflects light that comes through the roof and glass areas. This also contributes to the greater DF value in point eight.
2. The tension applied to the central membrane of the scale model is not even; this produces a non-symmetrical roof.

The influence of these two factors was evaluated in a third study. The fabric membrane of the scale model was tensioned again trying to reach a symmetrical roof. And this time the entrance of the building was placed facing wall 1 of the artificial sky.

Results from test 3

In this third study the greatest daylight factor (37.81%) was found over point 5, which is located at the centre of the playing hall (dark blue colour in Figure 5-42). The following sections show the variation of the daylight factors obtained through sections A-A′ and B′-B.



Study 3

Fig. 5-42 DF contour lines over plan of IRAB under the mirror box.

Figure 5-43 shows the same behaviour as in the previous studies with this scale model, the highest DF is found over the central area of the playing hall. Then, the DF decreases towards both sides of the building.

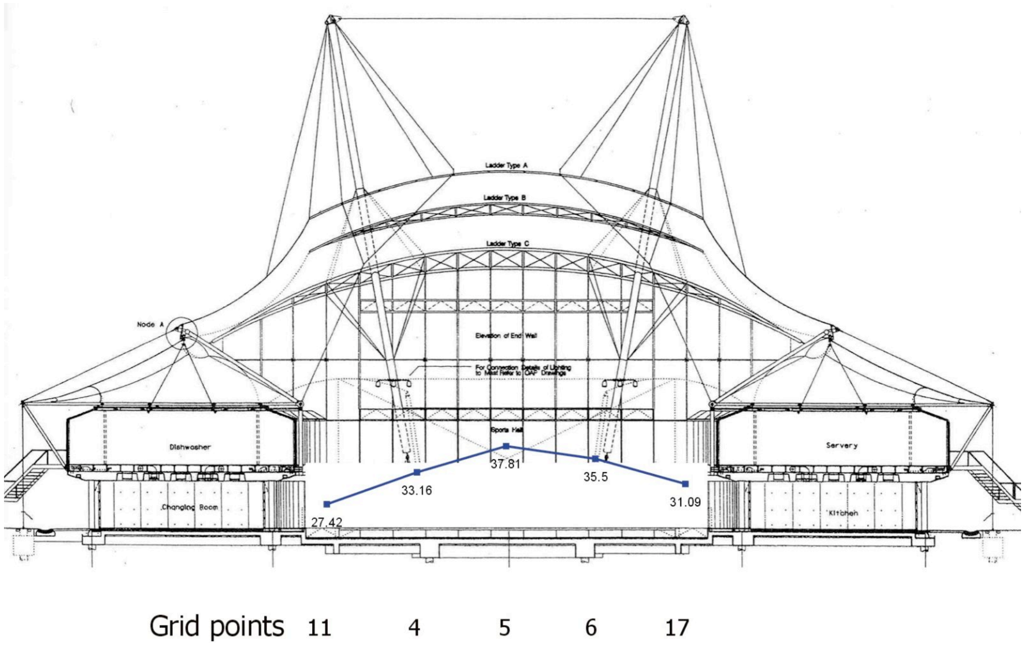


Fig. 5-43 DF (%) variation through Section B'-B

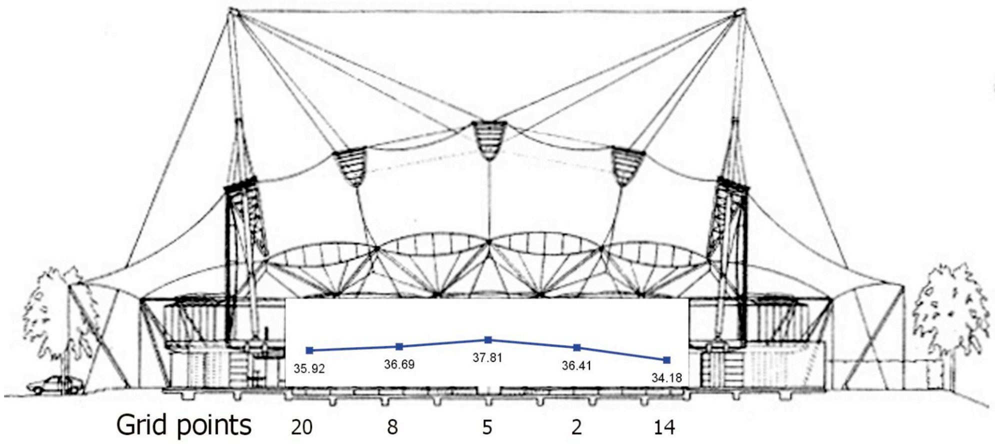


Fig. 5-44 DF (%) variation through Section A-A'

This last study has shown the effect that the tension of the fabric membrane has on the daylighting behaviour of the building. The illuminance distribution changed even though the average daylight factor did not change considerably. Daylight factor of test 1 is 32.97%, DF obtained in test 2 is 35.13% and the DF factor of test 3 is 30.94%.

The daylight factor obtained in test 3 was corrected for glazing transmission losses and dirt on surfaces. Three types of glazing were used in the Amenity Building:

1. Single 12mm toughened clear glass 86% light transmission
2. Double clear glass 73% light transmission
3. Single clear float toughened glass 87% light transmission

All this glazing covers a total area of 895.8 m^2. The light transmission factors were multiplied by a dirt factor of 0.9.

Using the building's Radiance model the percentage of daylight that penetrates through glazing was obtained. This is 14.03% of daylight entering the building comes through glazing areas. In order to identify this data avoiding the light that comes through the translucent fabric membrane, the membrane in the Radiance model was blackened out.

Hence, 0.1082 was used as a correction factor for glazing and dirt to the DF from test 3 which is 30.97%. Then, the final average daylight factor is **27.62%**. This figure does not significantly differ from the 24% DF measured in the real building.

5.4 CONCLUSIONS AND RECOMMENDATIONS

Although some factors such as cost, construction time, workshop space and modelling skills could be greatly reduced or eliminated with the increasing development of computer software that simulates daylight; still some architecture practices prefer to construct scale models for lighting studies, as a tool during the design process and for presentations to clients.

A number of problems were faced during this study. Probably the most important was the difficulty and time used getting the right or exact geometry of the real buildings. Even though, any of the scale models of the cricket schools represented the complete building, which also includes changing rooms, gym and offices, it was possible to analyse the behaviour of light inside the models.

5.4.1 Limitations of physical models

Scale modelling is a prediction technique that helps giving a general idea of the daylighting environment in buildings. However, there are certain restrictions or limitations when constructing physical models for daylighting studies:

- High construction time
- Elevated cost
- Scale of model is dependent of several factors, such as: dimensions of the building, dimension of the artificial sky and size of photometric sensors
- It is essential to accurately model the geometry of the building
- It is essential to accurately model the reflectance of interior surfaces and ground reflectance if side windows are modelled. If the scale model does not include glass or similar in windows, then a correction factor has to be applied for glazing transmission losses and dirt on surfaces
- When modelled in a mirror sky only overcast sky conditions can be simulated
- Sometimes the scale model could be difficult to store, to handle or to transport (if necessary) depending on dimensions and type of materials used
- It is essential to have measuring equipment: calibrated sensors, data loggers, sensors level, illuminance meter and luminance meter
- It would be advisable to be certain of the accessibility to an artificial sky or a daylight dome simulator, which are quite expensive structures and generally only available in architectural research centres and universities.
- It is important to make sure the artificial sky is in good condition, diffusing fabric and mirrors are clean and there is adequate maintenance to lamps.
- Access to drawing plans, materials' characteristics, function of the building, location and, if already built, access to the real building are

factors to be considered when deciding using scale modelling as a daylighting prediction technique.

5.4.2 Comparison of results with real buildings

The average DF obtained with model C (10.96%) of the Indoor Cricket School at Lord's Ground was very similar to the DF from model B (10.66%). The main difference between these two models is that Model B was constructed with a more simple representation of the roof trusses and fabric louvres than model C.

Definitely, the tension applied to the fabric and its angle of curvature represented in the physical model influenced the amount and type of daylight passing through. The daylight factor in Model A differed from model B by 38%; the main differences between models were the addition in model B of the net like fabric that divides the playing lanes, and the fabric louvres were replaced for a single fabric cut.

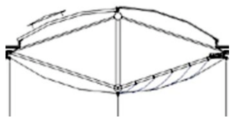
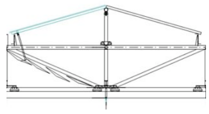
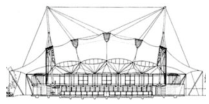
The scale models of the cricket schools overestimated the lighting behaviour of the real buildings. Both field data (Lord's: 4.4% DF, Loughborough: 5.9% DF) are similar to the average DF recommended by CIBSE[26] and the IES[27] which is 5%. However, this behaviour is yet to be compared with the computer simulation analysis included in chapter six in order to validate the results.

Table 5-7 compares the daylight factors resulted from the field and the scale models analyses of the three case studies. The initial design targets are also included. The physical model of the Inland Revenue Amenity Building (IRAB) is the one that closest represented the daylighting performance of the real building with a divergence of +13%.

Table 5-7 Daylight Factors (%) comparison between design target, physical modelling and field measurements

Building	design target	field	scale model
Lord's	20	4.4	10.96
Loughborough	30	5.9	16
IRAB	6	24	27.62

Table 5-8 Divergence between DFs and Illuminance Uniformity of scale models vs. field measurements

BUILDING	TENSILE MEMBRANE ROOF	DIVERGENCE BETWEEN SCALE MODEL AND REAL BUILDING*	ILLUM. UNIFORMITY REAL BUILDING	ILLUM. UNIFORMITY SCALE MODEL
Case study 1		59.8%	0.37	0.8
Case study 2		63%	0.55	0.56
Case study 3		13%	0.29	0.79

*The following equation was used: (SM-RB)*100/SM; where SM is the DF from scale model and RB is the DF from real building measurements.

The divergence between daylight factors obtained in case study 1 (Indoor Cricket School at Lord's) and case study 2 (National Cricket Academy) with physical models and field measurements is around +60% and +13% with the Amenity Building. Daylight factor values were overestimated by the scale models used in this study. However, it seems that evaluating fabric membrane buildings with scale models present similar results as previous studies using scale modelling to assess the daylighting performance of buildings. For instance, Cannon-Brookes obtained an overestimation of +60% of a preliminary study with the scale model of a museum building compared to real building measurements taken both under overcast sky conditions[14].

A possible source of error that leaded to the divergence between scale model measurements and field measurements is an imperfect estimate of the reflectance of the materials used to construct the physical models. The card papers used were assumed to be completely diffusing, but probably some specular reflections could influence the light distribution in the models and the estimated reflectance of these same materials.

On the other hand, the illuminance uniformity in all three cases was similar between the physical models and the field measurements, except for the Amenity Building. This indicates that in most cases scale models can simulate the behaviour of daylight throughout a space; but great care has to be taken when constructing and testing scale models if accurate results are expected.

In order to analyse the effect of sensor height on results accuracy a small test was conducted using the computer models of the three buildings and Radiance software to simulate the availability of daylight under two different parameters:

- Placing the analysis grid (or sensors) at 0.00m high
- Elevating the analysis grid at 1.25m high (building 1) and 1.80m high (buildings 2 and 3)

The real dimension of the light sensors used in the physical modelling study is 2.5cm high x 2.5cm of circular base diameter.

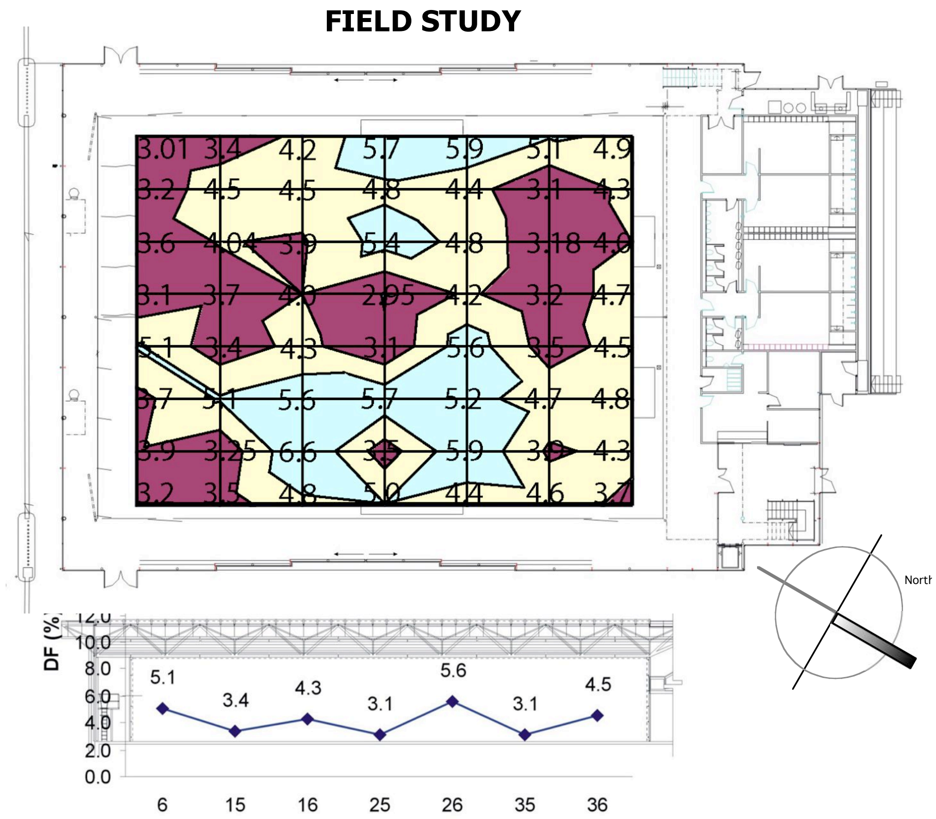
Table 5-9 presents the resulted daylight factors with sensors' height as a varying factor. The divergence found among results was then applied to previous average DF values obtained with the scale modelling analysis minimising the error caused by sensors dimension.

Table 5-9 Effect of sensor height on scale models accuracy

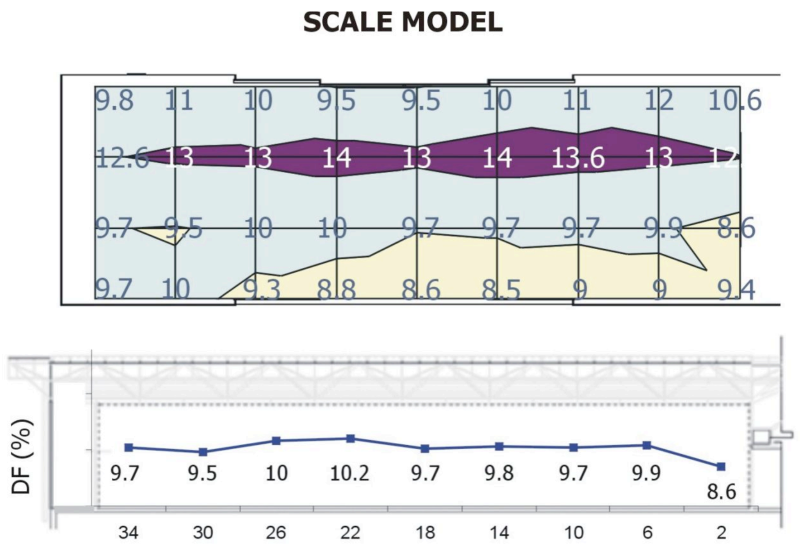
BUILDING	RADIANCE DF (h=0.0m)	RADIANCE DF (h=1.25m) (h=1.8m)	DIVERGENCE (%)	RESULTED DF FROM SCALE MODELLING
Lord's	4.71%	5.37%	-14%	9.16%
Loughborough	4.40%	4.50%	-2.27%	15.64%
IRAB	22.98%	23.71%	-3.18%	26.72%

Figures from Table 5-9 illustrate the importance that light sensors size has in scale modelling studies; it is definitely a factor to be considered when setting up an experiment. In this study big sensors caused an error in calculations of around 3% for buildings 2 and 3, and a higher error (14%) for the Lord's model (building 1). Sensors have to be chosen according to model's scale or must be positioned under the model leaving only the sensor’s head out on the model’s floor or at the working plane.

The following Figures show daylight factor contours and daylight factor variation through longitudinal sections of all three case study buildings, comparing data obtained in field measurements with results from the scale models’ analysis.

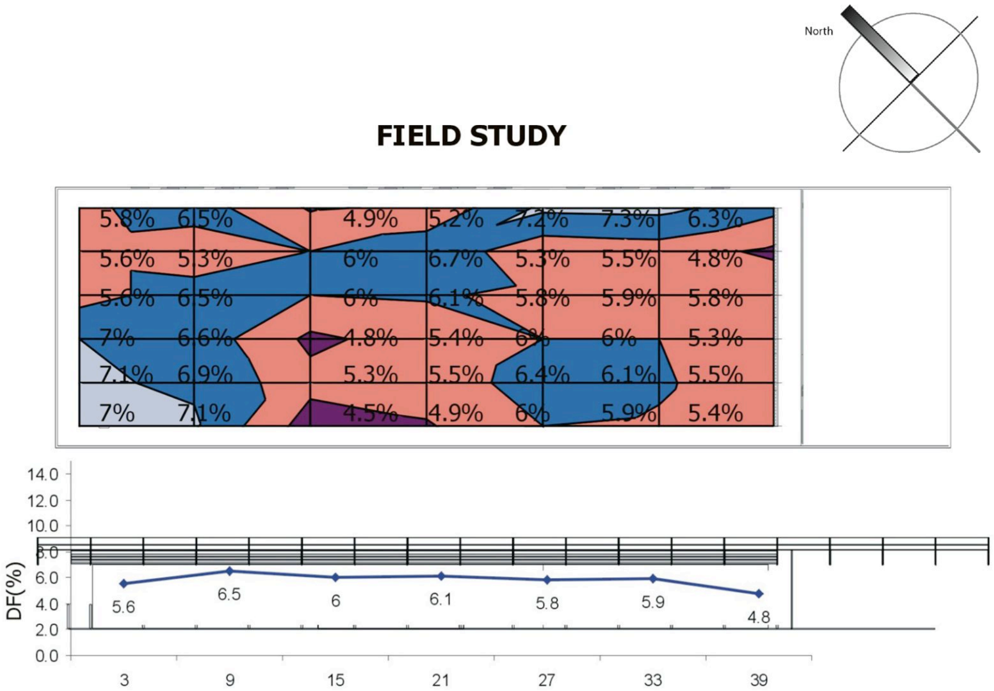


a

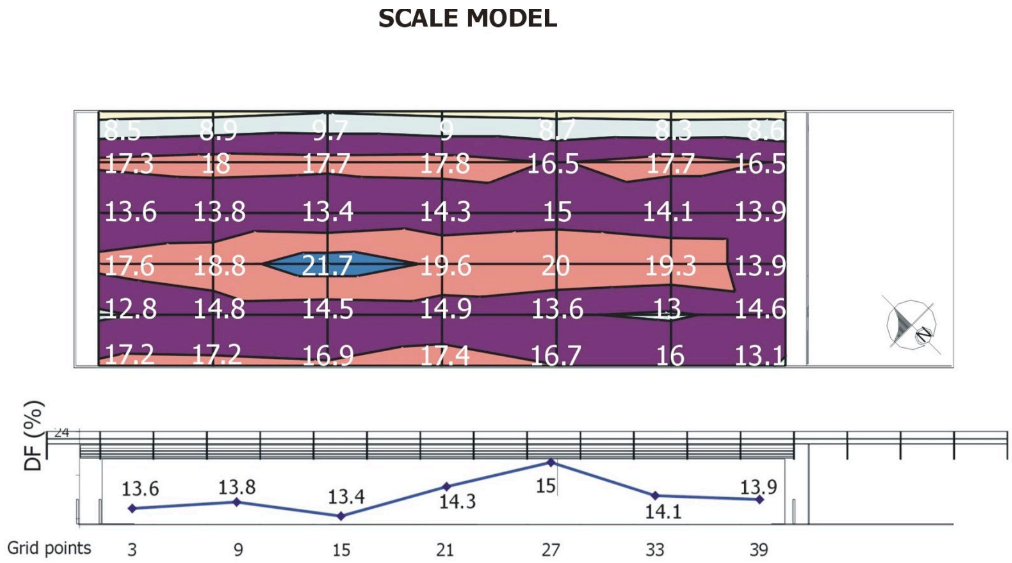


b

Fig. 5-45a DF from field data, plan & section
Fig. 5-45b DF from scale modelling (Model B), plan & section;
Indoor Cricket School at Lord’s Ground, London.



a



b

Fig. 5-46a DF (%) from field data, plan & section
Fig. 5-46b DF (%) from scale modelling (model A), plan & section; ECB National Cricket Academy, Loughborough University.

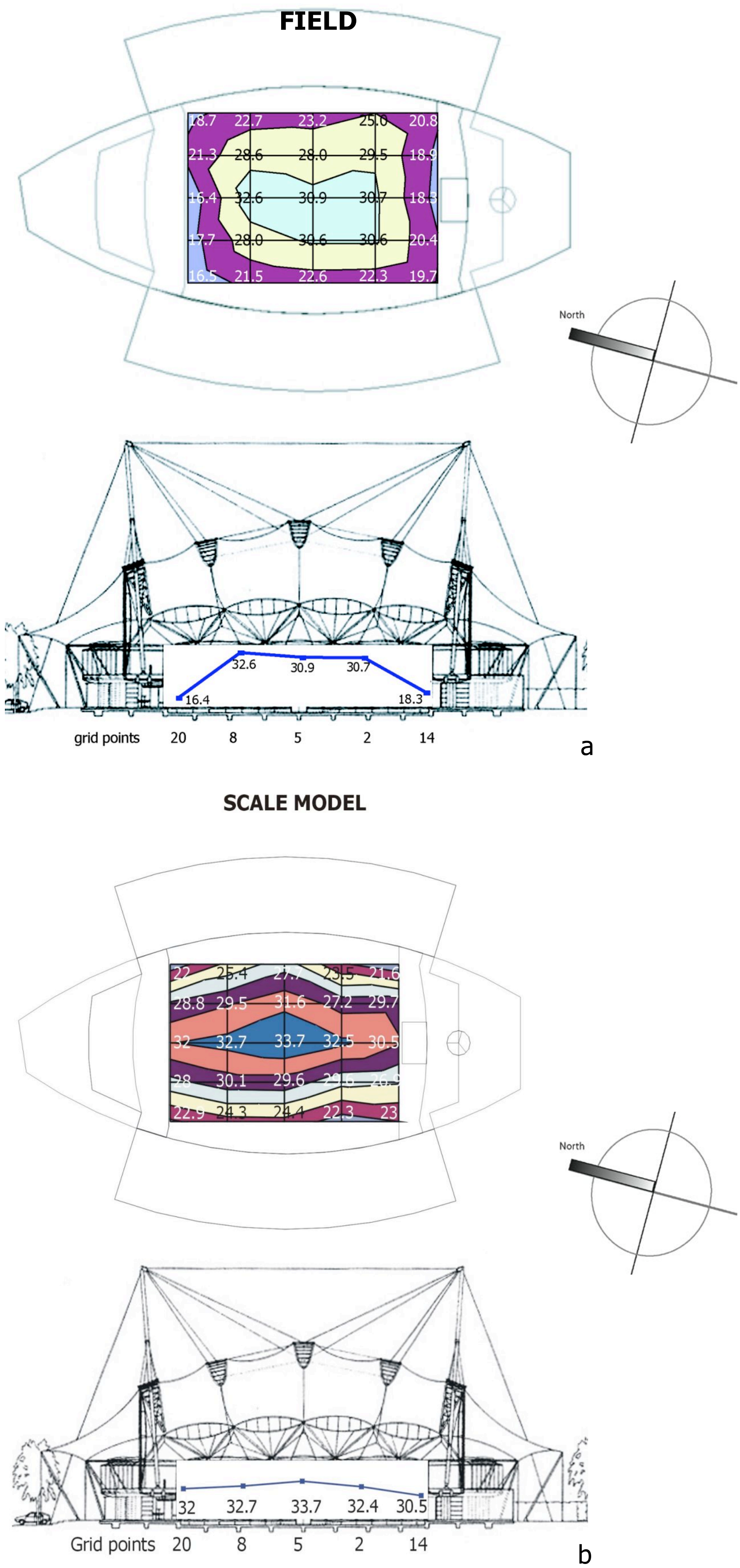


Fig. 5-47a DF (%) data from field study, contours plan & section
Fig. 5-47b DF (%) data from scale modelling, contours plan & section; Inland Revenue Amenity Building, Nottingham.

Finally, scale modelling provides a rough idea not only of the lighting atmosphere but also of the internal spatial environment and the geometry of the building. Though, whether is worth modelling the whole building or only a particular section depends on the purpose of the daylighting study and the accuracy desired.

In summary, the construction of scale models for daylighting studies has to be planned in advance and with great care. Possible errors found in this study when simulating daylight with scale models include:

- Appropriate scale of the model to allow an exact representation of the geometry. Due to the big dimensions of the buildings and the dimensions of the artificial sky, it was necessary to use rather small scales. The use of bigger scales would have facilitated the representation of the real geometry.
- Sensors calibration. The light sensors used in this study were calibrated by the manufacturers (see calibration certificates in Appendix). Nonetheless, the sensors were tested under the artificial sky and a slight divergence (5%) on the illuminance measurements registered by the six sensors was found.
- Accurate geometry and dimensions are essential to obtain precise results. In the Lord's scale model the areas of changing rooms, office, reception and entrance were not modelled causing, among other factors, a huge divergence with the real measurements.
- Correct photometric properties of surfaces, account for glazing transmission losses and surfaces maintenance. Matching the real reflectance of surfaces was a tough task, in the case of the cricket schools the paper used for walls and ceiling was too reflective increasing the amount of light due to inter-reflections. Although a glazing and dirt correction factors were applied to the final results, it seems that modelling the glazing light transmittance and geometry of windows or roof lights in the physical model could have provided better results, closer to reality.

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Six

6. ASSESSMENT OF COMPUTER SIMULATION TO PREDICT DAYLIGHTING PERFORMANCE OF MEMBRANE BUILDINGS

6.1 INTRODUCTION

In chapter five results from the lighting analysis of the case studies carried out with physical models were presented. Chapter six intends to show the capability of computer simulation to effectively predict the daylighting behaviour of tensile membrane buildings. For this purpose the lighting simulation software Radiance is used[1]. This computer software is being utilised by many lighting researchers around the world. It is a ray-tracing software which allows to simulate specular and partly specular materials in complex spaces[2].

Extensive research has been undertaken to validate Radiance as a tool to model lighting distribution and daylighting illuminance in complex buildings, such as: office spaces, shopping centres, atrium buildings[3,4,5,6,7,8,9]. The software has proven to be useful to simulate the impact of different daylighting control systems and shading devices on the lighting environment of buildings; while producing high quality and realistic images containing physically exact lighting data.

Although Radiance was used to predict daylight factors and illuminance availability in the New Bangkok Airport[10] which used fabric membrane structures to cover the concourse areas; the literature review carried out for this thesis did not show a validation study of Radiance modelling tensile membrane structures.

This chapter aims to assess the accuracy of Radiance to simulate daylight in tensile membrane sports buildings. The software accuracy is evaluated based on comparisons between the predicted and the illuminance measurements taken on site for the three case study buildings described in chapter three section 3.2. Advantages and disadvantages regarding the use of Radiance are analysed together with a method to best model the daylighting behaviour of tensile membrane buildings. The possibility of predicting daylight in this type of structures with reasonable accuracy can demonstrate the potential and architectural applications of fabric membranes for daylighting and solar control.

6.2 DESCRIPTION OF RADIANCE SIMULATION SOFTWARE

The development of Radiance simulation software began in 1988 by Ward at the Lawrence Berkeley National Lab[11]. Radiance can model complex spaces calculating daylighting and lighting systems' performance, and also provides photo realistic pictures of the modelled environment that can be helpful for the evaluation of visual comfort and light quality.

Radiance was developed under the UNIX operating system and comprises around fifty programs, which give the possibility of input control variables for calculation accuracy, image quality and detail, type of lighting analysis and light variability[1,11,12]. Sky conditions can be set to clear sky (with or without sun), CIE standard overcast or uniform sky.

The calculation method used by Radiance is a light backward ray tracing in which the path of a ray reaching the eye or a measurement point is traced back to an object in the scene and then to the light source. Each ray has certain intensity or 'weight', which changes after intersecting a surface depending on the reflection (Fig. 6-1a). In Radiance this process stops when one of the following points is met[1]:

- The intersected surface is a light source.
- The ray has reflected more than a specified number of times; where six is the default limit

- The ray intensity or 'weight' falls below a certain arbitrary value (the default limit is 0.005). The ray is then absorbed and a new process starts with a different ray emission[8].

This allows carrying out an accurate lighting analysis under any kind of reflection or transmission properties in geometrically complex environments.

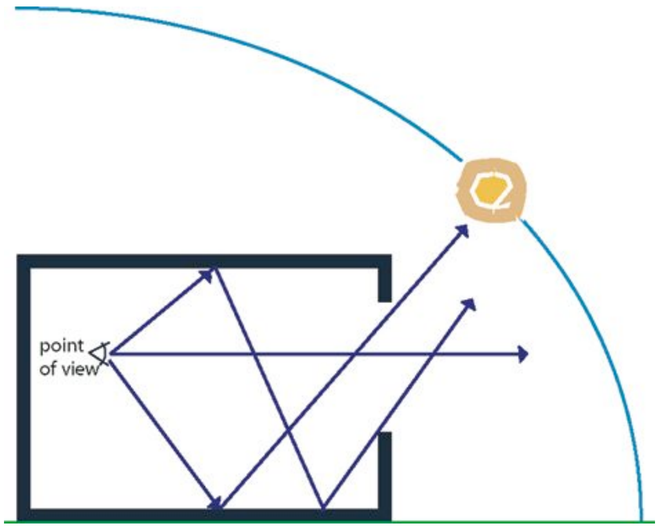


Fig. 6-1a Diagram of the ray tracing system used by Radiance

The software uses a combination of deterministic and stochastic[a] ray tracing in order to obtain a balance between speed and accuracy of calculations.

There are three main Radiance programs for ray tracing:

- *rpict* (produces a picture from a scene description);
- *rview* (computes and displays images interactively);
- *rtrace* (computes specific values for other purposes).

The following figure shows the main programs (boxes) and data (ovals) flow in Radiance[14].

---

[a] Using a *deterministic* algorithm the same result would be achieved for a certain rendering when repeated. For instance, considering a ray sent from an intersected object to a light source, the ray would be sent towards the centre of the light source every time, obtaining always the same illumination.
A *stochastic* algorithm uses random processes, and it would choose a random direction in which to send the ray, obtaining different results every time. The average of all results obtained will be close to reality [13].

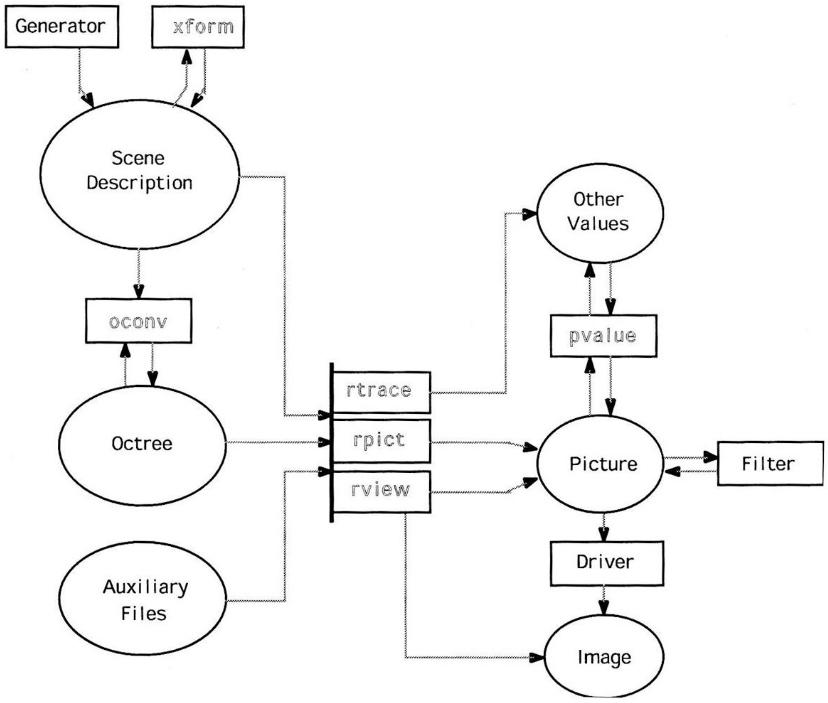


Fig. 6-1b Radiance main programs [14].

In addition, *oconv* is also a program that converts scene descriptions into the *octree* format that the rendering programs (rpict, rview) use as input.

A Radiance scene is created with surfaces and materials that create a specific environment. The basic surface types are spheres, polygons, cones and cylinders. It is possible to simulate materials such as glass, metal or plastic. Creating complex scene geometries, such as the case studies analysed here, using Radiance commands in a text editor could require many modelling hours and a good level of programming skills in the UNIX operating system. Therefore, many people prefer to use a CAD program to create scenes, and then, translate them into Radiance. An advantage of this method is that drawing using a CAD program is more visually interactive since you are constantly seeing what you are drawing, whereas, drawing with Radiance has to be done through a text editor using the command *objview* periodically to revise the model.

There is a Windows version of Radiance known as 'desktop Radiance'[15]. This version is integrated into the CAD package AutoCad and can be also used through the environment of a building analysis program called 'Ecotect'[16]. This software was used to carry out the work presented in this thesis.

6.3 METHODOLOGY OF THE LIGHTING SIMULATION

6.3.1 Modelling the geometry

In order to validate the usefulness of computer modelling to predict daylighting in daylit fabric sports buildings, the case studies described in chapter 3 were modelled in Radiance obtaining quantitative data that is compared with the field measurements analysed in chapter 4.

Moreover, a sensitivity study was developed and its findings are reported here. This study consisted on a parametric analysis of different light transmittances of the buildings' fabric membranes, and different reflectance factors of the interior surfaces. The results show the influence that materials' transmittance and reflectance factors have on the lighting environment and performance of our case study buildings.

Three-dimensional models of the fabric membrane sports buildings selected as case studies were created. These buildings are: the MCC indoor cricket school at Lord's Ground, the National Cricket Academy in Loughborough and the Amenity Building of the Inland Revenue Centre (IRAB) in Nottingham. Architectural 2-D CAD drawings of the cricket buildings were obtained from the designers, and from these drawings the 3-D models were completed. The 3-D model of the IRAB was created based on photocopies of detailed drawing plans of the building. These computer models were created in AutoCAD 2002. All surfaces in the 3D models were divided into different layers to facilitate attaching them specific materials properties later in the simulation process.

Once the 3D models were ready, they were exported from a *.dwg file into a *.3ds file, and finally, they were imported into Ecotect v.5.2. Most of the geometry was already completed, and final corrections were made adding some windows, exterior surfaces and the surrounding environment (adjacent buildings, trees, etc.) in Ecotect. A diagram showing the general methodology used in the computer simulation is included in chapter 3 section 3.3.2.

Ecotect v5.2 is a building analysis software mainly aimed at architects whose projects are at the early stage of design. The program integrates a modelling interface for environmental analysis of buildings. Preliminary studies of lighting, acoustics, thermal comfort and solar access can be developed with Ecotect. This program offers the possibility of exporting files to more powerful analysis software such as WinAir4 (computational fluid dynamics), HTB2 (thermal simulation), Energy Plus (energy simulation) and Radiance (lighting simulation).

Materials' characteristics were input in Ecotect including colour and reflectance factors of walls, floors, roofs; and transmittance of windows. The fabric membranes characteristics were modelled creating with a text editor a *.rad file that is read only by Radiance.

The level of accuracy at which the models were drawn was high including surfaces that could have influenced the lighting calculations in Radiance, though avoiding having too many surfaces that could slow the process. In all case studies the areas studied were the playing halls. In the cricket buildings these areas have the following surfaces:

- Green floor
- Aluminium walls and roof structure
- Vertical fabric partitions
- Opaque polycarbonate roof
- Transparent polycarbonate roof
- Net like fabric dividing playing lanes
- Fabric louvres

The model of the indoor cricket school at Lord's ground also included block walls in the office and gym areas, windows and staircases at both sides of the main façade.

The side window that goes along the playing area on the northeast façade of the National Cricket Academy was modelled too, since it could have some influence on the lighting performance of the building. The emergency staircase was also modelled.

The surfaces modelled in the Amenity Building included:

- Wooden floor
- White floor in corridors and main entrance
- Buildings surrounding the sports area were modelled as building blocks
- Walls in reception area
- Windows (vertical)
- Fabric membrane roof (central and side membrane roofs)
- Windows located in between the central roof and lateral roofs (eye-shaped), and glass in ladder trusses

The final level of accuracy in all three models is illustrated in the following Figures. Initial simulations with more simple models showed low accuracy in the calculations; therefore, more detail was put in modelling windows, stairs and interior partitions that could have an effect on the daylighting behaviour at floor level in the playing areas.

1. INDOOR CRICKET SCHOOL AT LORDS GROUND, LONDON.

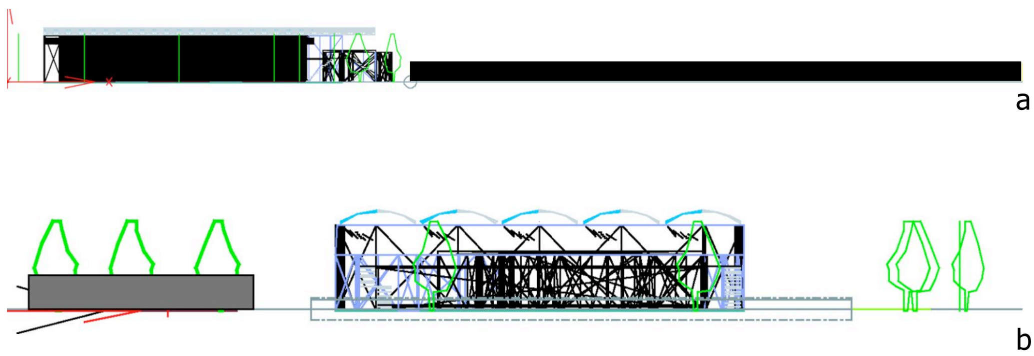


Fig. 6-2a Side elevation of Lord's indoor cricket school and adjacent building
Fig. 6-2b Main entrance elevation

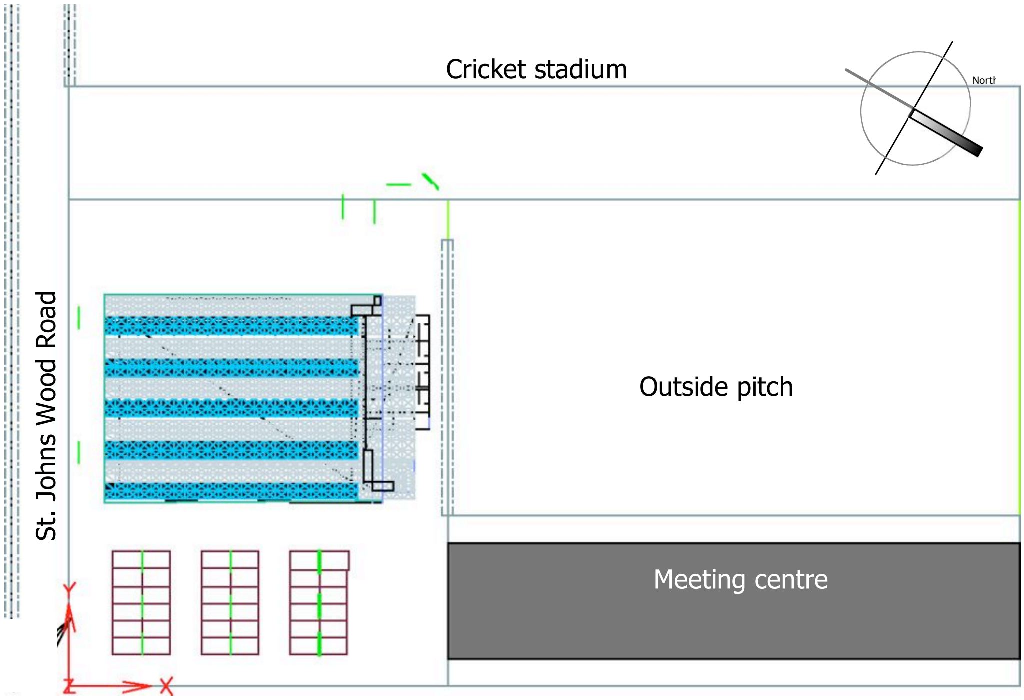


Fig. 6-3 Site plan of the indoor cricket school, Lords Ground, London.

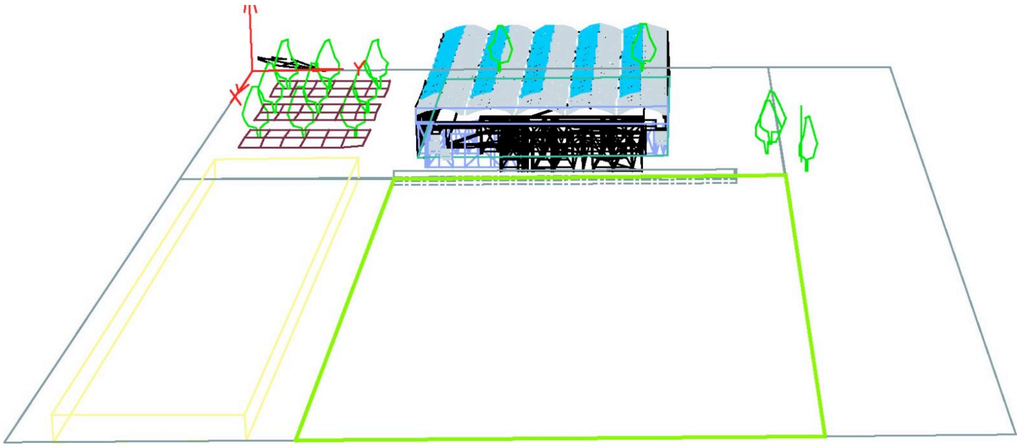


Fig. 6-4 Perspective view of site

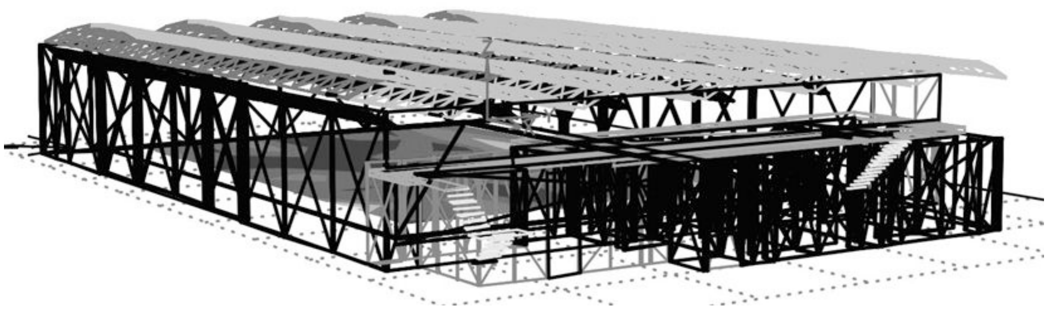


Fig. 6-5a Perspective view of the Cricket School model

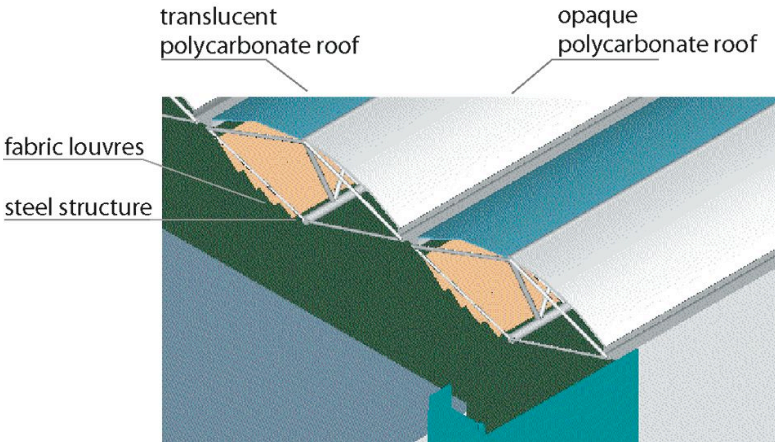


Fig. 6-5b 3D perspective detail of the roof structure

2. NATIONAL CRICKET ACADEMY, LOUGHBOROUGH.

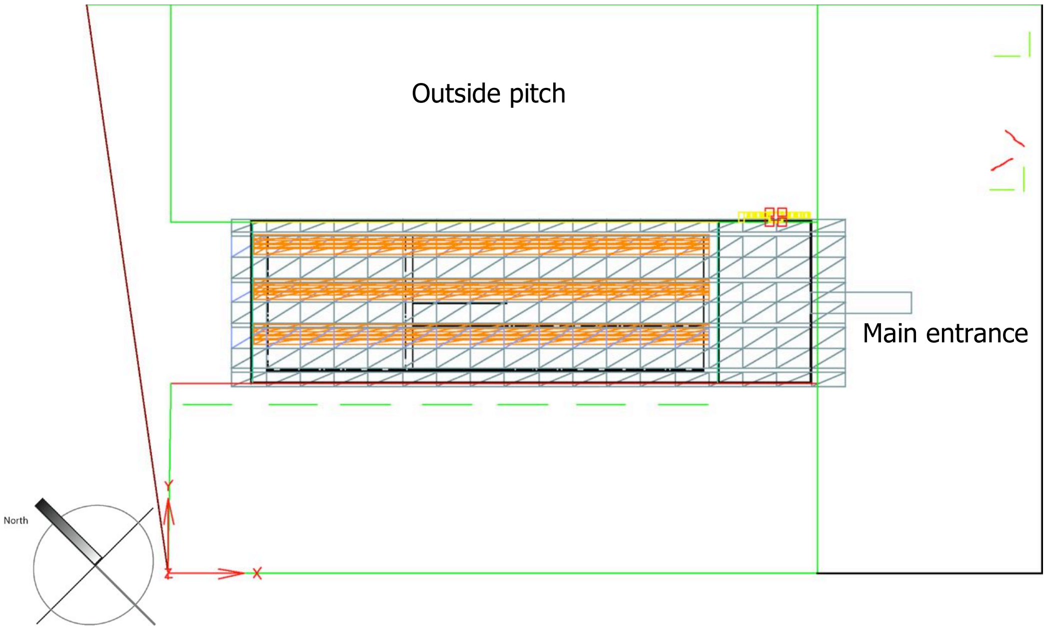


Fig. 6-6 Site plan of National Cricket Academy

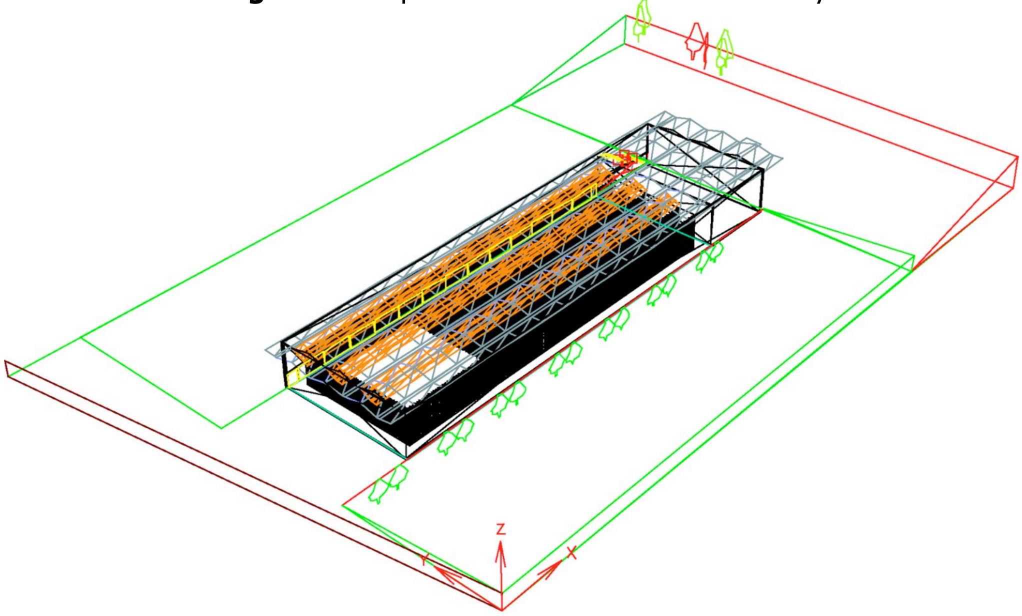


Fig. 6-7 Perspective view of site

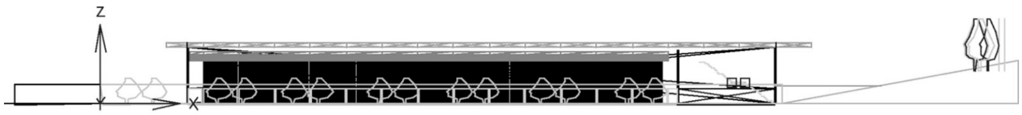


Fig. 6-8 Side view of the model

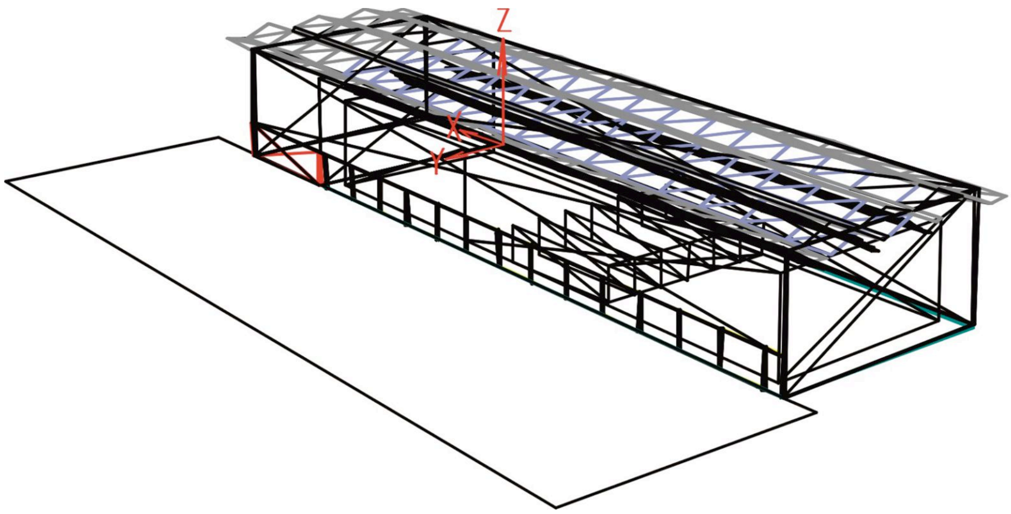


Fig. 6-9a Perspective view of the building

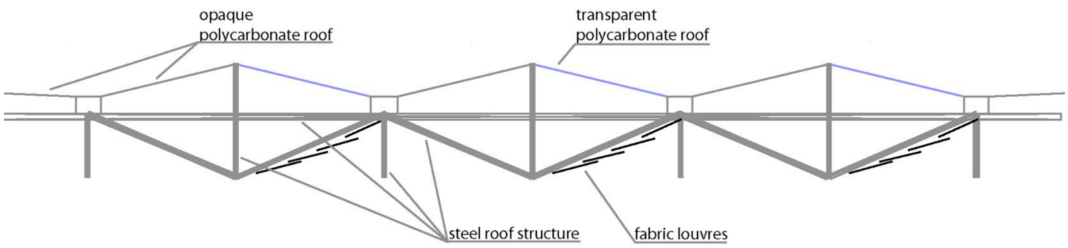


Fig. 6-9b Roof section of the computer model

3. AMENITY BUILDING, INLAND REVENUE CENTRE. NOTTINGHAM.

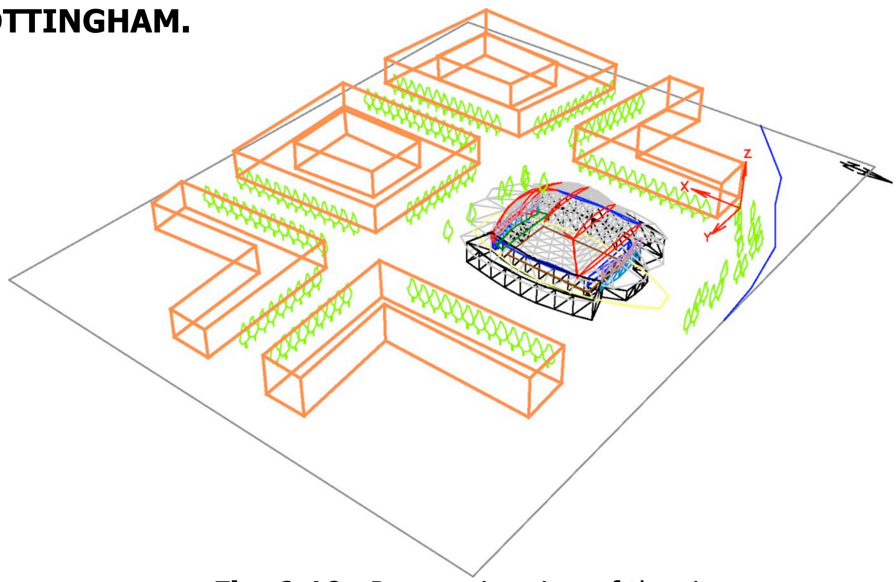


Fig. 6-10a Perspective view of the site

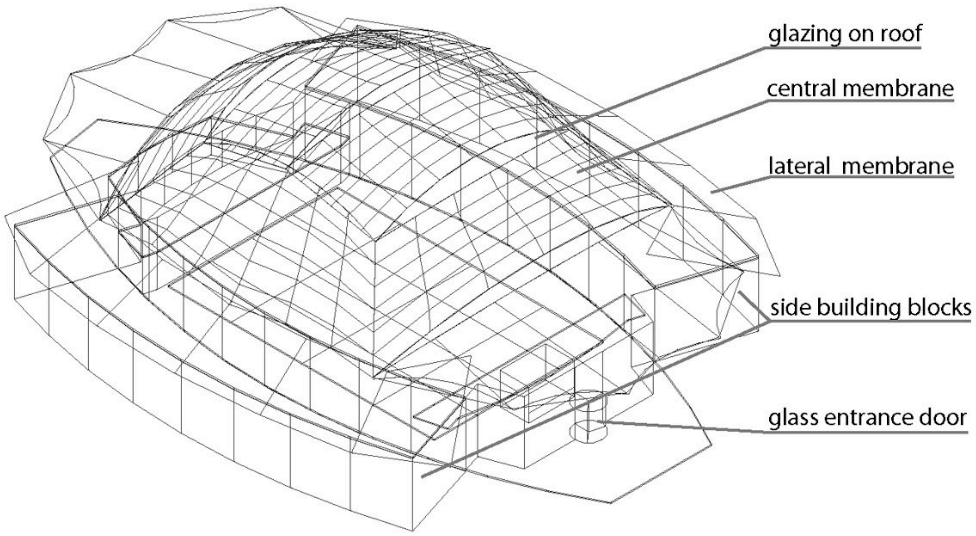


Fig. 6-10b Model perspective of IRAB

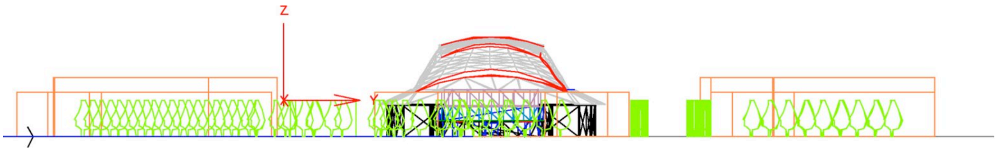


Fig. 6-11 Front elevation

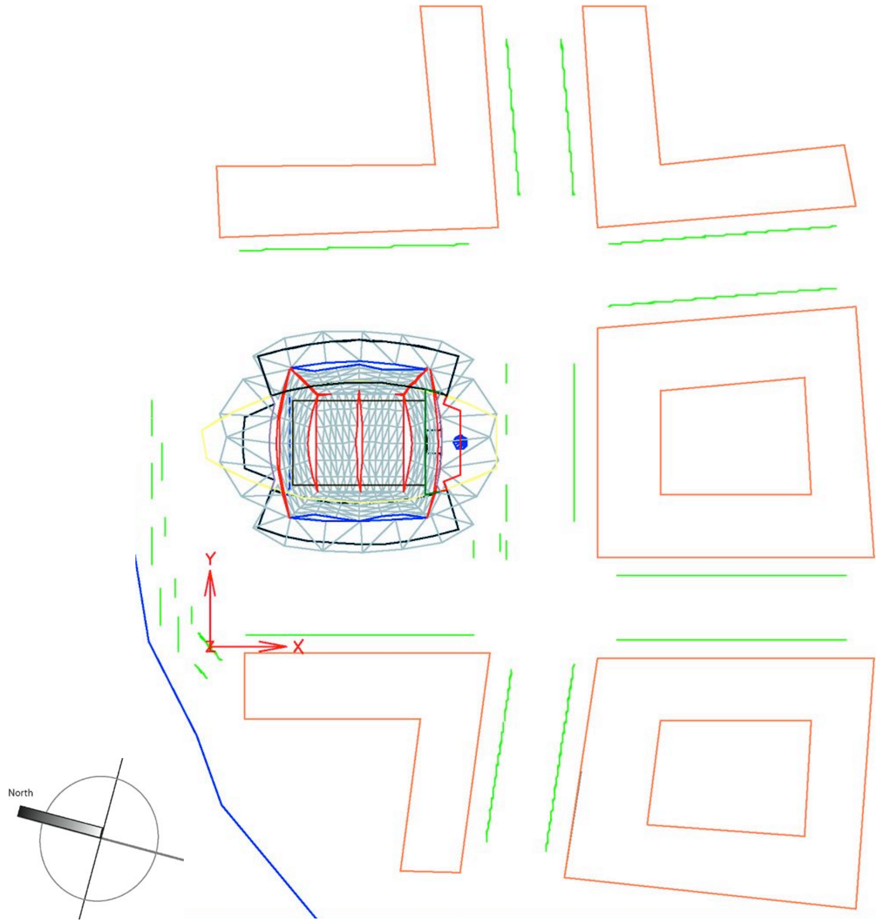
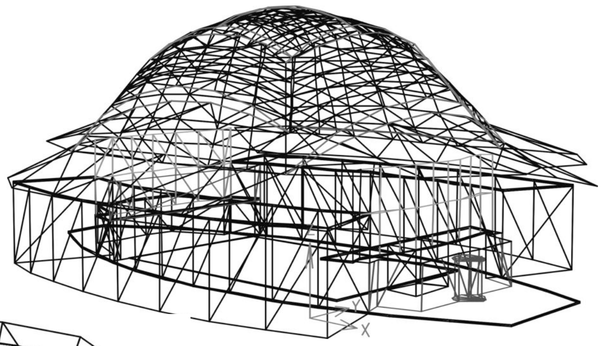


Fig. 6-12 Site plan of the Inland Revenue Centre



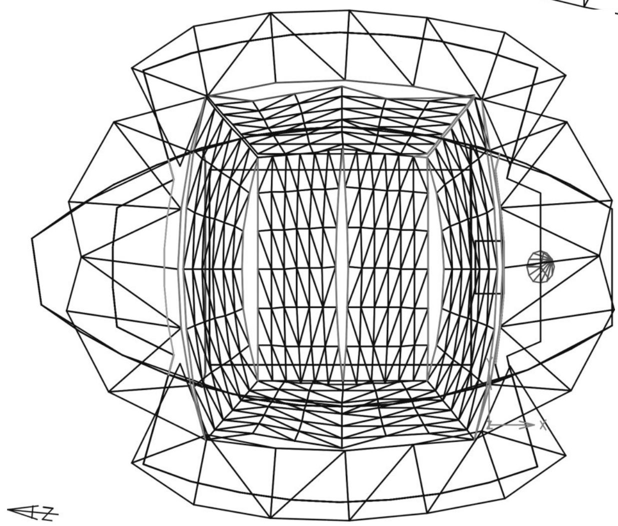


Fig. 6-13 Above: perspective view of the Amenity Building.
Left: plan view.

An analysis grid was placed in all three models, following the analysis grids used in the field and the scale modelling studies (chapters 4 and 5). During the lighting calculation carried out in Ecotect, a file (*.pts) is created. This information is read by Radiance and the output calculations generated by this program are sent to the specified grid points.

The defined calculation grids are horizontal and placed at floor level. In case study 1 (Lord's cricket school) a grid of 36 x 25 meters and a total of 56 nodes were defined (Fig. 6-14).

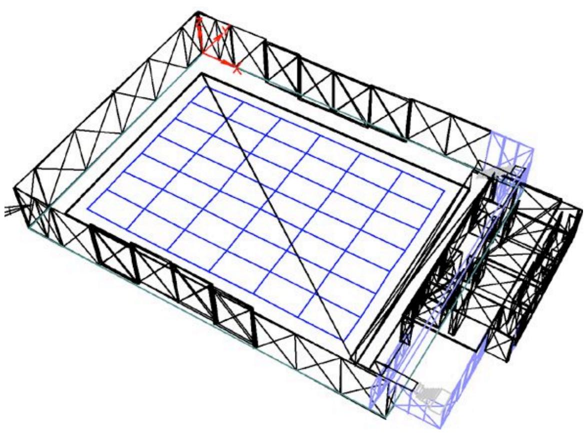


Fig. 6-14 Analysis grid position in the Indoor Cricket School at Lord's (the roof has been removed for clarity of image).

The grid set for case study 2 (Loughborough Cricket Academy) included 42 points with a total dimension of 62 x 18 meters (Fig. 6-15).

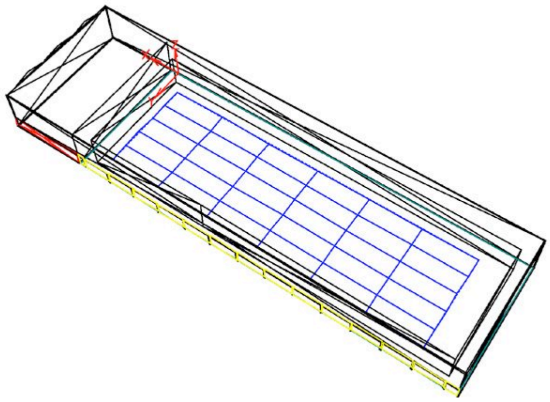


Fig. 6-15 Analysis grid position in the National Cricket Academy (the roof has been removed for clarity of image).

In case study 3 (the Amenity Building) a grid of 29 x 28.5 m containing 25 nodes was specified (Fig. 6-16).

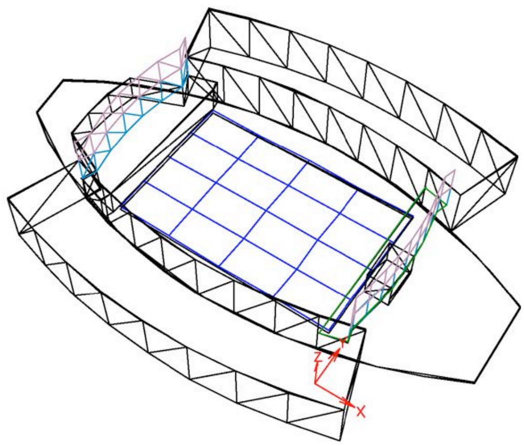


Fig. 6-16 Analysis grid position in the Amenity Building (the roof and upper glazing has been removed for clarity of image)

The location of the building, orientation, date and time of the calculations were specified for each one of the Ecotect models. Weather files for London and Birmingham (closest location to Nottingham and Loughborough) were downloaded from Ecotect. A preliminary lighting analysis was run in Ecotect for each building, setting the simulation under a CIE overcast sky. In both software, Ecotect and Radiance, the models were simulated under overcast sky conditions. This was necessary in order to develop a comparative analysis with field measurements and physical scale models. For that reason, simulations under clear or sunny skies are beyond the scope of this research.

Once these models were finished, they were exported to Radiance as *.rad scene files. A file conversion window is opened (Fig. 6-17). Here Radiance was asked to generate grid point illuminance values under a CIE overcast sky (same as in the field study and the scale modelling analysis under the artificial sky). The program is also asked to check for materials properties defined in Ecotect and for *.rad materials which were created specifically to be used by Radiance. Electric lighting was set to be off.

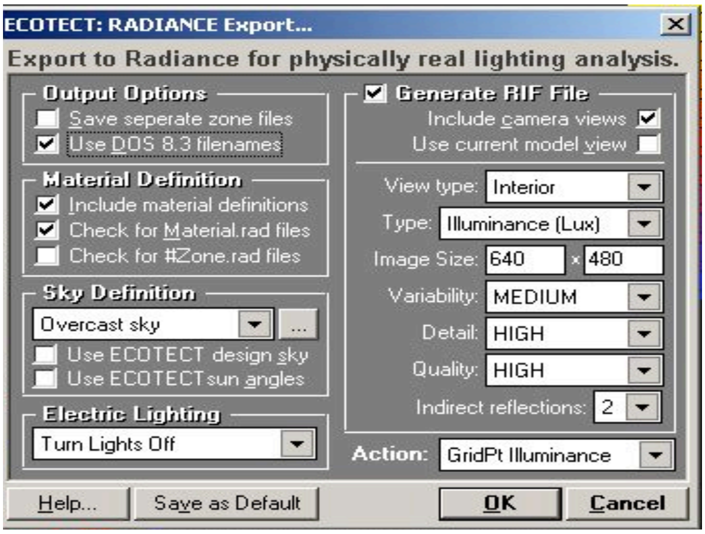


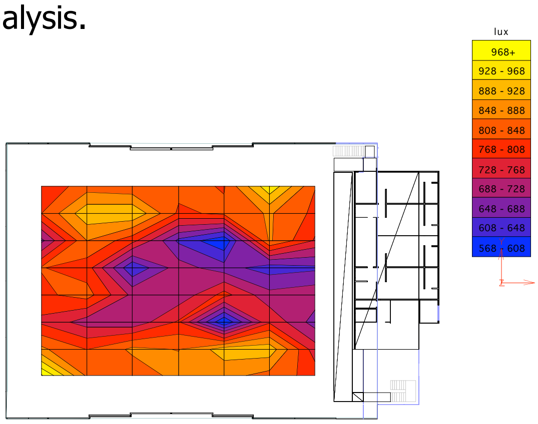
Fig. 6-17 Ecotect window for exporting files to Radiance

Then an MS-Dos window is opened showing the Radiance calculations being made for different camera views. A series of files are created by Ecotect when exporting one scene to Radiance, these are the following:

- Radiance files (*.rad): Contain geometry and photometry information; sky.rad contains a description of the sky conditions. Files such as material.rad are created by hand using a text editor.
- Radiance Instruction file (*.rif): describes how a calculation should be performed. This file is necessary to invoke the Radiance Control Panel to edit settings or renderings.
- Points file (*.pts): contains the position of the grid points defined in Ecotect.

- Octree file (*.oct): a description of the scene with information converted from *.rad files using the *oconv* program in Radiance.
- Ambient file (*.amb): stores data of ambient values within the scene.
- Batch file (*.bat): starts the simulation, can render a series of images. Future simulations with changes to ambient parameters can be done here.

Once the simulation finished, the results were imported back into Ecotect through the Analysis Grid menu of this program. A file *.dat is imported into Ecotect, and the results are displayed onto the analysis grid showing illuminance contour lines, node values and the average illuminance value. In order to obtain clear images, the chosen output display for this study was shaded contour lines (Fig. 6-18). The results can be exported as *.txt file and then imported into an Excel datasheet for extra analysis.



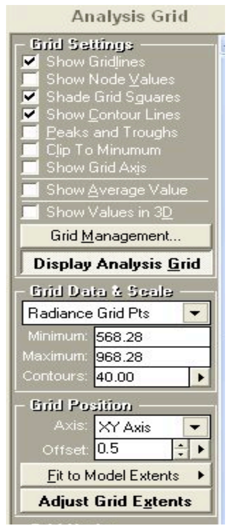


Fig. 6-18 Analysis grid with shaded contour lines and the analysis grid window.

For the purposes of this study it was necessary to obtain daylight factors in each grid point of the models, together with an average daylight factor that could then be compared with the data obtained from the field measurements and the physical modelling study.

Once obtaining illuminance values from Radiance calculations, the unobstructed sky illuminance on a horizontal plane was found in the RadTool program that can be accessed from Ecotect. The file *.rad created before has to be opened, and from the Render menu the Unobstructed Sky Illuminance item is chosen. *rview* is opened with a simple square polygon model. Using the Trace command (T) and clicking on the centre of the polygon, a small window with the unobstructed sky illuminance in lux appears. This value is stored for future reference.

A code provided in the help menu of Ecotect was used to obtain daylight factors in each grid point. This program divides the visible data in the analysis grid by the specified Unobstructed Sky Illuminance (USI) found in RadTool. This code was copied as a *.txt and opened with the control scripting tab of the tools menu in Ecotect. Once the USI is edited and the code is run, daylight factor values appear in the model over each grid point. The code is as follows:

```
-- Set this value to the unobstructed sky illuminance.
SkyIlluminance = 18063.1 (this is the value to be edited)
-- Get data index.
input = get("grid.data")
output = input + 1
if output > 5 then
  output = input - 1;
end
-- Get grid dims.
x,y = get("grid.size")
-- Convert data.
for j = 0, y-1 do
  for i = 0, x-1 do
    value = get("grid.cell", i, j, input)
    value = (value / SkyIlluminance) * 100.0
    set("grid.cell", i, j, value, output)
  end
end
-- Rename and redraw.
set("grid.data", output)
set("grid.description", output, "Radiance DF")
set("grid.units", output, "%")
cmd("grid.fit.values")
cmd("view.redraw")
```

6.3.2 Creation and application of materials

6.3.2.1 Modelling transmitting media: membranes

One of the most important steps of the modelling process was to model the optical characteristics of the three fabric membranes used in the case studies. The accurate modelling of the photometry characteristics of these materials is vital to obtain meaningful simulations with Radiance.

Fabric membranes are translucent materials that can be treated as such by Radiance's material *trans*. According to Ward and Shakespeare[17] "a *trans* material transmits and reflects light with both diffuse and specular components going in each direction. This type is appropriate for thin translucent materials".

In addition, the material colour modifies the transmitted and diffusely reflected light. Therefore, translucent materials are defined by[18]:

```
mod trans id
0
0
red green blue spec rough trans tspec
```

The material is described combining arguments of a *modifier* (mod), *type* (the material type, in this case is *trans*) and *identifier* (is a name given to the material to identify it). The following two zero's denote there are no arguments for the modifier and type, which is the case when creating a material.

The last line contains seven arguments, which are denoted by the number seven located at the beginning of the line. This line includes the red, green and blue (RGB) reflectance values of the material colour, its fraction of specularity (incident light that is immediately reflected) and roughness value (a value of 0 corresponds to a perfectly smooth surface and a value of 1 to a very rough surface). According to the Radiance Manual[18], specularity fractions greater than 0.1 and roughness values greater than 0.2 are not realistic.

Trans is the diffuse transmittance of the material (where 0.0 is opaque and 1.0 is transparent) and *tspec* is the specular transmittance (where 0.0 is a diffuse material and 1.0 is clear).

In order to define the rgb components of the material (known as Cr, Cg and Cb) it is possible to use an image manipulation package such as Adobe Illustrator or Photoshop to select a colour. In most packages the colour range varies between 0 and 255; therefore, it is necessary to scale these values down to a range between 0 and 1 to be able to use them with Radiance. For instance, a white colour will be red=255, green=255 and blue=255; where, Cr=255/255=1, Cg=1 and Cb=1. Radiance takes Cr+Cg+Cb for a white material. An example of the modelling of a fabric cloth can be found on the Radiance web site[19].

The next step was to create a *trans* material following the method described in Rendering with Radiance[20]. The red, green and blue components of the fabric colour were called Cr, Cg and Cb. Rd is the diffuse reflectance of the material, Rs is the reflected specularity, Sr is the surface roughness, Td is the diffuse transmissivity and Ts is the transmitted specularity. The following formulas are used to calculate the seven parameters (A1 to A7) for the *trans* material:

A7= Ts/ (Td+Ts)

A6= (Td+Ts) / (Rd+Td+Ts)

A5= Sr

A4= Rs

A3= Cb/ ((1-Rs)*(1-A6))

A2= Cg/ ((1-Rs)*(1-A6))

A1= Cr/ ((1-Rs)*(1-A6))

The following table shows the reflectance and transmittance properties of the three fabric membranes modelled. The characteristics of the PTFE fabric were obtained from the manufacturer (Skyspan), while the characteristics of the other two membranes were measured following the method described in chapter 4, section 4.2.

Table 6-1 Optical properties of fabric membranes

BUILDING	MATERIAL	TRANSMITTANCE (%)	REFLECTANCE (%)	COLOUR
Case study 1	Sunbrella 8604	6.7	46	Ivory
Case study 2	Holiday 707	14.4	57.4	Ivory
Case study 3	PTFE fibreglass*	16	75	White

* This data was provided by the fabric manufacturers: Skyspan, web site available at http://www.skyspan.com

Since the fabric of case study 1 is the same colour as the fabric of case study two, their Cr, Cg and Cb parameters are the same: Cr=0.894, Cg=0.82, and Cb=0.686. For the white fabric membrane of case study 3, the rgb components are: Cr=1, Cg=1 and Cb=1.

The reflected specularity of the membranes was set to 0 since they are light diffusers and no light is reflected in a mirror-like way as metal surfaces or glass do. The surface roughness was specified as 0.025 since the membranes modelled are not perfectly smooth surfaces, but are not very rough either. The light transmitted is divided into two parameters: the fraction of light that is diffusely transmitted (Td) and the fraction of light that is transmitted as a beam not diffusely scattered (Ts)[20]. In order to model the membranes material only ten percent of the transmitted light was considered to be specular because of the characteristics of the material, which is mainly a diffuser fabric following recommendations available on the Radiance web site[19].

The following texts describe the translucent membranes used in the models of the case study buildings together with the original values input to create these materials. They were saved as *.rad files and applied to the geometry through fake materials (with the same name as the *.rad file) previously assigned to fabric membrane layers in Ecotect.

- CASE STUDY 1:

```
void trans Sunbrella
0
0
7 1.024 0.939 0.786 0 0.025 0.127 0.149
```

Sunbrella:
Rs=0.0 Td=0.057
Rd=0.46 Ts=0.015
Sr=0.025

- CASE STUDY 2:

```
void trans holiday
0
0
7 1.113 1.02 0.854 0 0.025 0.197 0.071
```

Holiday:
Rs=0.0 Td=0.13
Rd=0.57 Ts=0.013
Sr=0.025

- CASE STUDY 3:

```
void trans PTFEfabric
0
0
7 1.21 1.21 1.21 0 0.025 0.176 0.0625
```

PTFE:
Rs=0.0 Td=0.15
Rd=0.75 Ts=0.015
Sr=0.025

Changes to materials photometric properties modifying the *.rad file results in a new octree created by Radiance after re-running the simulation. Many combinations of materials can be rapidly achieved through modifying the *.rad file, or creating several different *.rad files and substituting their names in the layer with the assigned material in Ecotect. The effects of varying the transmittance and reflectance properties of fabric membranes in the studied buildings are described later in this chapter.

6.3.2.2 Modelling other materials

Separate layers for different surfaces materials were assigned in AutoCad and Ecotect. The characteristics of these materials were given in Ecotect, following data from glazing manufacturers (chapter 5) as well as from measurements taken on site and described in chapter 4. The following table shows materials properties assigned for the computer simulation.

Table 6-2 Photometric properties of materials assigned in models.

Building	Surface	Colour/material	Reflectance factor (%)	Transmittance factor (%)
Case study 1: INDOOR CRICKET SCHOOL	Side walls	White aluminium	52	-
	Green Floor	Dark green synthetic grass	8.48	-
	Opaque roof	Polycarbonate sheet	52	-
	Transparent roof	clear Lexan Exell D double sheet polycarbonate*	-	80 & 0.8 dirt correction factor
	Floor in corridors	Dark green carpet	7	-
	Offices walls	Concrete Block plaster	Exterior: 68	-
	Nets	White net like panel	50	95
Case study 2: NAT. CRICKET ACADEMY	Side walls	White aluminium	53	-
	Walls behind wicket and bowler	White cotton fabric	54	-
	Green Floor	Dark green synthetic grass	6	-

Building	Surface	Colour/material	Reflectance factor (%)	Transmittance factor (%)
Case study 2	Opaque roof	Polycarbonate sheet	53	-
	Transparent roof	MakroClear polycarbonate sheet	-	80 & 0.8dirt correction factor
	Side windows	10mm toughened Pilkington glass+	-	87 & 0.9 dirt correction factor
	Floor offices	Conc. Slab carpeted	75	-
	Nets	White net like panel	95	95
	Panel to divide lanes (15m long)	White cloth panel	53	-
	Outside pitch	Exposed ground grass	18	-
Case study 3: AMENITY BUILDING	Playing area floor	Brown timber floor	42.47	-
	Floor in corridors	Concrete slab white tiles	47.29	-
	Lateral buildings	Dark grey	8.0	-
	Roof of lateral blocks	Metal deck roof	47	-
	Reception roof	Suspended concrete ceiling	50	-
	Glass type 1	Single 12mm toughened clear glass✜	-	86 & 0.9 dirt correction factor
	Glass type 2	Double clear glass low E^	-	73 & 0.9 dirt correction factor
	Glass type 3	Single clear float toughened glass✜	-	87 & 0.9 dirt correction factor

* From GE structured products web site: www.GEStructuredProducts.com Product data sheet (polycarbonate sheetel124.pdf file).
 From Arla technical manual, provided by Vulcan Roof Glazing Systems, Hosey Hill, Westerham, Kent, TN16 1TZ.
+ From www.Pilkington.com/europe. Tel. 01744692000.
^ From APS web site available at: http://www.aps.com/aps_services/business/waystosave/BusWaystoSave_29.html
✜ Light transmittance factors were calculated using the Spectrum program created by Pilkington, can be downloaded for free at www.Pilkington.com (information for Architects).

6.3.3 Setting Radiance ambient parameters

Once the scene description is created, it is important to correctly configure the simulation parameters in order to obtain meaningful quantitative data from Radiance. The models of all case studies were simulated under an overcast sky, this to later obtain daylight factor values that will be compared with the data measured in the real buildings.

It is possible to try an infinite number of choices for ambient parameters; however, extensive research has been done regarding this topic showing practical default parameters that provide a good compromise between accuracy and reasonable calculation times.

According to Mardaljevic[21] once the sky and camera view are defined, the most important parameter is the number of ambient bounces (-ab). This value sets the number of ray inter-reflections between surfaces that the program calculates. He suggests setting the value to two ambient bounces, which are enough to calculate indirect illumination for surfaces that are not directly in the light path of the sky or sun patch. Therefore, this parameter is set at two in all models.

Illuminance images were requested to Radiance. These images do not appear very realistic since they show the amount of light falling on each surface, opposite to luminance images which show the light reflected off each surface into the scene and into the eye (this is what we normally see in reality or in photographs). Illuminance images provide quantitative results in Lux, which are useful to calculate daylight factors and to refer to lighting design guidelines where minimum illuminance values are specified for particular tasks.

Variability was set to medium for all the case studies (the National Cricket Academy, the Indoor Cricket School and the Amenity Building). This selection tells Radiance how much lighting variation is present in the scene. Setting variability to high could increase calculation times considerably. Moreover, since the models were tested under daylight but with an overcast sky, not a lot of lighting variation is present.

The geometry detail at which Radiance bases its calculation can be selected between low, medium or high. According to the help pages of Ecotect v.5.2, Radiance calculates its surface sampling distance based on the difference between the largest and smallest objects in the scene. This difference is not very significant in either model due to the modelling of only big surfaces (floors, walls, roofs) and any small objects. Models of case study 1 and case study 2 were calculated with medium detail; and case study 3 with high detail since the membrane roof structure dimension is larger than the playing area. This last model includes fewer surfaces than models of case 1 and 2, and this setting did not significantly increase the calculation time.

The quality of the final render can also be selected between low, medium and high. It is defined by the amount of anti-aliasing in the final render. Anti-aliasing is a technique that reduces jagged edges in the image, caused by the regular pixel grid in the image (aliasing)[22]. The method used by Radiance is *supersampling*, which consists in "sending multiple samples to arrive at an average value for a particular area, such as a pixel" [23]. To do this Radiance generates a larger image with *rpict* and then filters it back down to the required size with *pfilt*. Choosing low quality, no anti-aliasing is performed; medium creates an image double the target size in each direction (four times larger); and high means the image is three times in each direction (nine times larger). Medium was chosen to render the camera views of the three models, since apparently *pfilt* is less stable when filtering images down three times[24].

6.4 RESULTS

Simulating the lighting performance of existing buildings offers the possibility of validating Radiance results, while pointing out possible sources of error that can produce inaccurate data. This section presents results from the lighting simulations of the three case studies analysed in this thesis.

6.4.1 Case study 1: MCC Indoor Cricket School at Lord's Ground, London.

After modelling as close as possible to reality the Indoor Cricket School, the average daylight factor obtained is 4.71%, which is very similar to the measured daylight factor (DF) of 4.4%. The average illuminance obtained with Radiance is 783.31 lux measured over a 56 nodes grid.

Figure 6-19 Illustrates the daylight factor distribution over the playing area. An increment on the light availability is found at both sides of the building, which can be caused by the light coming through the transparent sections of the roof. This light is internally inter-reflected by the sidewalls and the opaque sections of the roof located at the extremes of the school (northwest and southeast facades).

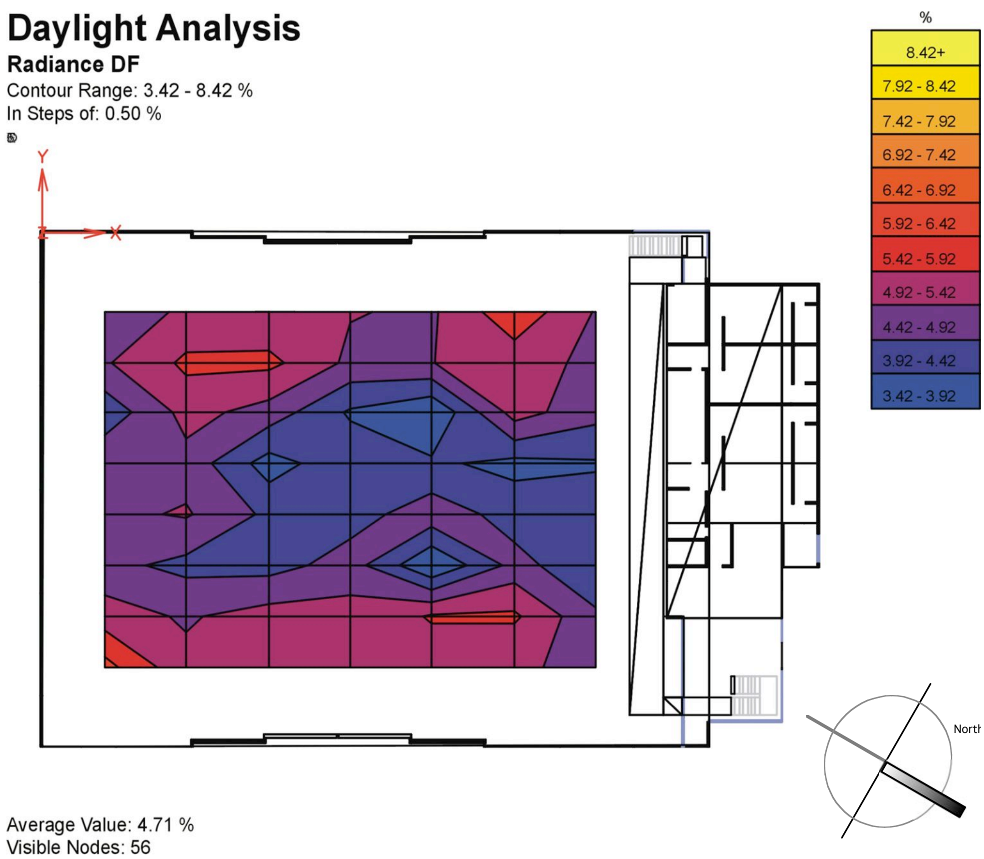


Fig. 6-19 Daylight factor variation over playing area

The illuminance uniformity is 0.73, which is close to the 0.9 required for indoor cricket. On the other hand, illuminance uniformity in the real building is 0.37, which indicates that in reality there is a greater variation of illuminance levels in the building than the value obtained with the computer model. One source of error could be the presence of players in the real building. Even though the site measurements were taken in areas where no one was training at the time, it could have happened that someone walked close to the sensors affecting the readings.

However, the sky distribution could also have influenced the results. Radiance was set to calculate illuminance levels under a standard CIE overcast sky, which is a grey sky with no sun and fully characterised by the horizontal illuminance. Although physical measurements were also taken under an overcast sky, in reality the sky's brightness can change very quickly. Values of exterior horizontal illuminance varied during the measuring period between 14,000 and 30,000 lux. In Radiance the unobstructed sky illuminance value was 16,600 lux and did not vary during the calculation, producing then, higher illuminance uniformity over the playing area than the field measured data.

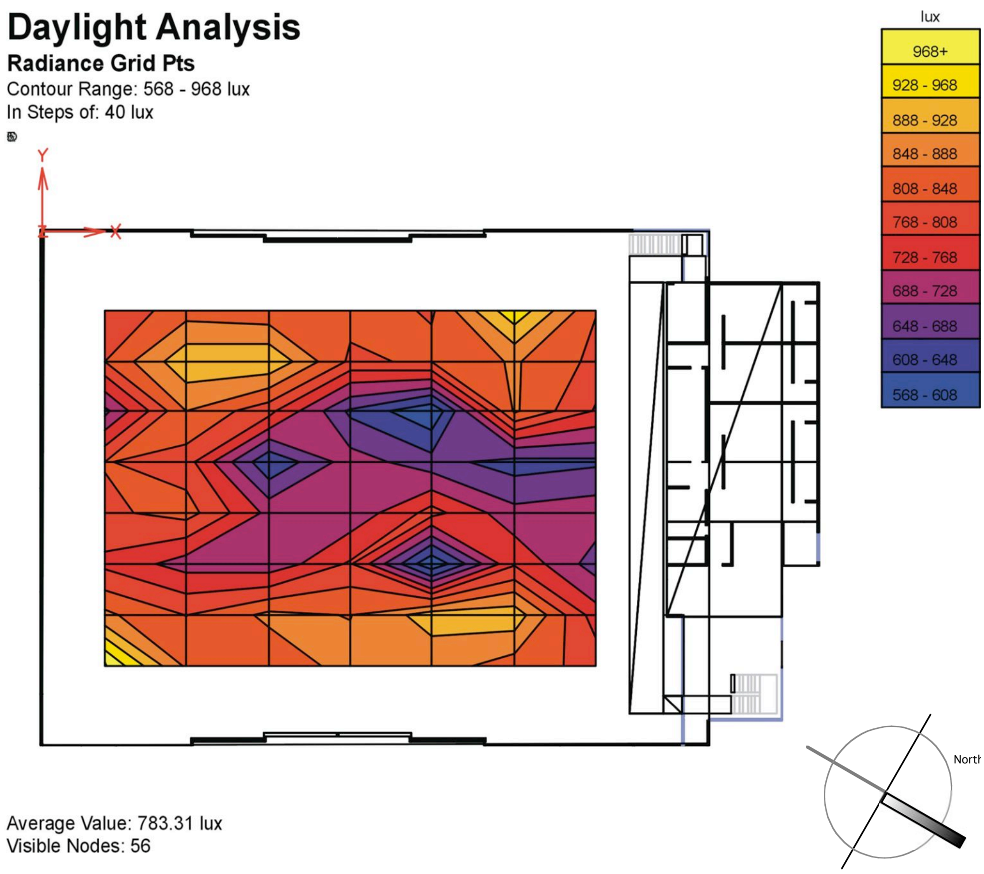


Fig. 6-20 Illuminance distribution over playing area

The following plan shows the location of two sections cut through the playing area. Both sections illustrate daylight factors variation throughout a longitudinal section that follows the length of one playing lane, and a cross section showing the DF variation according to the roof design.

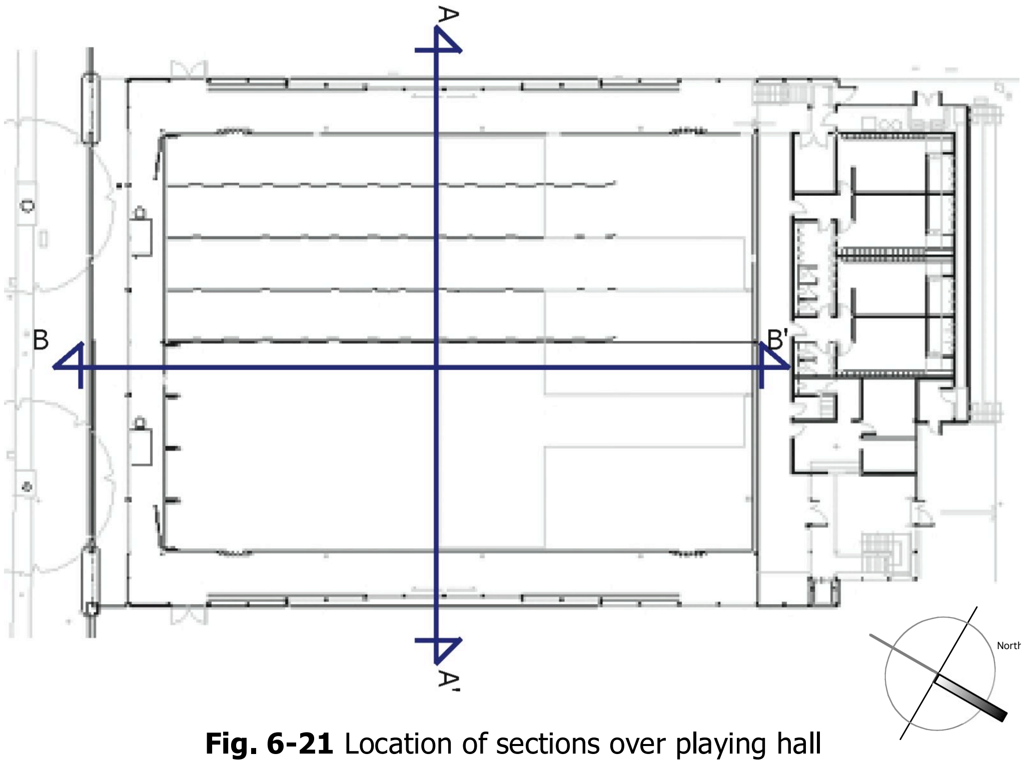


Fig. 6-21 Location of sections over playing hall

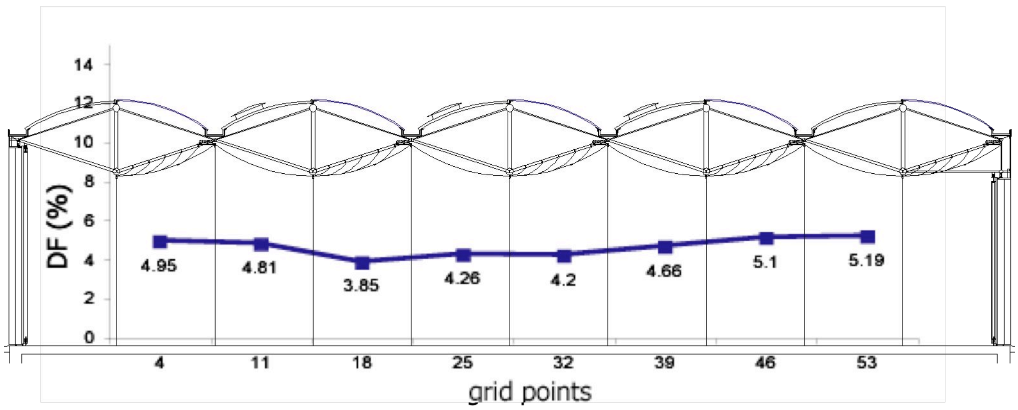


Fig. 6-22 DF variation through section A-A'

Section A-A' shows little variation of daylight factors with a difference between the minimum and the maximum DF of 1.34%. Definitely, there is more daylight availability in the area near the wall facing the car park (grid point 53). This is due to the small opening located in the upper section of the wall, and the dimensions of the entrance hall with its glass door and windows.

Section B-B' (Figure 6-23) illustrates the variation of Dfs through one playing lane. In this case a cricketer (the batsman) would be standing on point 29, and the bowler would be running from point 35 to point 33 approximately. It is in this direction where illuminance uniformity and level are most important for the performance of the players. They need constant high levels of light in order to see the ball clearly avoiding their eyes to frequently adapt to light changes. Between grid points 29 and 35 there is a difference in daylight factors of 0.77%; and the illuminance uniformity within these points is 0.93, which indicates a low variation of illuminance levels. The measurements taken in the real building on the same grid points show a greater daylight variation, with a difference between the maximum DF and the minimum DF of 2.5%; and an illuminance uniformity of 0.75.

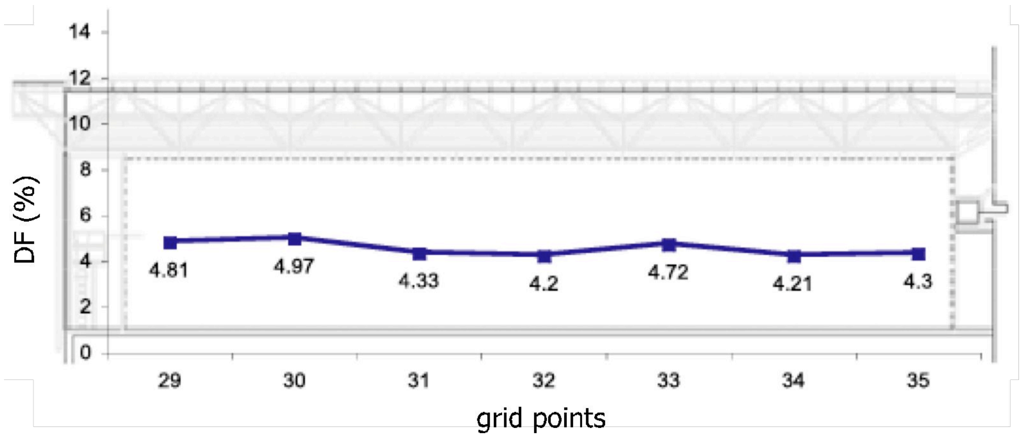


Fig. 6-23 DF variation through section B-B' (lane 4)

Apparently, Radiance can simulate very well the amount of daylight that penetrates in the building, but in terms of the actual lighting behaviour of the building it is difficult to represent real sky conditions even for an overcast day. However, computer simulations seem appropriate to estimate the daylighting performance of buildings with fabric membranes in order to predict the light levels in the building and possible energy savings due to the reduction of electric lighting use. For instance, to illuminate the cricket school at Lord's Ground only with daylight considering a 4.71% daylight factor, and a minimum interior horizontal illuminance of 1,000 lux; it will be necessary to have at least 21,200 lux as exterior illuminance. In London this occurs 53.9% of year (between 9am and 5.30pm)[25]. The rest of the year the playing area can be lit with a combination of artificial and natural light.

Fig. 6-24 Luminance image of a preliminary model showing only half the building

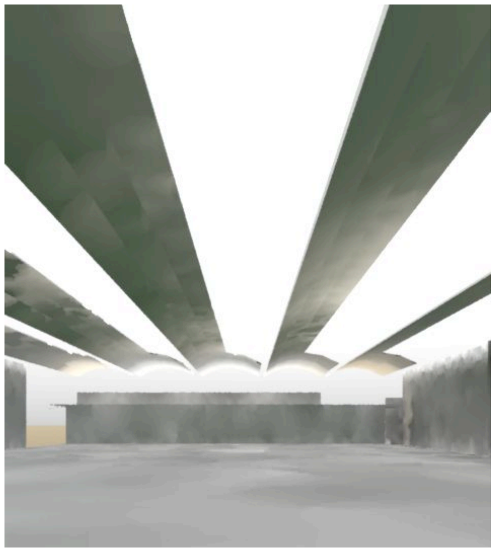


Fig. 6-25 Illuminance image of interior of the cricket school

6.4.2 Case study 2: ECB National Cricket Academy, Loughborough.

The computer model of the National Cricket Academy had an extra geometric feature, which could cause confusion at the time of the simulation. This is the side window that is located in the northeast façade of the building connecting the interior of the Academy with the exterior cricket pitch. Apparently such long window would be an important light source but the simulations proved differently.

The average daylight factor resulted is 3.6%, which is lower than the DF measured in the real building of 5.9%. The illuminance uniformity is 0.33 with a minimum illuminance value of 136.96 lux and an average illuminance of 408.99 lux. This value is lower than the uniformity obtained in the field measurements of 0.55. This indicates that Radiance is increasing the variation of light throughout the space.

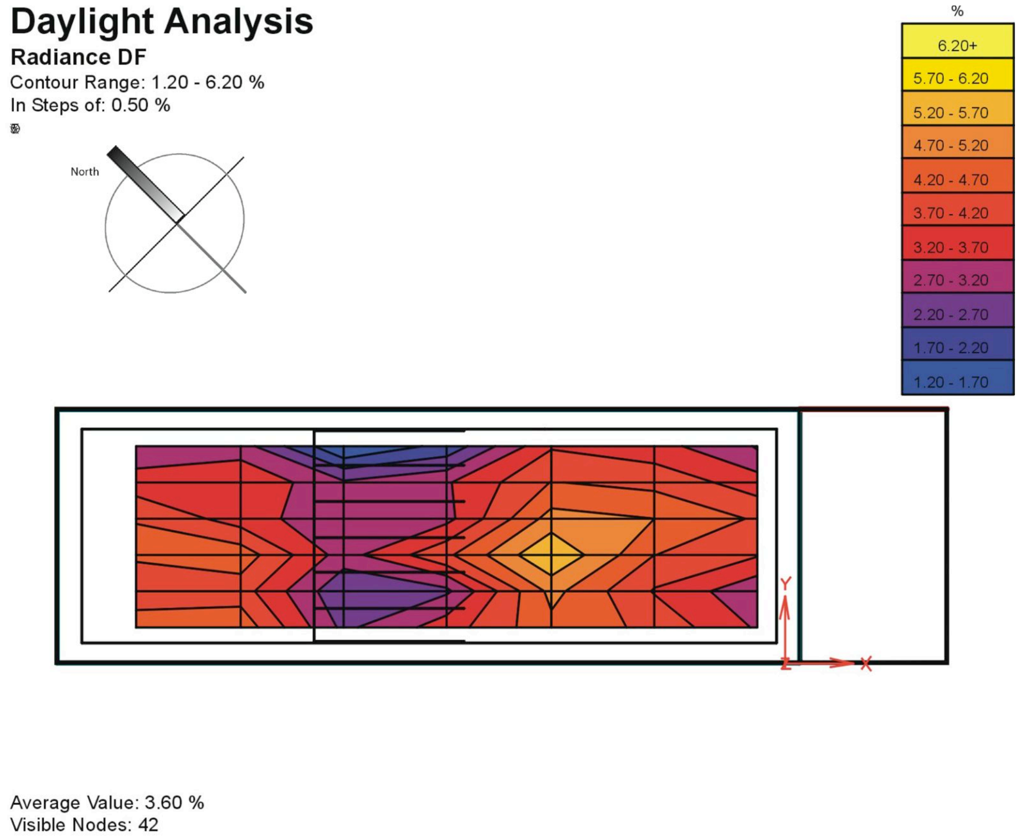


Fig. 6-26 DF variation through playing area

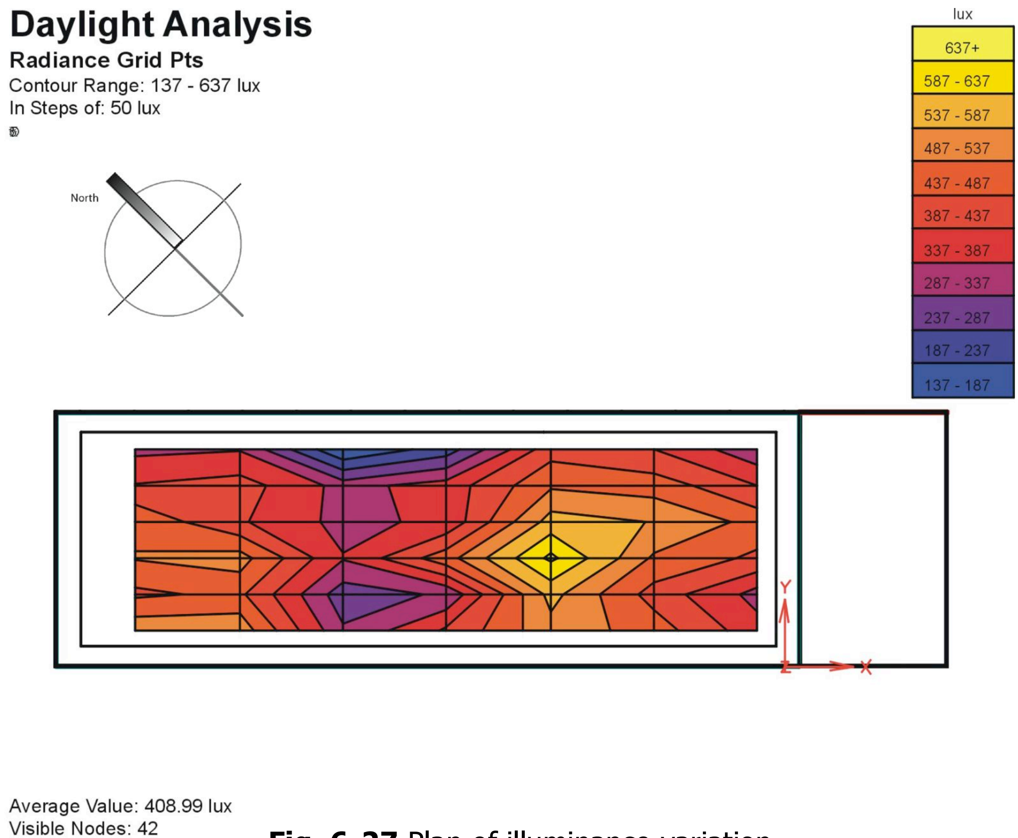


Fig. 6-27 Plan of illuminance variation

According to Figures 6-26 and 6-27, the area with lower daylight availability is located exactly where the batsman stands. In each lane, an opaque fabric (2.40m high x 15m long) encloses the area where the batsman stands dividing all six playing lanes and avoiding distractions because there is no visual contact between players practicing in different lanes. Therefore, it seems logical to have the lower Dfs in these areas of the playing lanes.

As it was mentioned before, the contribution of the side window to the overall lighting performance of the building was not very important, as it would be expected. In order to assess the window impact on daylight factor results, the attached material to the layer of the side window was changed for the same material used on the walls. The resulted daylight factor was 3.25%, which represents 9.72% of the total daylight factor (3.6%). Daylight coming through this window is mainly reflected from the exterior cricket pitch (grass ground), which is a low reflectance surface. In addition, even under a clear sky the contribution of this window to the interior lighting environment would not be very important due to its orientation (northeast), which means there would never be direct sunshine coming through this window.

Figure 6-28 illustrates the location on plan of three sections cut through the building.

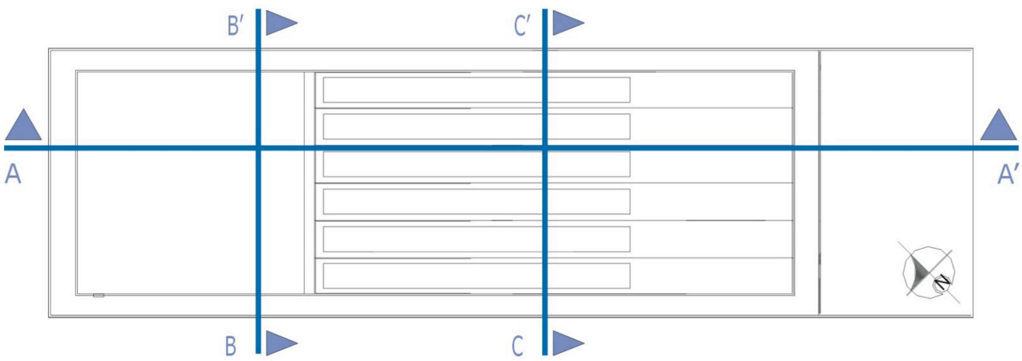


Fig. 6-28 Location of sections on plan

Section A-A′ (Figure 6-29) shows the behaviour of daylight passing across the centre of one playing lane. The lowest DF values are located over points 15 (2.82%) and 21 (3.08%); and the difference between the maximum DF and the minimum DF is 2.09%. Again, these low values are caused by the vertical fabric that divides the lanes exactly at the batsman position. This figure is very similar to Figure 4-6 (chapter four) that shows daylight factors obtained in field measurements.

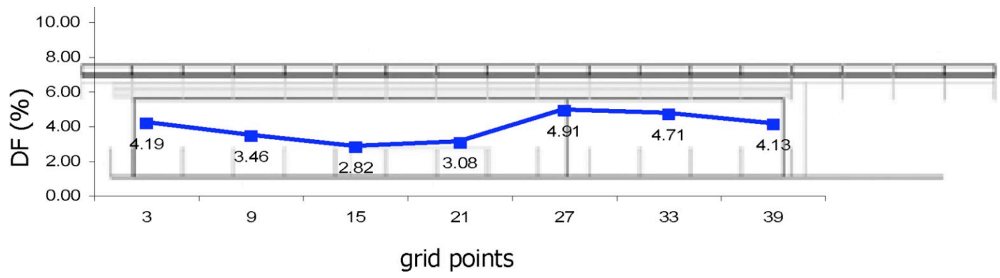


Fig. 6-29 DF variation through section A-A'.

The variation of daylight factors in section B-B' (Figure 6-30) seems to correspond to the roof geometry, where DFs decrease under the transparent section of the roof where the fabric louvres are located. In this area, the rear of the building, is where players warm up before practicing. There are no divisions between lanes, so the light coming through the skylights is diffused by the fabric louvres and part of it is absorbed by the floor surface. Therefore, there are minimal inter-reflections of light and the values obtained are produced mainly by light coming from outside. Despite of having an opaque section in the roof, light could penetrate through a small section of the transparent roof that the fabric louvres do not cover (in between the red arrows), allowing daylight to pass directly to the interior increasing daylight factors in points located under opaque roof.

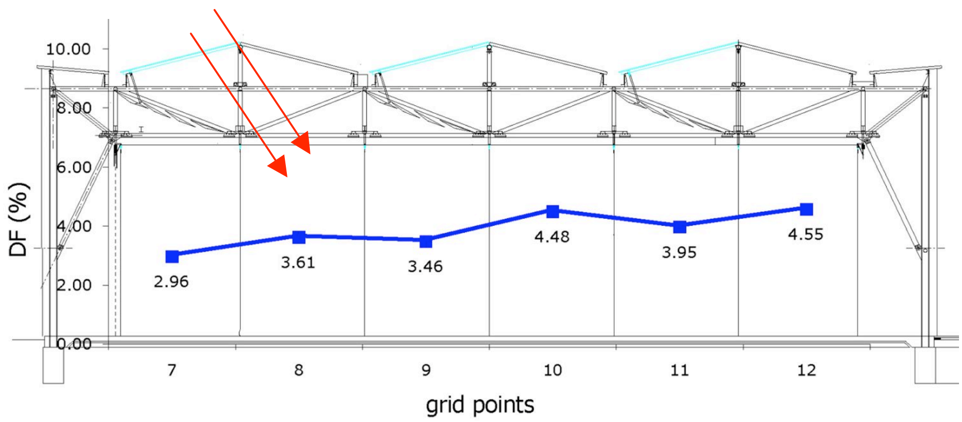


Fig. 6-30 DF (%) variation through section B-B'

Section C-C′ does not follow the same pattern as Figure 6-30. In this section the greatest DF is found at one of the central lanes over point 28; and the lowest is located next to the side window (point 25). In the real building the results show a higher DF in points located close to the window (points 25, 31 and 37), than in the rest of the sections' grid points presented in Figures 4-11 and 4-12 of chapter four.

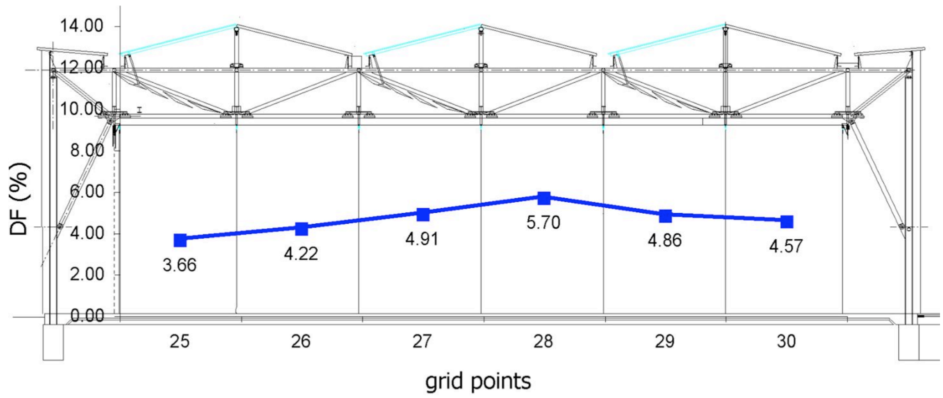
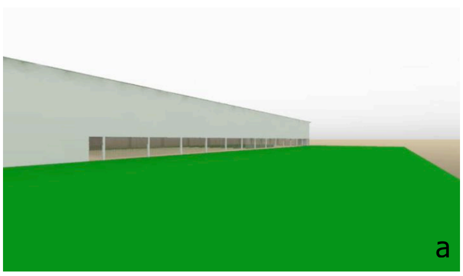


Fig. 6-31 DF (%) variation through section C-C′

According to results presented in this section, Radiance is underestimating illuminance values inside the playing hall. After revising the photometric properties of each material in the model, there is probably a parameter that is affecting the results. This is the ambient bounces parameter (-ab) explained in section 6.3.3. This value was set at two for all the simulations, but considering that in this building there are several surfaces dividing playing lanes (net like fabric plus the opaque fabric between grid points 13 and 24) the –ab value would probably had to be higher. Four or five ambient bounces would have better simulated light inter-reflections providing more realistic quantitative data. This is explored in the following section.



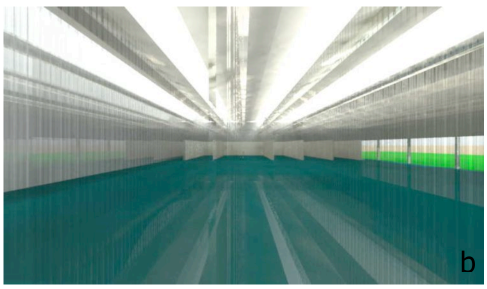


Fig. 6-32a Radiance luminance image of the exterior of the Cricket Academy
Fig. 6-32b Radiance luminance image of the interior of the Academy

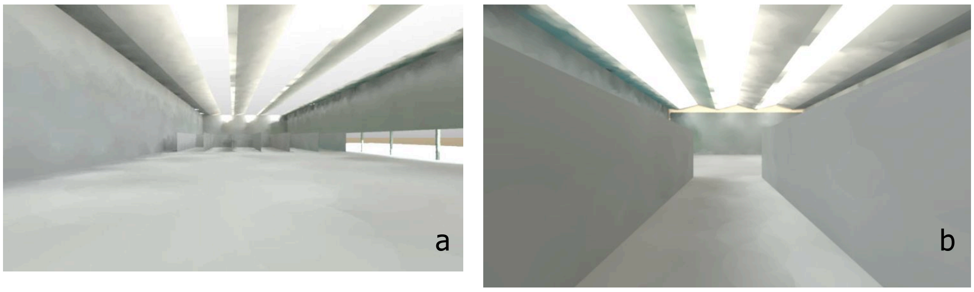


Fig. 6-33a Radiance illuminance image of the playing hall
Fig. 6-33b Radiance illuminance image of one playing lane

6.4.2.1 Effect of changing ambient bounces

The value given for ambient bounces is the number of diffuse inter-reflections between surfaces that are calculated by Radiance. For instance, if –ab is set to 0 the inter-reflection calculation is off; and if -ab is three, sampling of a light ray could occur at three different surfaces after leaving the source (the sun, the sky or an artificial light). The program will tend to underestimate illuminance levels if the ambient bounces are low, since it will finish the calculation before all the light flux is considered. Since the results obtained with Radiance in case study 2 are lower than data obtained in the real building, it is possible that the –ab set at two was too low for the number of interior surfaces existing in the building and the possible contribution that inter-reflections could have on illuminance values and daylight factors.

Therefore, a parametric study was made changing the number of ambient bounces in the National Cricket Academy model. The results can be seen in Figure 6-34. It is clear that incrementing the number of –ab from two to three provided a higher average daylight factor which seems to be more realistic; and incrementing –ab to four again increased the DF to 4.37%. Then with five and six –ab there was a slight decrement and not much variation between these results.

The effects on calculation time are negligible. Simulations with two, three and four ambient bounces took ten minutes; whilst simulations with five and six ambient bounces were finished in eleven minutes.

Changing the –ab parameter produced a different behaviour of daylight; these effects are shown across sections A-A' (long section) and C-C' (located in the middle of the hall).

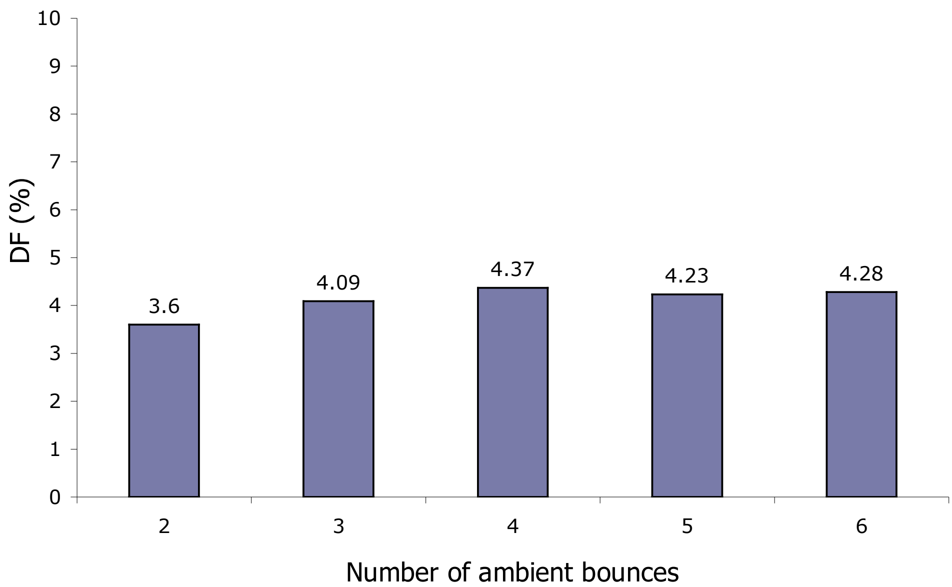


Fig. 6-34 Effects of increasing the –ab parameter on the average DF

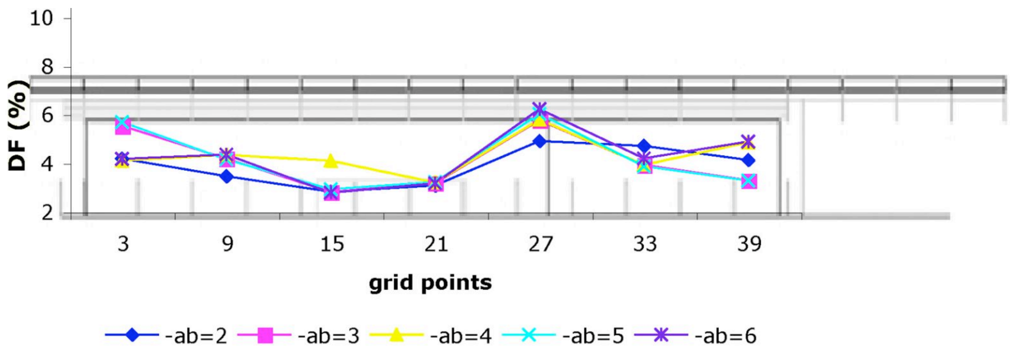


Fig. 6-35 The effect of changing the –ab parameter across section A-A'

The variation of daylight factors shown above follows a similar behaviour except for –ab 4 that increased to 4.10% over point 15 while the other –ab results dropped to 2.82, 2.82, 2.93 and 2.78% for –ab2, -ab3, -ab5 and –ab6 respectively. From the results, it seems that the calculation has converged at three and five ambient bounces.

In Figure 6-36 it appears that results from –ab four and –ab five are very similar; –ab six also presents almost equal results except for point 29. This behaviour did not exactly correspond to the expected increment of

DFs caused by increasing the number of ambient bounces and inter-reflections of light. In general, it seems that the calculation has converged into a more logical performance with five ambient bounces, resulting in an average daylight factor of 4.23%.

Moreover, there is a tendency of obtaining higher levels of light in the area surrounding point 27, this is probably a result of the daylight coming through the side window, which in this area has a more unrestricted penetration since there are no fabric partitions dividing the lanes. It seems that increasing the number of light inter-reflections produces higher levels of light in the central area over points 27, 28 and 29. However, results from the field measurement study show this increment of light in the central area of the playing hall but in the opposite side of the window, between points 29 and 35 (Figure 4-5, chapter four). Though there was also a visible increment over points 27, 28, 33 and 34.

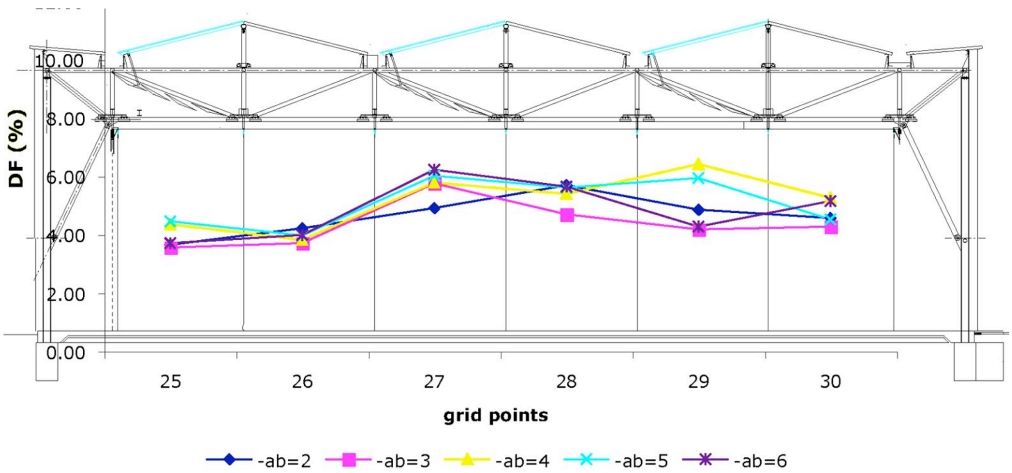


Fig. 6-36 The effect of changing the –ab parameter across section C-C'

6.4.3 Case study 3: Inland Revenue Amenity Building, Nottingham.

The Radiance model of the Amenity Building was simulated under an overcast sky. The average interior horizontal illuminance obtained is 2,155.88 lux, and the average daylight factor is 18.53%. This DF value is lower than the average daylight factor of 24% measured on site. The exterior unobstructed illuminance used by Radiance was 11,632.5 lux.

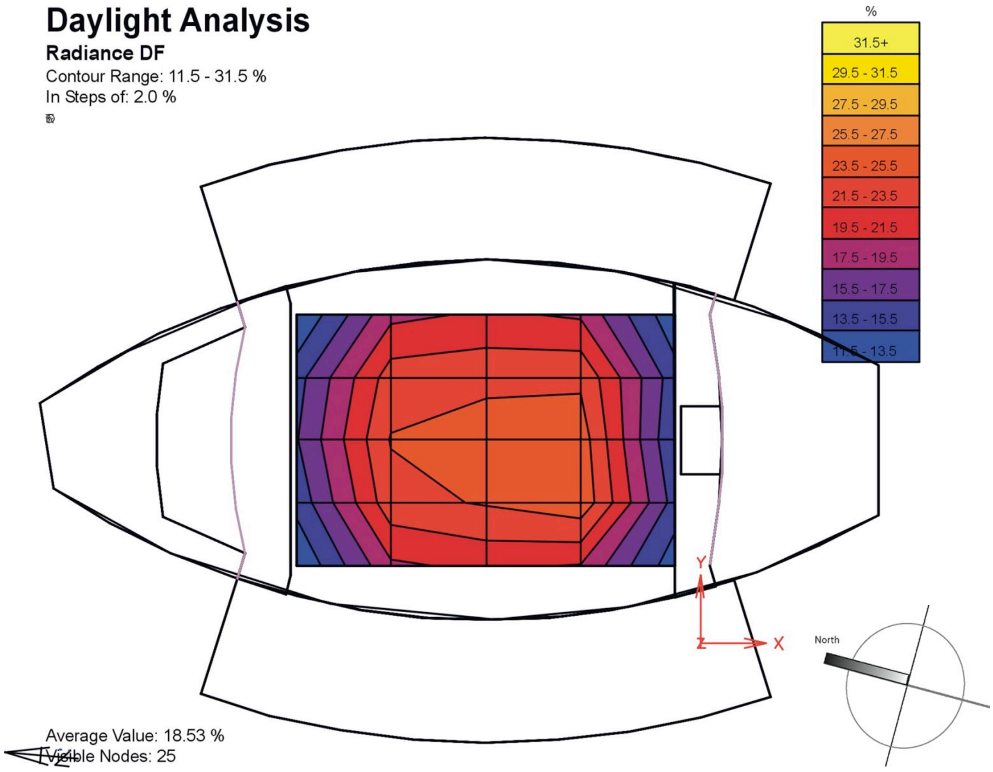


Fig. 6-37 Daylight factor distribution over plan of the Amenity building

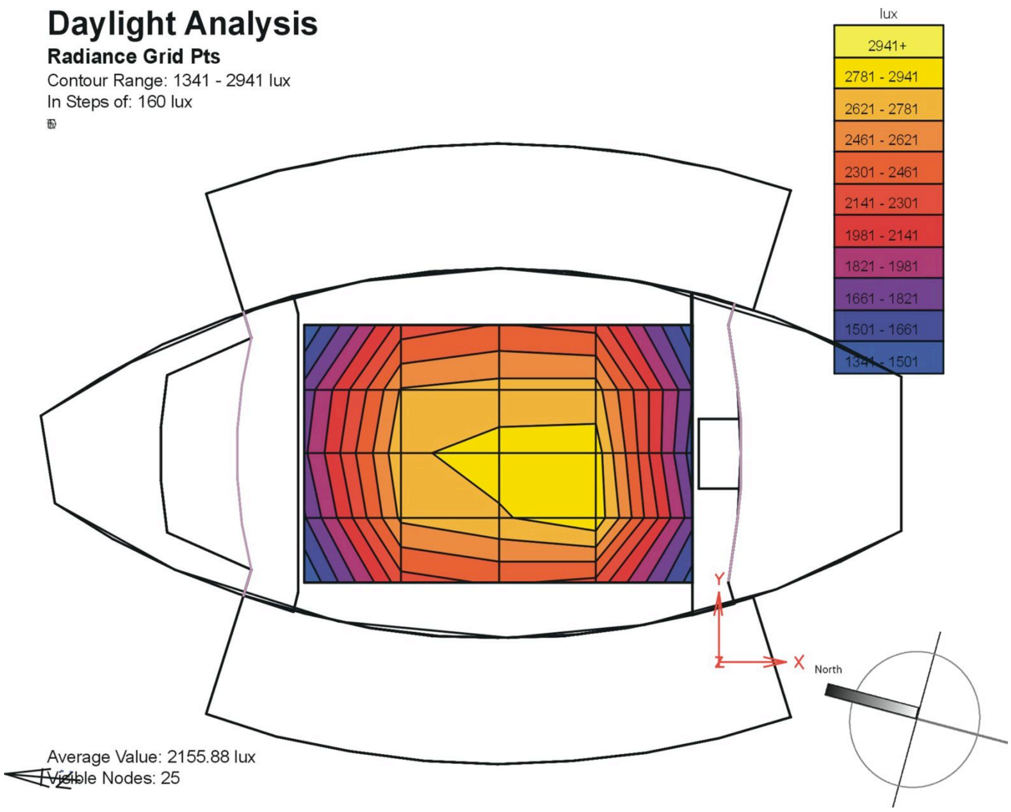


Fig. 6-38 Illuminance distribution over playing hall

The illuminance ratio obtained with the Radiance simulation is 0.62, which is lower than the minimum illuminance ratio of 0.8 required to play the sports performed in this building[26]. However, in the field study carried out in this building and reported in chapter four section 4.3.2.3, it was found that the membrane roof is an environmentally sensitive structure that responds very quickly to the exterior weather conditions. In a first stage of that analysis developed during wintertime the measured illuminance uniformity ratio was 0.89, while the study developed at the end of the summer showed a 0.29 illuminance ratio.

Even though both studies were carried out under overcast skies, the February sky had less lighting variations and brightness than the September sky; producing higher illuminance uniformity during wintertime. In addition, the geometry of the building combining a membrane roof with glass provides the availability of interior diffuse and direct daylight, and this fact causes a variation of light levels where direct daylight reaches the playing area.

Figures 6-37 and 6-38 illustrate the distribution of daylight factors and illuminance in the sports hall. These figures are almost symmetrical following the geometry of the Amenity building and its adjacent buildings and trees. Clearly the area with higher lighting levels is the centre of the hall, which is the most exposed area to daylight. This is the more distant point from the side blocks and from the highest point of the roof. The area is then extended towards the reception of the building. This is the expected behaviour since glass walls and a glass door together with the openable window located above the reception area limit the entrance of the building.

Figure 6-39 shows the location of two sections (A-A’ and B-B’) in the building that later will be used to illustrate the variation of daylight factors through the central grid points.

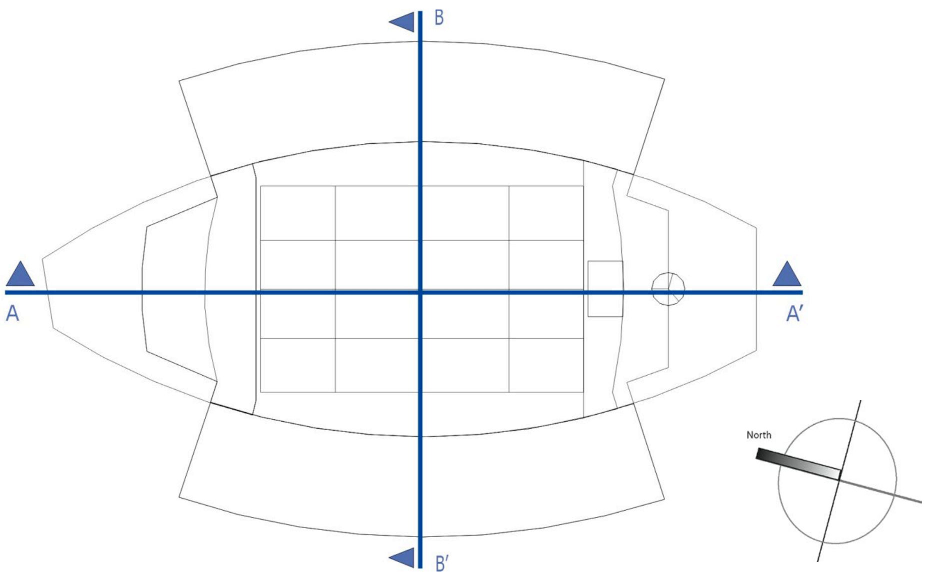


Fig. 6-39 Location of sections on plan

The following figure demonstrates the behaviour of daylight across the long section of the building (A-A′), where the highest DF values are located over the central point (point 5) and the subsequent point in the direction of the building reception (point 2). DF decreases to 13.42% in the nearest point to the reception wall.

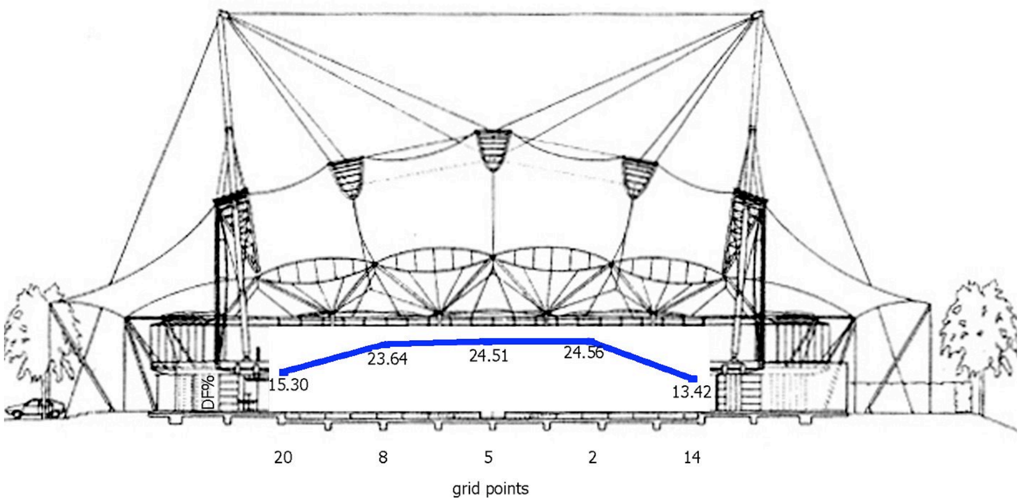


Fig. 6-40 DF (%) variation across section A-A′

Daylight factor values across section B-B′ form a symmetrical curve where the highest DF value (24.51%) is located at the central point of the curve (point 5) decreasing then towards the building blocks at both sides of the building. It is evident that Radiance is properly simulating the behaviour of daylight produced by the model's geometry.

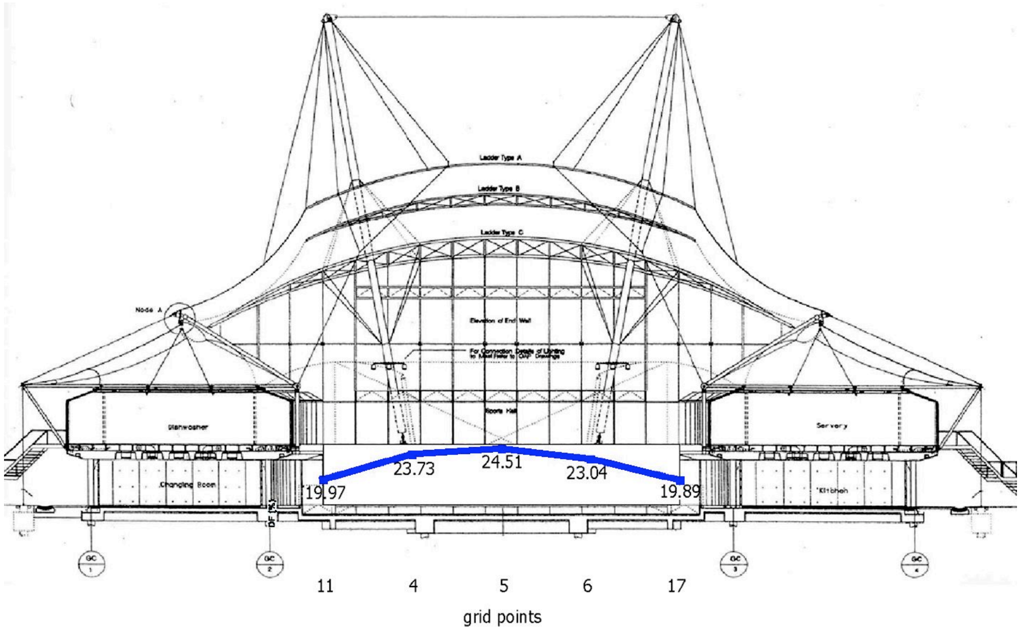


Fig. 6-41 DF (%) variation across section B-B'

Comparing Radiance results with the information gathered on site (chapter four section 4.3.2.3) there seems to be an agreement in certain aspects, such as: the high daylight levels found in the playing area of the building, the central zone of the hall has more daylight reaching the space decreasing almost symmetrically towards the building blocks located around the playing area. In addition, the behaviour of light across section B-B' is very similar in both cases; having a curve with the highest value at the centre of the building section. However, this is not the case in section A-A' where the highest DF value in the real building is located in point 8 (towards the back of the building), and with Radiance is located in point 2. Nonetheless, the values in the central points (8, 5 and 2) in both cases (real building and computer model) are very similar among them.

The difference between results of these performance analyses may be caused by any geometrical discrepancy between the computer model and the real building. Although the computer model was carefully made following Hopkins' building drawings, the four masts and cables that hold the central membrane were not modelled because they were considered to have little influence on daylight penetration. However, this simplification of the model plus possible discrepancies between the building's plans and the actual Amenity Building that could have resulted from changes and adaptations throughout its usage period might be responsible for some results differences.

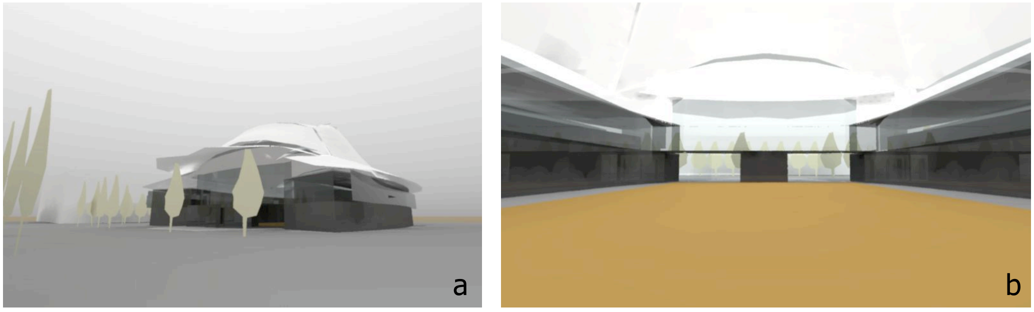


Fig. 6-42a Luminance Radiance image of the exterior of the Amenity Building
Fig. 6-42b Luminance image of the interior of the Amenity Building rendered with Radiance

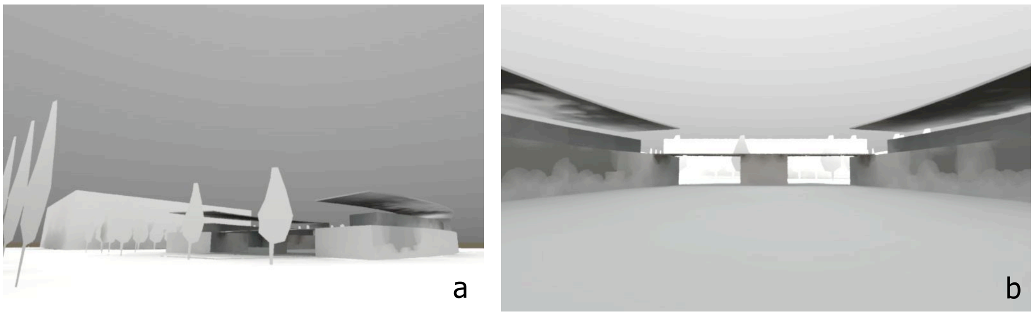


Fig. 6-43a Illuminance image of the exterior of the Amenity building
Fig. 6-43b Illuminance image of the interior

6.5 A SENSITIVITY ANALYSIS: transmittance and reflectance parameters

One of the advantages of computer simulation is the possibility of changing parameters in a scene simulation without spending much time making changes. Simulation time, however, is dependant on the chosen parameters. Materials photometric properties can be one of those parameters that can be modified in order to assess the sensitivity of the models to variation in light transmittance and reflectance of main surfaces. Results are analysed taking into consideration illuminance levels and distribution of daylight factors over the measuring grid.

Through modifying the light transmittance and reflectance of the fabric membranes, walls and floors in the three case studies, the effects and contribution of these factors in the daylighting performance of sports buildings can be evaluated.

6.5.1 Methodology

Simulations in all three models were performed for the same analysis grid as in the previous section. The Radiance ambient parameters were the same as explained in section 6.3. For the Indoor Cricket School at Lord's Ground simulations were run for the fabric membrane transmittances of 5.9%, 15%, 25%, 50% and 75%; and reflectance of 10%, 15%, 25%, 60% and 75%. Walls reflectance were simulated at 10%, 25%, 40%, 74% and 90%; and floor reflectance of 15%, 25%, 50%, 75% and 90%.

The National Cricket Academy model was simulated with fabric membrane transmittances of 5%, 25%, 50%, 75% and 90%; and reflectance of 10%, 25%, 40%, 60% and 80%. Walls reflectance were changed to 10%, 25%, 40%, 60% and 75%; and floor reflectance to 15%, 25%, 50%, 75% and 90%.

Finally, the materials properties of the Amenity Building were simulated with membrane transmittances of 10%, 20%, 40%, 60% and 80%; and reflectance of 10%, 15%, 25% and 50%. Walls reflectance was changed to 16%, 25%, 50%, 75% and 100%; and floor reflectance was modified to 5%, 15%, 25%, 75% and 100%.

The impact of these parameters on the overall lighting performance of the buildings will offer a panorama of the importance that setting materials properties correctly has in order to obtain realistic daylight factors and illuminance distributions.

6.5.1.2 Findings: case study 1

The impact of the membrane light transmittance (fabric louvres) on the overall performance of the building can be seen in Figure 6-44. Increasing membrane transmittance increases illuminance levels inside the building, and therefore, the average DF increases as well. The difference between the initial DF of 4.71% and the DF obtained with 75% light transmittance is 1.66% (absolute) and 35% (relative). Consequently, attaching the correct light transmittance of the membrane to this material in the computer model is very important to obtain accurate results. The building daylighting performance is sensitive to this parameter, and so is the illuminance distribution over the measuring grid; low illuminance levels were accentuated in the centre of the hall when increasing transmittance factors and this variation corresponded to the roof arrangement (Fig. 6-46).

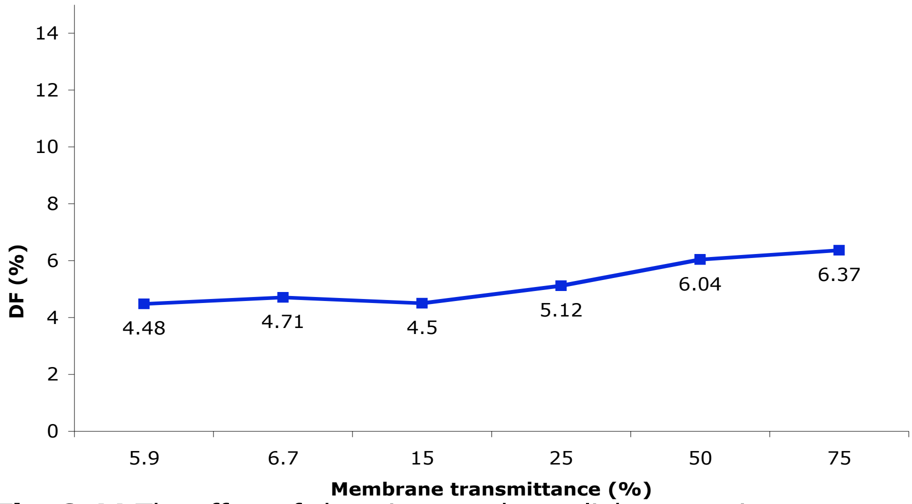


Fig. 6-44 The effect of changing membrane light transmittance on overall building performance.

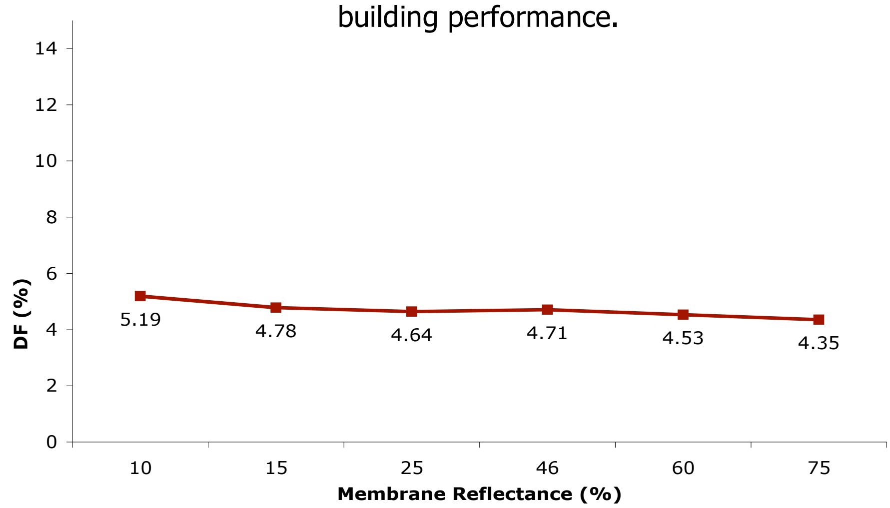


Fig. 6-45 The effect of changing membrane reflectance factors on overall building lighting performance.

On the other hand, the average daylight factor in the building decreases when increasing the reflectance factor of the membrane (Figure 6-45). The difference between setting the membrane reflectance at 10% and at 75% is not very significant, only of approximately 0.84%. It seems that with a higher reflectance factor the membrane tends to reflect light back to the sky and as a consequence, less daylight reaches the interior of the building. This daylight is reflected from the upper side of the membrane louvres back to the exterior before it is absorbed, transmitted or internally reflected by the same membrane or the adjacent membrane louvres.

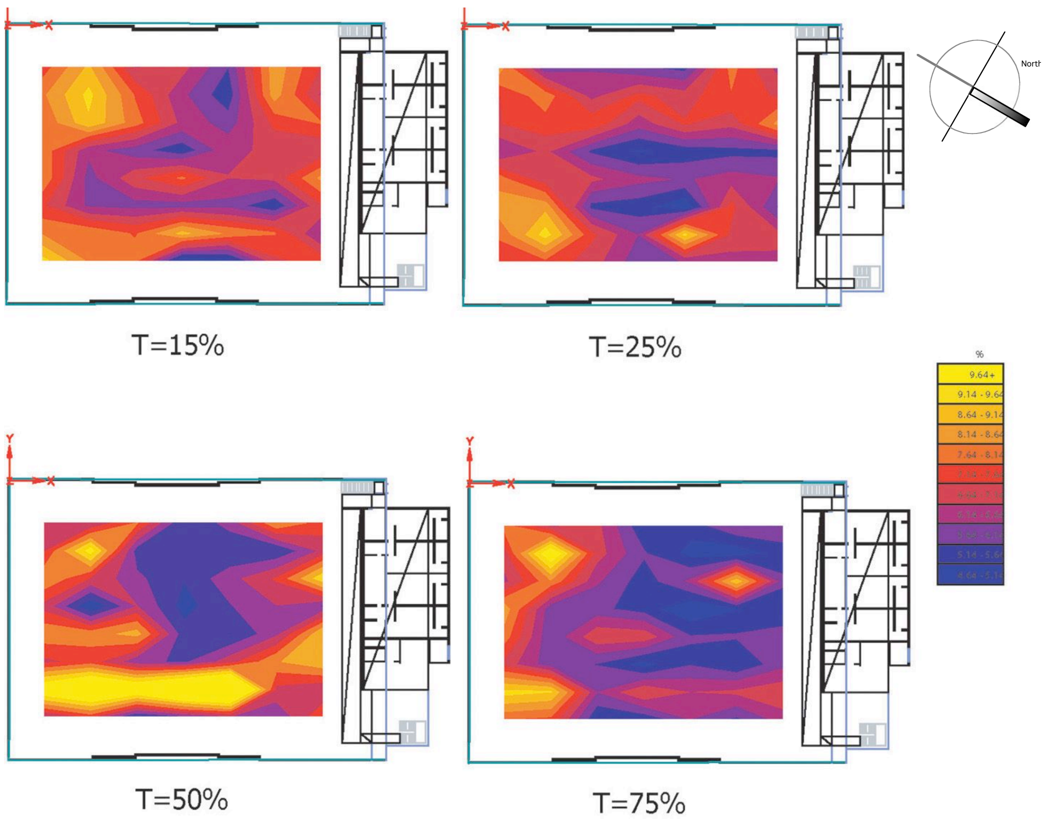
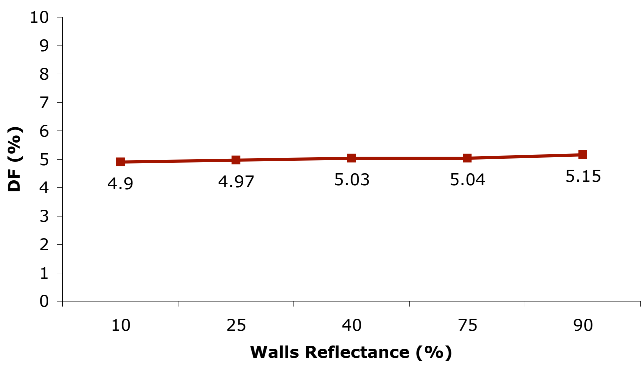


Fig. 6-46 The effects of increasing membrane transmittance (T) on overall illuminance distribution

The effects of changing the reflectance of the surrounding walls and the green floor of the School are shown in Figures 6-47a and 6-47b. Increasing the walls' reflectance factor produced a 6% increment on the average DF; from 10% to 90% reflectance factors. On the other hand, changing the reflectance of the floor caused a 16% increment on the average DF; with a floor reflectance of 9% the DF is 4.71%, while a reflectance of 90% produced a DF of 5.45%. This difference between both surfaces' behaviour are logical since the floor covers the entire playing surface; whilst the white walls are located surrounding the playing area with corridors in between, having less influence on the lighting behaviour of the interior space. These figures illustrate the sensitivity of the software and the lighting performance of the building to changes of photometric properties of materials. Setting these properties correctly is essential for obtaining accurate results from the computing simulation.



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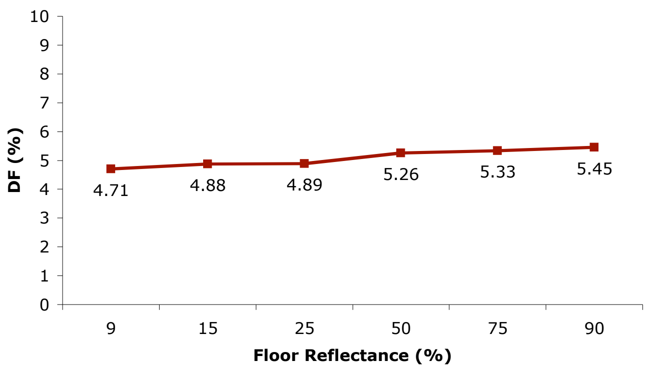


b

Fig. 6-47a The effect of changing walls reflectance on overall lighting performance. **Fig. 6-47b** The effect of changing floor reflectance on building's lighting performance.

6.5.1.2 Findings: case study 2

Case study 2 (National Cricket Academy) showed similar results to case study 1. Though, in this case the increment of DF produced when increasing membrane transmittance is more evident. Over a range of transmittance values of 5% to 90%, DFs increased approximately 6.75%.

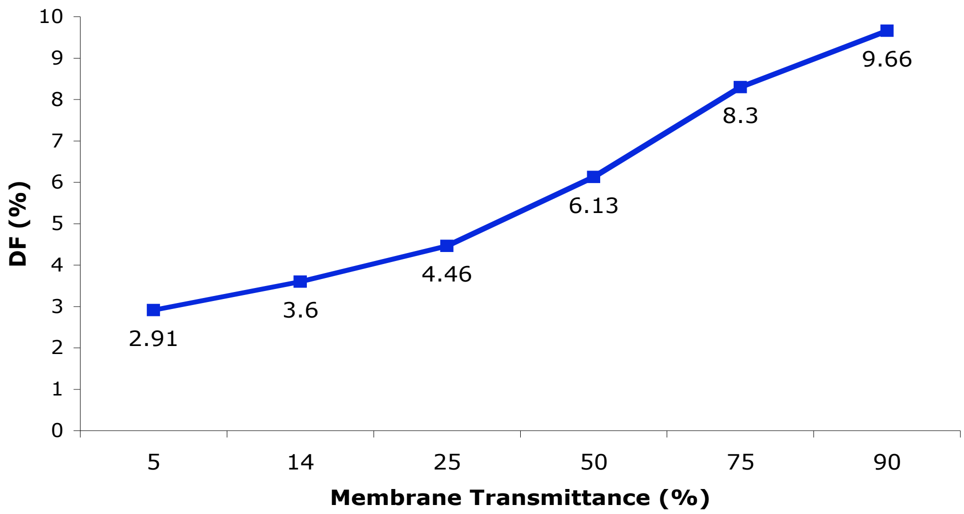


Fig. 6-48 The effect of changing membrane light transmittance on overall building performance.

Again, increasing membrane reflectance produced lower daylight factors (Figure 6-49). Variation in these results is clear having an average DF of 8.91% with a membrane reflectance of 10%, and 3.2% DF with a reflectance of 80%. The question now may be why these differences are more evident in case study 2 than in case study 1?

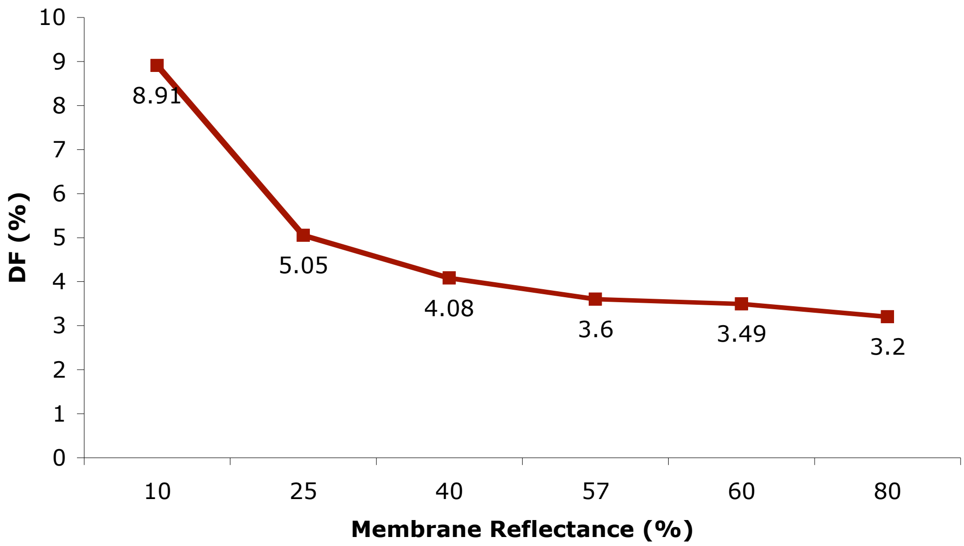


Fig. 6-49 The effect of changing membrane reflectance on overall building performance.

Modifying reflectance and transmittance properties of the membrane material located underneath the roof in both buildings represent significant changes to their lighting performance. Although the architectural and lighting solutions of both buildings are similar, the effects of changing membrane's photometric properties are more significant in case study 2. Although the percentage of skylight roof covering the playing hall in case study 1 is 46.74% of the whole roof in this area of the building, in case study 2 is lower with only 36% being a transparent roof. These leave us to think that the geometry of the membrane louvres influences the way daylight changes with different transmittance and reflectance values. At the National Cricket Academy, membrane louvres in each roof vault are only four while at Lord's there are five. These four are more tensioned in case study two than in case one, allowing a more unobstructed penetration of daylight. Therefore, any change to membrane's properties will have a higher effect on the overall lighting levels than in case study one.

The effects on illuminance distribution in the building are displayed in the following figure. Illuminance levels and daylight factors increased when membrane transmittance was incremented; however, light distribution continues to be the same: low values are located next to vertical partitions and high values at both extremes of the hall (Fig. 6-50).

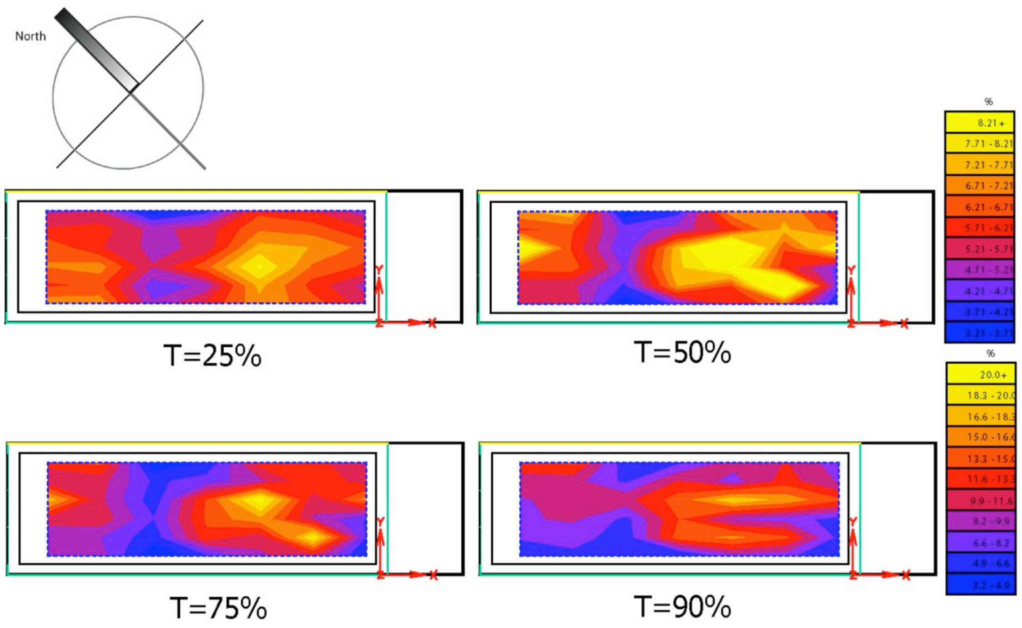


Fig. 6-50 The effects of changing membrane transmittance (T) on illuminance distribution over playing area

Regarding the effects of changing floor and walls reflectance, according to results obtained these parameters do not have a significant effect on the overall lighting performance of the building. Again, higher surface reflectance causes lower daylight levels. However, in the case of the walls the results varied between 3.45% DF with a 10% reflectance, and 3.21% with a 75% reflectance. It seems rational that the influence of walls' properties on daylight levels in all six playing lanes is minor since these surfaces are located around the playing hall, which is mainly lit by skylight coming from the roof located above the playing lanes.

Results from changing floor reflectance varied between 3.21% with reflectance of 90%, and 3.65% with reflectance of 15%. This is a 0.44% difference.

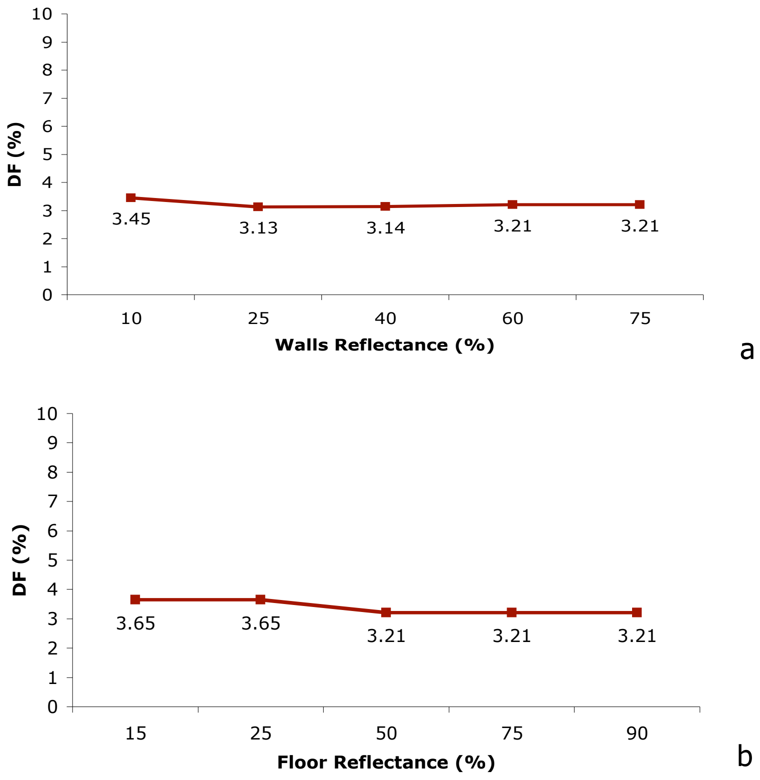


Fig. 6-51a The effect of changing walls reflectance on average daylight factor. **Fig. 6-51b** The effect of changing floor reflectance on average DF

6.5.1.3 Findings: case study 3

The effect of changing transmittance and reflectance properties of the Amenity building's membrane roof is clear in this sports hall where the main roof structure is the fabric membrane. Increasing membrane's transmittance produced an increment of daylight in the playing area. From a transmittance of 20% to 80% in 20% increments, the relationship between transmittance and daylight factor is linear (Figure 6-52). Clearly, to properly simulate the daylighting performance of this building and others with a similar tensile membrane structure, it is fundamental to have the correct photometric properties of the membrane to input in the computer model. Then, it would be possible to use data obtained with this type of simulations to make design decisions or to evaluate the performance of a building at a design stage or an already built project.

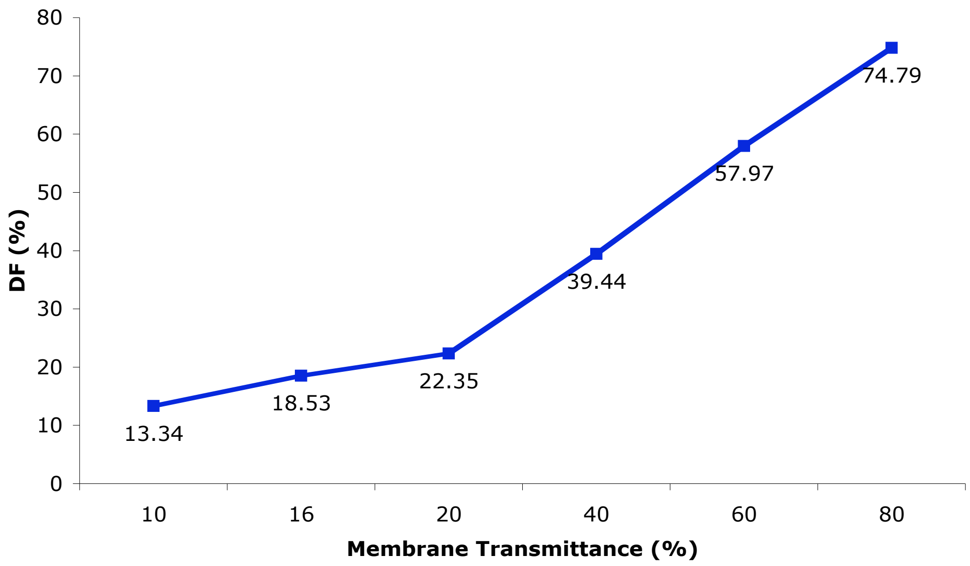


Fig. 6-52 The effect of changing membrane transmittance on overall building lighting performance

As it was expected, increasing the reflectance factor of the membrane decreases the availability of daylight in the playing hall due to a greater quantity of daylight that is reflected back to the sky (Figure 6-53). Running the model with the initial reflectance of 75% and transmittance of 16% the resulted DF is 18.53%, whilst with a reflectance of 10% and transmittance of 16% the DF is 92.5%. In order to further investigate this assumption, it would be necessary to study the effects of changing surfaces' photometric properties changing also some Radiance parameters such as ambient bounces or ambient value parameters.

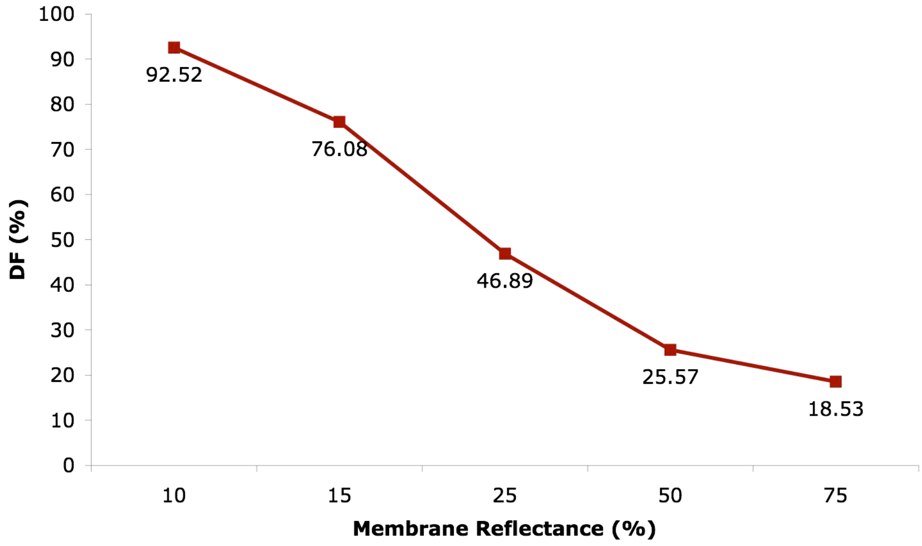
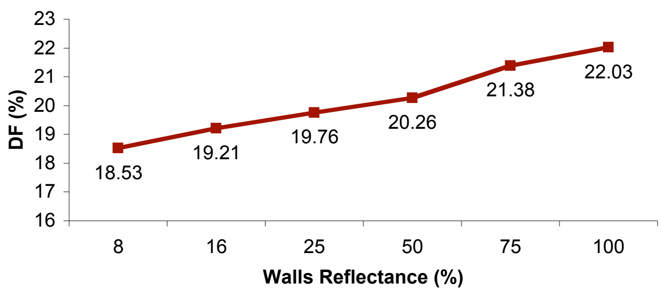


Fig. 6-53 The effect of changing membrane's reflectance on overall building performance.

Nonetheless, altering reflectance of walls and floor in this building influenced the behaviour of daylight. In both cases daylight factors increased when increasing reflectance values. However, changing walls reflectance has a major effect on the overall performance of the building. These walls are situated surrounding the playing area at a close distance and with any partition in between. Therefore, it is normal to expect an important influence of these surfaces on the playing court (Figure 6-54).



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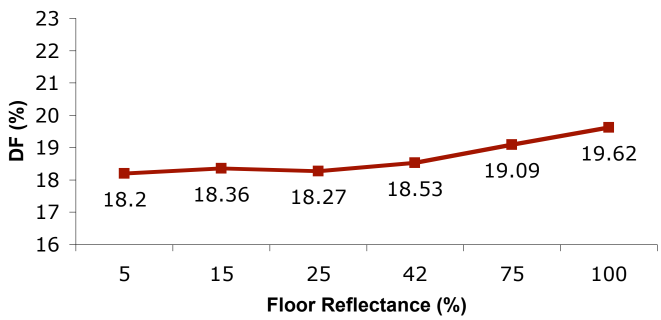

b

Fig. 6-54a The effect of varying walls reflectance on overall lighting performance **Fig. 6-54b** The effect of varying floor reflectance on average DF

Figure 6-55 illustrates the effect of changing membrane transmittance on general illuminance distribution in the building. Higher transmittance factors produced higher illuminance levels at playing level, but the distribution of daylight continue unchanged.

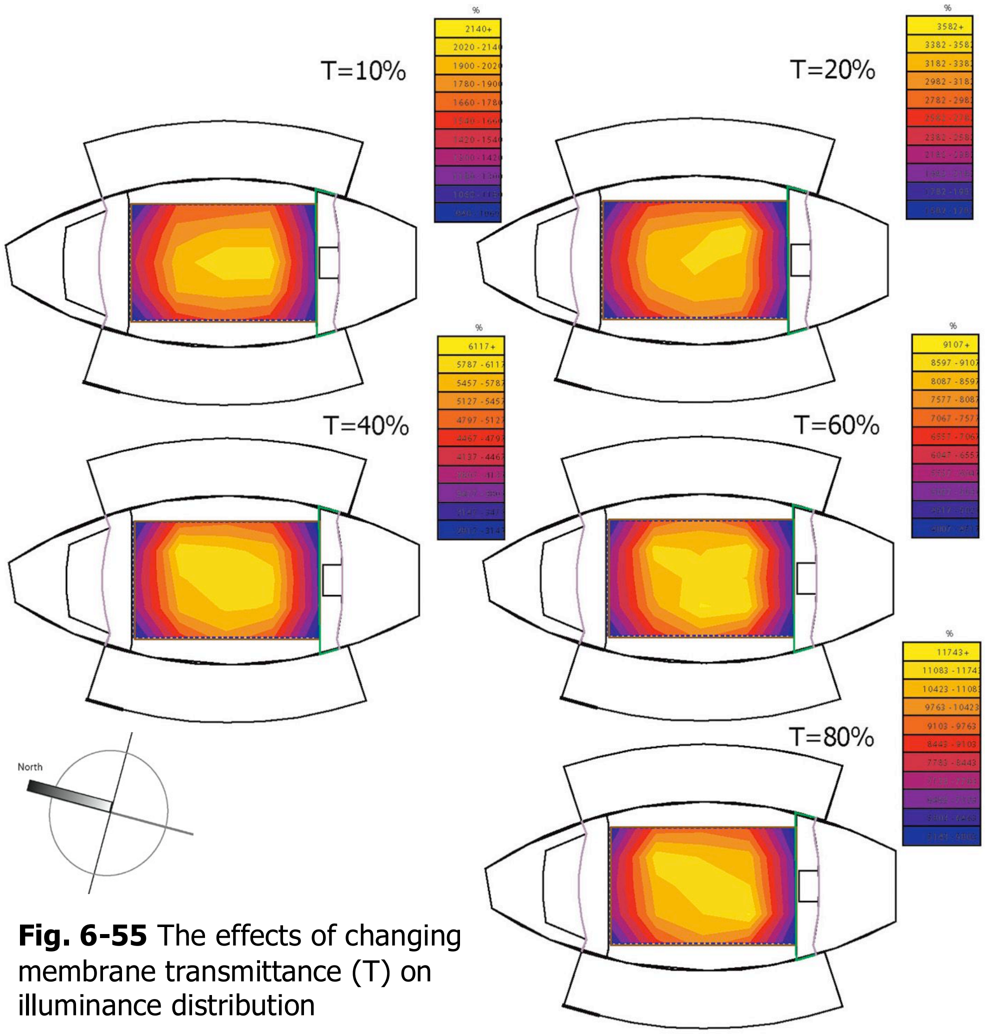

Fig. 6-55 The effects of changing membrane transmittance (T) on illuminance distribution

6.6 PHYSICAL ILLUMINANCE MEASUREMENTS AND COMPUTER SIMULATIONS COMPARED

Comparing physical illuminance measurements with computer simulations allows the researcher to evaluate the use of Radiance (and Ecotect) for accurately modelling daylighting performance of sports buildings that use membranes to control daylight access. In order to reduce possible simulation errors the same analysis grid (number and location of grid points) was used in each case study building and its corresponding computer model. Exterior horizontal illuminance was recorded simultaneously with the interior horizontal illuminance in the physical measurements; and from this data, daylight factors were obtained. These DFs are then compared with data obtained with computer simulations. The following comparative Table shows results found with physical measurements and computer simulation for the three case study buildings evaluated in this thesis.

Table 6-3 Results from real building analysis and computer simulation

BUILDING	DF (%) FIELD STUDY	DF (%) RADIANCE	DIVERGENCE BETWEEN RESULTS	ILLUM. UNIFORMITY REAL BUILDING	ILLUM. UNIFORMITY RADIANCE MODEL
Case study 1: Lord's	4.4	4.71	6.5%	0.37	0.73
Case study 2: Nat. Cricket Academy	5.9	3.60	-63%	0.55	0.33
Case study 3: Amenity Building, IRC.	24	18.5	-29.7%	0.29	0.62

There is a good agreement between the physical measurements recorded in the Cricket School at Lord's and the simulated results. The divergence between both results is 6.5%. This result is very encouraging to continue using computer simulation as a daylighting prediction tool.

However, in the case of the National Cricket Academy the simulated average daylight factor was 63% lower than the DF recorded in the physical measurement. Nevertheless, the illuminance uniformity ratio between the real and the simulated results are quite similar, in both cases lower illuminance values are found at the batsmen position enclosed by fabric partitions.

In the case of the Amenity building Radiance again underestimated the building's lighting performance by almost 30%. However, illuminance distribution maps show a good match between the physical and the simulated data, higher illuminance values are found at the centre of the playing hall and decrease towards the sides and back building blocks.

Radiance can be a very powerful simulation tool but it can also be very sensitive to certain parameters and materials characteristics. When input data into the model it is necessary to have the correct photometric properties of surfaces materials and the correct geometry of the building in order to obtain accurate results that can be useful during the design process or the evaluation of a building's performance.

Aizlewood et al[26] have tested Radiance simulating an atrium building and comparing results with an analytical method and scale modelling data. The authors concluded that Radiance underestimated the reflected component for deep, high reflectance atria. Possible simulation errors mentioned by the researchers are:

- Inappropriate ambient parameters in Radiance.
- Definition of surface properties: reflectance, specularity and colour.

According to the authors, reflectance and specularity values are difficult to measure and they propose conducting a sensitivity analysis to see the effect of these values in Radiance simulations. Colour is difficult to model with Radiance since the software repeats its calculations based on three colours, red, green and blue. The illuminance results are given in their red, green and blue components. Aizlewood et al pointed out that this has no effect if all surfaces are neutral, but if they are not, then the colour will affect light inter-reflections. In the sensitivity analysis carried out in this thesis it was possible to see how changing reflectance values influenced the resulted illuminance; higher reflectance will produce lower average illuminance. Therefore, it is possible that a mistake was made simulating the reflectance and colour of surfaces and this could be one reason for the discrepancy between physical measurements and the underestimation of Radiance simulations.

Figures 6-56a, b and c illustrate a comparison between the physically measured daylight factors and the Radiance daylight factors across a section of each building.

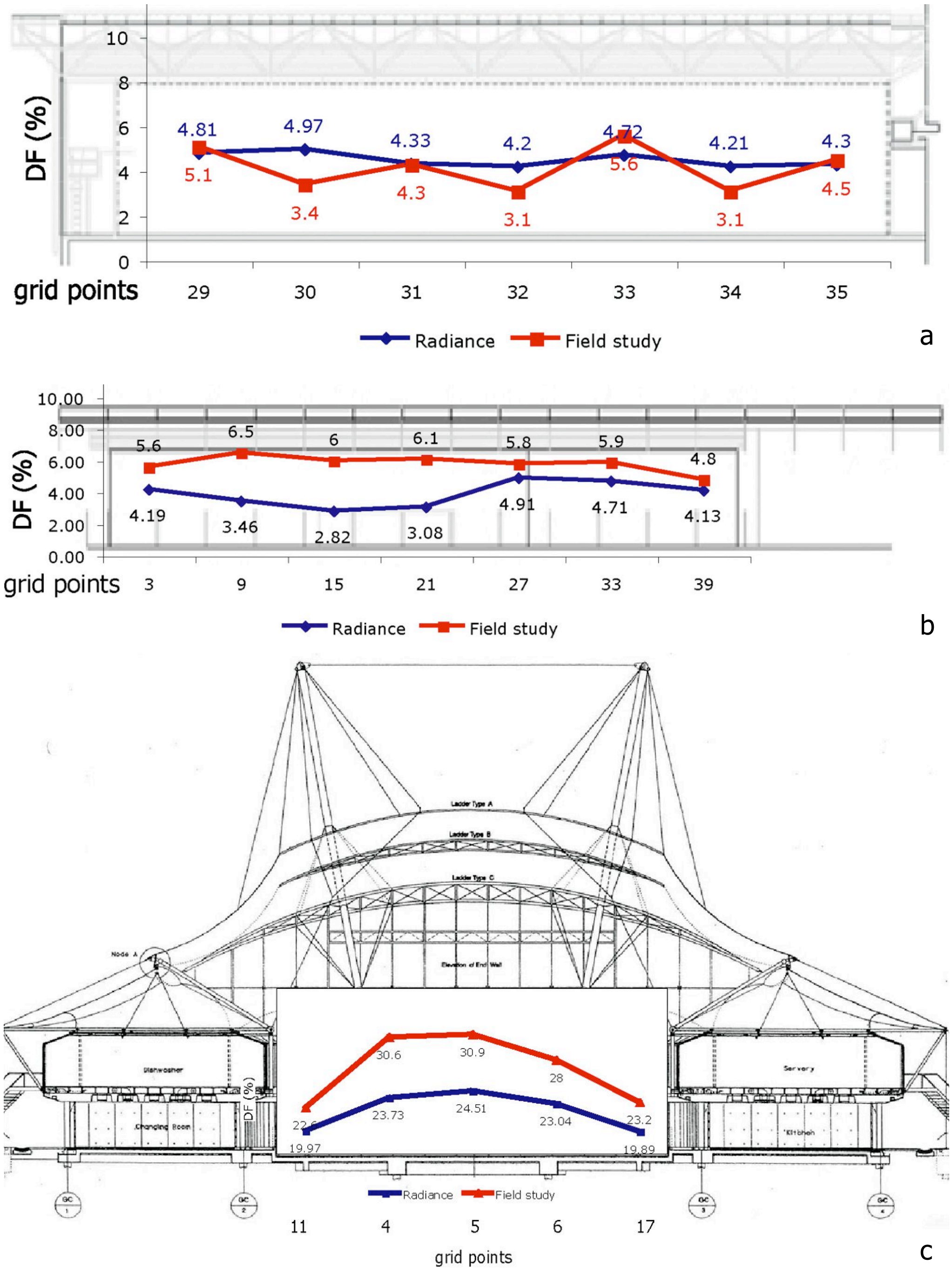

Fig. 6-56 Daylight Factor: comparison of computer simulated and field results. **6-56a** Cricket School at Lord's. **6-56b** National Cricket Academy. **6-56c** Amenity Building.

6.7 CONCLUSIONS

The comparison presented in this chapter between measured field daylighting performance and computer simulations of three case study buildings has shown the potential of computer models to predict daylighting in buildings with membranes used as lighting control systems.

Definitely, learning specialised software, understanding it and knowing how to avoid possible simulation errors are not easy tasks.

This chapter has described the methodology for the simulation of all case studies; has presented results obtained from these simulations and also results from a sensitivity study. This sensitivity study illustrated the importance of setting correct photometric properties of surface materials, particularly fabric membranes, because illuminance levels in the buildings are highly dependant of the transmittance and reflectance factors of the membranes.

Possible sources of error have been distinguished, among them are:

- Geometry differences. Even though computer models of the three buildings were carefully made, it is possible that discrepancies exist especially because the geometry modelled was complex in all three cases. Moreover, computer models were based on architectural drawings developed during the design or construction stages of the buildings; and it is possible that changes to geometry have been made after construction and during the years that these buildings have been in use.
- Definition of materials properties. One of the reasons that makes Radiance a powerful lighting simulation software is that it offers the possibility of defining materials' characteristics such as reflectance, transmittance, specularity, roughness and colour. However, some of these properties are not easy to measure; for instance, specularity in the simulations made in this study was set to a default value recommended for diffuse materials (fabric membranes in this case). In addition, the colour of the material seems to have some influence on light inter-reflections, even if certain reflectance value is also set. For example a white wall can have a reflectance of 50% but if it is set to be grey or some type of other colour hue, then the output could be different. For this study membranes and white walls were simulated as different tones of grey, and this could have caused high number of

inter-reflections producing an underestimation of illuminance within the interior space.

- Definition of Radiance ambient parameters. The ambient parameters used were explained earlier in this chapter. Some of them were left with the default parameters, but considering the results obtained and being these buildings complex structures it seems appropriate to recommend carrying out deeper sensitivity analyses of some parameters before doing the simulations. For instance, the number of ambient bounces set for a certain model has to be tested for different values before running final simulations. A precise number of bounces has to be reached where lighting variations become stable and this number has to be set for future simulations.

In addition, some materials' properties in this study were modelled in Ecotect. It could be advisable for further studies to model all surfaces' properties with Radiance to evaluate the program's sensitivity to photometric characteristics of materials. Although, it has been proven that it is possible to model translucent membranes with Radiance obtaining an excellent agreement with measurements taken in the existing building for the case of the cricket school at Lord's Ground.

Chapter 7 illustrates the complete evaluation analysis of scale modelling and computer modelling as tools to accurately predict daylighting in sports membrane buildings. Findings of both analyses are compared with physical lighting measurements taken in all three case study buildings. Finally, recommendations to improve the adopted methodology to properly use these prediction tools are presented.

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6.8.1 Figures and tables

Seven

7. COMPARATIVE ANALYSIS

7.1 INTRODUCTION

Throughout the past chapters of this thesis it has been pointed out the importance of designing buildings with appropriate lighting conditions. Particularly, good lighting design in sports buildings is essential for the performance of players, instructors and comfort of spectators. The introduction of daylight in sports buildings contributes to reductions on energy costs and CO_2 emissions.

The three existing buildings chosen as case studies are daylit sports halls where membrane structures have been integrated as part of the roof solutions in order to control the access of daylight. In the case of the Amenity building the membrane structure is also the main enclosure of the hall. The analysis and modelling of all three buildings have represented a challenge since these sports centres are geometrically complex large structures.

Field measurements of levels of illuminance were taken in the buildings under overcast skies and during different days. Physical models were constructed and tested under an artificial sky. Finally, three dimensional computer models of the case studies were made and daylighting analyses were undertaken using Radiance lighting simulation software. The findings of these evaluations have been reported in separate chapters. In this chapter results are analysed as an integral daylighting assessment of the different buildings and of the simulation tools evaluated in this study.

7.2 ASSESSMENT OF TOOLS USED TO PREDICT DAYLIGHTING BEHAVIOUR IN THE CASE STUDY BUILDINGS

A summary of results obtained from field measurements, physical models and computer model simulations are compared for the three case studies: Lord's Cricket School, the National Cricket Academy at Loughborough University and the Amenity building of the Inland Revenue Centre.

The DF% obtained with the physical scale models of case studies 1 and 2 (the cricket schools) was much higher than the DF recorded on site and the DF obtained with Radiance models. However, the physical scale model of the Amenity building better performed the lighting environment providing similar DF to those obtained with the Radiance model and the field measurements.

In all three cases, the calculations made with Radiance were very close to both findings: the daylight factors measured in the real buildings, and the distribution of illuminance along the playing areas.

7.2.1 Case study 1

7.2.1.1 Illuminance values

Field illuminance measurements in the indoor cricket school at Lord's Ground in London were recorded in 56 different grid points located along the playing hall and following the building's configuration of eight playing lanes distributed through the long axis of the building.

Results presented in chapter four section 4.3.2.1 show fairly uniform illuminance levels and an average daylight factor of 4.4%. This figure means that in order to achieve an interior illuminance of 1,000 lux only with daylight, it would be necessary to have an unobstructed sky illuminance of 23,000 lux. This condition is met 46.9% of the year in London between 9am and 5.30 pm[1]; and during the rest of the time a combination of artificial and natural light has to be used. Then, it can be said that the cricket school is a naturally lit building.

Daylight factor values found across the playing lanes indicate that in a lane covered by the transparent section of the vault with membrane louvres underneath the roof, the variation of daylight is quite high compared to the variation found in a section across a playing lane situated under the opaque area of the roof. This behaviour can also be seen on a DF contours plan in chapter four.

7.2.1.2 Uniformity Ratio

The physical scale model of this building provided more uniform results with an illuminance uniformity ratio of 0.8 compared to a field uniformity ratio of 0.37 and a Radiance model uniformity ratio of 0.73. It seems that both simulations, scale modelling and computer modelling, presented more illuminance uniformity than reality. It is possible that the number of internally reflected components was not accurately represented in the models, and therefore the variation of light was underestimated. This was tested using Radiance and results are presented later in this chapter. Moreover, the brightness of a real overcast sky varies depending on the season of the year or the time of day causing illuminance variation inside the buildings; and the brightness of the overcast skies (the mirror box and Radiance's sky) used with the models is always constant.

Figure 7-1 displays the variation of DF across a playing lane with membrane louvres under the roof; these data was obtained from the scale modelling study, field measurements and Radiance simulation.

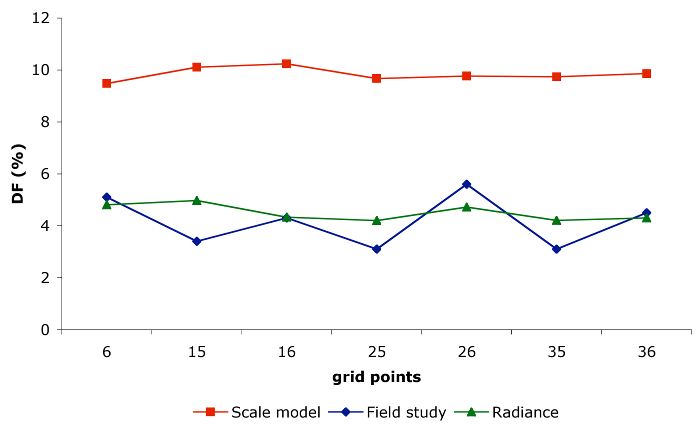

Fig. 7-1 Field measured and scale and computer models predicted DF variation across a long section under transparent roof and membrane louvres.

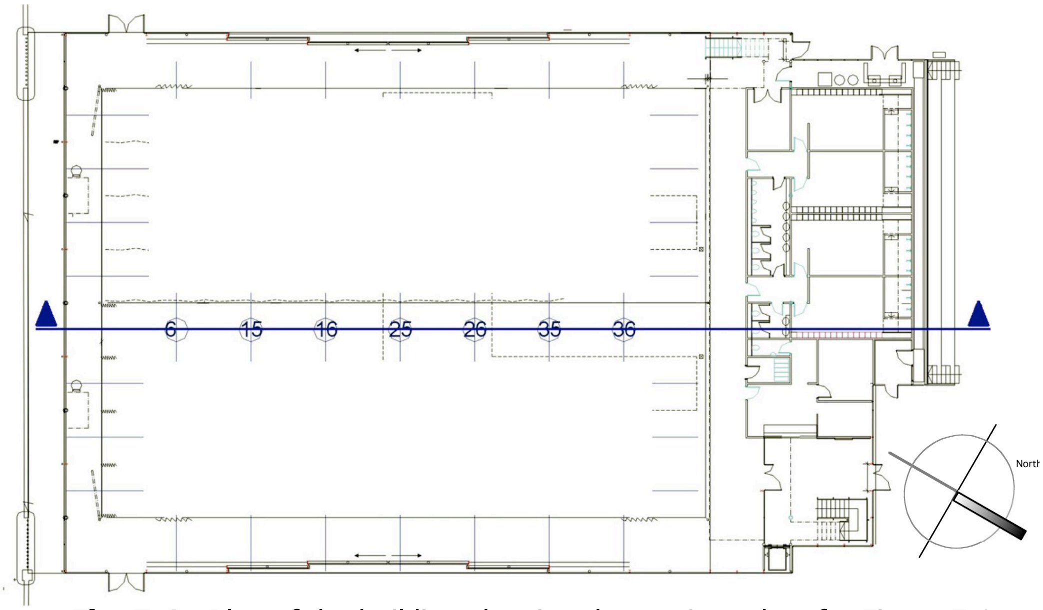

Fig. 7-1a Plan of the building showing the section taken for Figure 7-1

Clearly, results from Radiance simulation are closer to field measurements than results obtained from scale modelling. However, changes between grid points of the field study are more dramatic, perhaps this is a result of the reflectance of real materials, which produce light reflections back to the membrane louvres and back again to playing level. Moreover, in reality even under an overcast sky the levels of daylight are not constant producing more dramatic changes in DF% in the field study than in the scale and computer models, where the exterior daylight is maintained throughout the calculations. In addition, the structure that holds the louvres was not completely modelled in Radiance because it was thought that it could be insignificant due to its small dimension, but these results may prove that in fact this structure blocks out some of the daylight that comes through the roof.

Figure 7-2 illustrates the variation of daylight factors across a long section of the building located under an opaque section of the roof parallel to section shown in Figure 7-1. Here, it is possible to see that light variation is smaller than in Figure 7-1. In this case, DF varies 0.443% in field study results, 0.112% in scale modelling and 0.188% in Radiance simulation results.

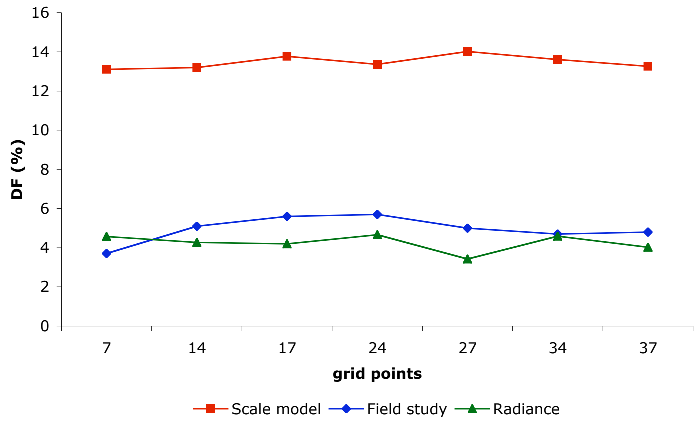

Fig. 7-2 Field measured and scale and computer models predicted DF variation across a long section under opaque roof.

The following Table shows a comparison between results obtained with field measurements, scale modelling and computer modelling. These data includes average daylight factors, illuminance uniformity ratios and relative error between measured data and predicted data with scale models and computer models. This relative error is defined as[2]:

$$RER= ((I_{predicted} - I_{measured})/ I_{measured}) *100 \quad (7.1)$$

Where I = illuminance; but in this study 'I' has been substituted by the average daylight factor for comparison purposes since measured illuminance in the three different studies varied considerably because it was measured and predicted under overcast sky conditions but in different dates and at different times during the year.

Table 7-1 Comparison of DF, uniformity ratio and relative error of field measurements, scale modelling and computer simulation for case study 1.

BUILDING	FIELD STUDY		SCALE MODEL			RADIANCE MODEL		
	DF	UNIFORM. RATIO	DF	UNIFORM. RATIO	RER	DF	UNIFORM. RATIO	RER
Lord's Cricket School	4.4%	0.37	10.6%	0.8	140%	4.71%	0.73	7%
			9.16%*	-	108%			

*Result corrected (14%) for sensor size error.

The Radiance model best simulated the daylighting performance of this building, with a relative error of only 7%. On the other hand, the physical model overestimated the existing building with a very large relative error.

This big difference of DF% presented in the above comparative table between field measurements and scale modelling is caused by several factors:

- **Geometrical inaccuracies**. The geometry modelled did not include the full geometry of the building. The reason to be modelled with only two playing lanes and side corridors (instead of 8 existing lanes) was the large dimension of the building; this decision allowed the use of a bigger scale for the model and suited the dimension of the available mirror box. Furthermore, the reception, staircase and changing rooms were again not included in the scale model because apparently there is hardly any relationship with the playing area, but looking at the results it seems like these areas of the building could actually have some effect on the lighting environment of the playing lanes. The real steel structure of the building was not very detailed in the physical model due to its complexity; this may be another inaccuracy responsible for the large difference of the results.
- **Surfaces' reflectance**. The luminance of the real surfaces was measured on site and their reflectance was calculated using that data. The method is explained in chapter four Section 4.1.1. The reflectance factors of real materials and materials used in the scale model are included in Table 7-2. Although the materials used in the physical model have similar reflectance factors to the real materials' reflectance, the results suggested possible inaccuracies. The colour of the paper cards used to model walls and roof surfaces was pale pink, which could have incremented the amount of light internally reflected. The same reflectance factors were assigned to the surfaces of the computer models, but Ecotect gave darker colours from a range of grey hue to these same values. The results of the Ecotect-Radiance modelling are much more accurate than the physical modelling results. Nonetheless, the physical model has provided useful information regarding the behaviour of light across the long section of the building, and

experience constructing models with fabric roofs and specific reflectance factors of surfaces.

Table 7-2 Reflectance factors of real, scale model materials & radiance materials

SURFACE	REFLECTANCE REAL MAT.	REFLECTANCE MODEL MAT.	REFLECTANCE RADIANCE MAT.	GLAZING & DIRT CORRECT.
Green floor	8.48%	8.26%	9%	0.64
Walls and roof	52%	41.33%	52%	
Fabric membrane	46%	46%	46%	Transmit=6.7%

The following figure illustrates daylight factors contours maps generated with data from the three analyses: field study, scale modelling and computer simulation.

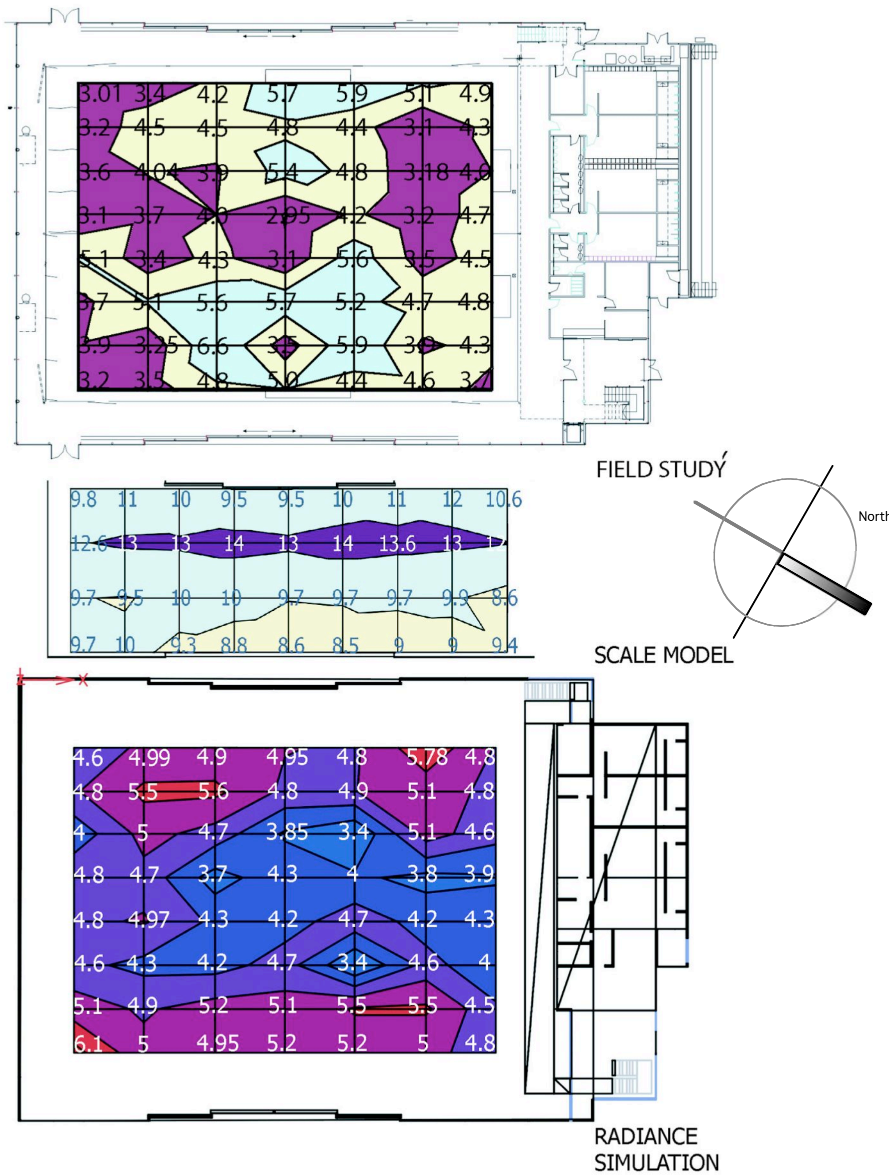

Fig. 7-3 Comparison of measured and predicted DF (%) contours

7.2.1.3 Radiance simulations

The Radiance model of case study 1 produced results much closer to the field measurements. In this case the geometry of the building and site context was completely modelled. Photometric properties of materials were assigned following the values obtained with field measurements and the testing of the fabric light transmittance carried out under the artificial sky. As it was commented before, it seems that the grey colours assigned to surfaces by Ecotect (following the reflectance factors input in the software) worked much better than the colours used for the physical model, which produced a brighter visual environment than the Radiance simulations.

Glazing transmittance as well as a factor for light losses due to dirt were attached to each one of the windows simulating a more real environment than the one created in the physical model where no glazing was modelled and a factor for light transmittance losses and dirt was applied to the final results. The transmittance attached to the front windows is 0.783 and a thickness of 10mm, and the light transmittance of the skylights is 0.64 with a thickness of 80mm.

One of the parameters set for the Radiance calculations of illuminance values and daylight factors is the number of light bounces (-ab). The recommended value is 2, but for this investigation –ab=3, -ab=4, -ab=5, -ab=6 and –ab=7 were also considered. Results show similar lighting behaviour with –ab=2, -ab=3 and –ab=7; the average DF (%) obtained are: 4.71, 4.94 and 4.78 respectively. The difference on Radiance calculation times varied by three minutes, from 9 minutes with –ab=2 to 12 minutes with –ab=7. Hence, for the purposes of this research the calculations made with –ab=2 or –ab=3 are enough to obtain accurate results. Figure 7-4 illustrates a comparison of DF% across a long section of the building that resulted from changing the –ab parameter.

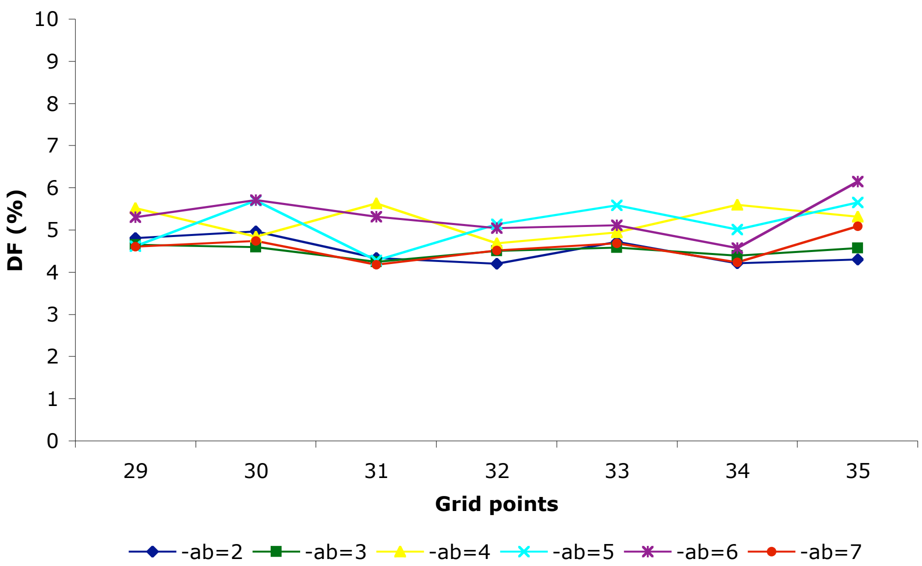

Fig. 7-4 Comparison of DF(%) obtained with different ambient bounces (-ab)

7.2.2 Case study 2

7.2.2.1 Illuminance values

The National Cricket Academy is a bright daylit building. Site illuminance measurements provided an average daylight factor of 5.9%. The lighting target in this building is to reach an illuminance of 1500 lux on the playing area. Considering a DF of 5.9% it would be necessary to have a horizontal exterior illuminance of 25,500 lux to illuminate the training area only with daylight. This occurs approximately between 40 to 46 per cent of the year (9-5 pm)[1].

The physical scale model of this building overestimated the existing building with a daylight factor of 16% and a RER of 171%. In this case the whole playing area was modelled including the side window and the fabric partitions between lanes. The fabric louvres were modelled with the real material and geometry. It seems that the reflectance of surfaces was not properly modelled, although the paper-cards' reflectance was measured trying to match the real materials' reflectance, their colours were probably too bright (Table 7-3 includes the reflectance of real materials, physical model materials and the radiance model materials).

In addition, the scale of the light sensors has influenced the recorded light levels by around 3%. Due to the relative small scale of the model, sensors heads were located at around 1.8 meters over the floor level, and therefore, they were not very influenced by the light reflected or absorbed on the floor and diffused by the membranes. The effect of sensor size on the availability of daylight in scale models with membranes is a topic that has to be further analysed in future studies.

Table 7-3 Reflectance factors of real, scale model materials & radiance model materials. National Cricket Academy, Loughborough.

SURFACE	REFLECTANCE REAL MAT.	REFLECTANCE MODEL MAT.	REFLECTANCE RADIANCE MAT.	GLAZING & DIRT CORRECT.
Green floor	5.8%	7.8%	6%	0.783 (side window)
Walls and roof	53%	46.5%	53%	0.64 (skylights)
Fabric membrane	57.4%	57.4%	57.4%	Transmit=14.4%

Despite the overestimation of the physical model, the illuminance uniformity ratios obtained with the model and the real building are very similar. This encourages the continuing using of scale models during the lighting design stage of architectural projects. Minimising errors with photometric properties of materials could lead designers to construct accurate scale models that can be reliable when making design decisions.

7.2.2.2 Radiance simulations

On the other hand, Radiance simulation underestimated the performance of the building with a DF of 3.6%, which is 2.3% lower than the real building daylight factor. As it was explained in chapter six, the number of ambient bounces (-ab) set was probably too low resulting in Radiance underestimation of light levels. This is mainly caused when the calculation is stopped after two ambient bounces for instance, and the program does not have time to consider all inter-reflections providing low daylight levels. The ideal number of –ab depends on the complexity of the building and the accuracy required; several testing simulations have to be run before deciding the final number of ambient bounces to be used. Seven different simulations were calculated for this building, with –ab=2, -

ab=3, -ab=4, -ab=5, -ab=6 and –ab=7. A comparison of the resulted DF is presented in the figure below.

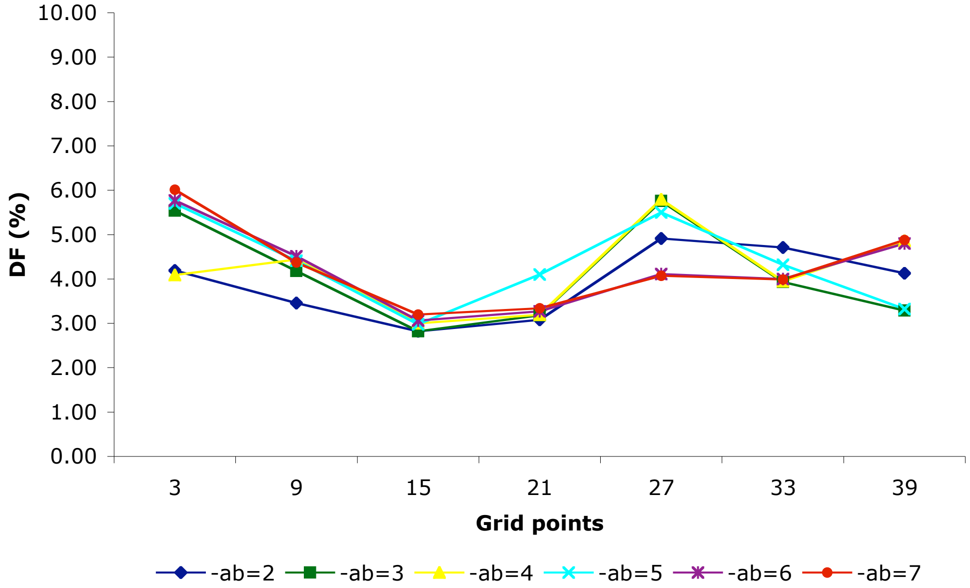

Fig. 7-5 Comparison of DF% obtained with different ambient bounces (-ab) across a long section of the building

According to Figure 7-5, results obtained with 3, 6 and 7 ambient bounces converge at almost every grid point. However, average daylight factors differ from 4.09% (-ab=3), 4.18% (-ab=6) to 4.4% (-ab=7). Because the DF obtained with 7 bounces is closest to the field study DF (5.9%), and the calculation time only increased one minute from the previous calculations; it is possible to consider –ab=7 as the most appropriate parameter for this building.

Figures 7-6 and 7-7 show a comparison between the daylighting behaviour of the building across two sections; results are from site measurements, scale modelling and computer simulation. DF values tend to decrease towards points 15 and 21 where the opaque divisions between playing lanes are situated. Then, light levels in the existing building become more uniform than in the radiance model.

Clearly, results from radiance simulation and the field study are more similar than results obtained with scale modelling. This occurs as a result of the higher accuracy of the geometry modelled in AutoCad and Ecotect for the Radiance model, the use of exactly the same reflectance factors of materials in Radiance than the values measured in the real building, and the attachment of glazing light transmittance values and dirt factors to windows and skylights in the computer model made Radiance simulations more realistic.

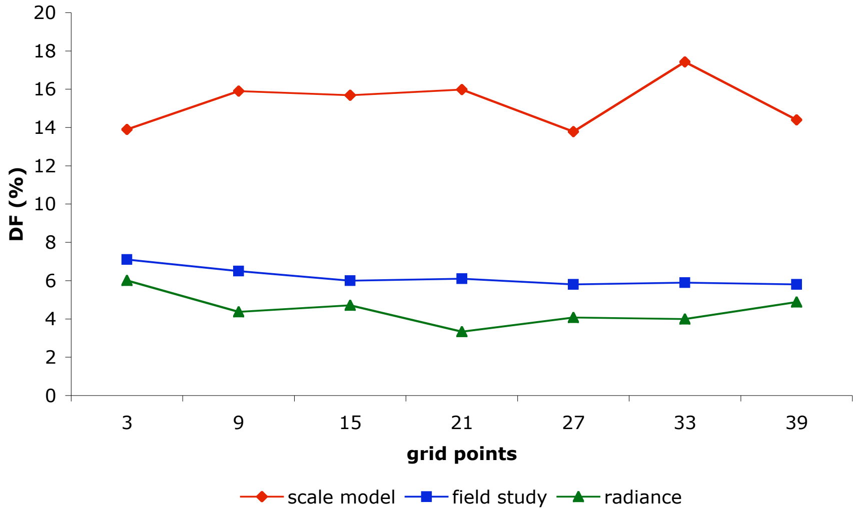

Fig. 7-6 DF predicted with scale model, computer model, and measured on site, across a longitudinal section of the building.

Figure 7-7 shows results across a section through the width of the building. Here, the physical model again overestimated the light availability, but it also suggested that differences between points were greater than in the radiance simulation and the site measurements. The large dimension of the light sensors in comparison with the scale of the physical model could have led to this false simulation of the daylight behaviour in the playing area. With the sensors being closer to the roof, the differences between opaque and transparent sections of the roof became more evident, greatly influencing the variation of light across the section.

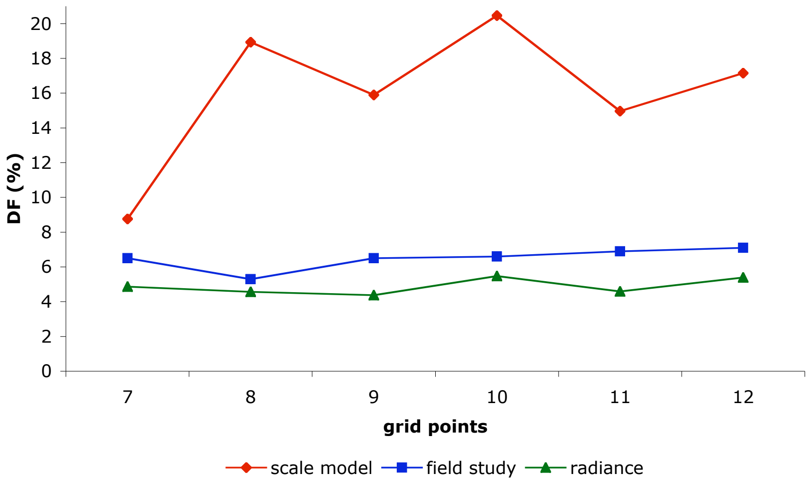

Fig. 7-7 DF predicted with scale model, computer model, and measured on site, across a section of the building passing through all playing lanes.

Table 7-4 presents a comparison of the results obtained in the analysis and simulations of the National Cricket Academy. The Radiance simulation can potentially be an accurate daylighting prediction tool in sports membrane buildings if the simulation settings are chosen appropriately according to the complexity of the building's geometry, and the accuracy needed. In addition, the software can produce realistic luminance and illuminance images that help to visualise the lighting environment and/or to detect possible glare sources.

Table 7-4 Comparison of DF, uniformity ratio and relative error of field measurements, scale modelling and computer simulation for case study 2.

BUILDING	**FIELD STUDY**		**SCALE MODEL**			**RADIANCE MODEL**		
	DF	UNIFORM. RATIO	DF	UNIFORM. RATIO	RER	DF	UNIFORM. RATIO	RER
National Cricket Academy	5.9%	0.55	16%	0.56	171%	3.6% (-ab=2)	0.33	-38%
			15.6%*	-	164%	4.4% (-ab=7)	0.56	-25%

* This result has been corrected (2.27%) for the sensor size error.

A comparison of the illuminance distribution obtained with site measurements, scale modelling and Radiance modelling are presented in DF contour maps (Figure 7-8).

Daylight distribution over the playing area in the field study shows high values on the lower left corner, on column five (from left to right) and on the upper right corner which is close to the side window. This behaviour is similar in the Radiance simulation where the highest light levels are found on the lower left corner and on column five (from left to right). In the Radiance map the lowest levels are located close to the side window and over column three (from left to right) where vertical opaque partitions are located.

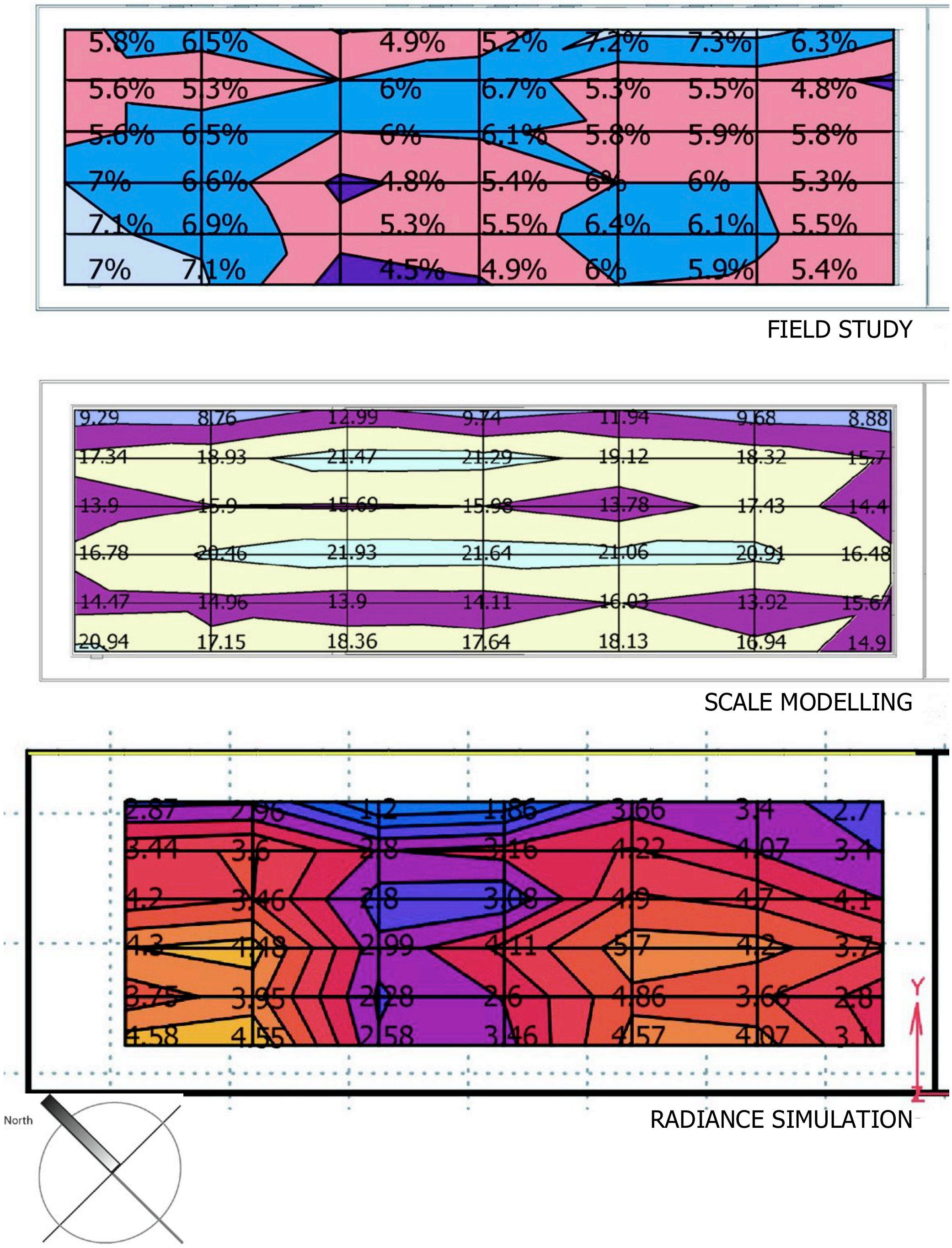

Fig. 7-8 DF (%) contour maps of the measurements taken on site, and the physical and computer simulations.

In this building David Morley Architects included a long side window that visually connects the interior of the Academy with the outdoor cricket pitch. However, this window does not significantly contribute to the interior lighting environment due to its orientation (north-east), the existence of a corridor that separates the window with the playing area, and the fabrics delimiting the playing area (an opaque fabric and a net like fabric). Therefore, most of the daylight that enters the building comes through the roof.

The contour map plotted from the physical scale model results illustrates clear differences between daylight levels recorded in each playing lane. These differences correspond to the geometry of the roof, which is opaque above a playing lane and transparent (with fabric louvres underneath the roof) above the following playing lane, then opaque again, then transparent and so on. In theory this could be the expected behaviour, but in reality it seems that inter-reflections of light affect the illuminance distribution resulting in a more uniform distribution without evident differences between the lanes.

7.2.3 Case study 3

The Amenity Building of the Inland Revenue Centre in Nottingham is a mainly daylit sports building and crèche, with a central membrane structure covering the playing area and reception, and two side membranes covering the cafeteria, gym and changing rooms.

7.2.3.1 Illuminance values

The average daylight factor measured in the existing building is 24% under an overcast sky with an average exterior illuminance of 4,257 lux; this is a rather high DF. This high level of daylight comes through the translucent membrane, glazing on front and back facades and glass sections combined with the membrane roof. The playing hall is a very exposed area to daylight and to the exterior environment in general.

Sports regularly played in the Amenity building require only 300 lux horizontal illuminance since they are not played at a professional level. With a 24%DF it is possible to have 300 lux on the playing hall with only 1500 lux exterior horizontal illuminance; this occurs 91.8% of the year between 9 and 17.30 hrs[1]. Therefore, it is possible to illuminate the playing area with only daylight for 55.7% of its total annual opening hours considering that the building is open from 8am to 10pm from Monday to Friday. There is no doubt that incorporating natural light into the lighting strategy of the Amenity building has provided a bright interior environment and energy savings reducing artificial lighting consumption.

The light transmission characteristic of the real membrane was physically modelled using two layers of white lycra fabric. The following table shows the transmittance and reflectance characteristics of the materials used in the scale model and the real building materials.

Table 7-5 Photometric properties of materials: real vs. scale model vs. radiance model

SURFACE & MATERIAL	**Reflectance: REAL BUILDING**	**SCALE MODEL**	**RADIANCE**
Membrane	75%	72.33%	75%
Walls/ dark green card	8%	7.8%	8%
Wooden floor/pale pink paper	42.47%	39.26%	42%
Floor corridors, entrance/ beige card paper	47.29%	46.5%	47%
	Light Transmittance: REAL BUILD.	**SCALE MODEL**	**RADIANCE**
Glazing:		Correction factors:	
W1 (roof & single)	0.783	0.783	0.783
W2 (openable)	0.774	0.774	0.774
W3 (double)	0.657	0.657	0.657
PTFE membrane/ lycra fabric (2 layers)	16%	15.8%	16%

7.2.3.2 Discussion of results

The scale model of the Amenity building overestimated its lighting performance with a DF of 27.6%, presenting a divergence between the model and the real building measurements of 13%, which is fairly good when using physical models for lighting prediction. On the other hand, the Radiance simulation underestimated the building's performance with a DF of 18.5% and a relative error of –23%. Although the illuminance distribution in the building followed similar patterns between field measurements and Radiance model, it seems that once again the number of ambient bounces set was low stopping the calculation before it could take into account all significant inter-reflections causing an underestimation of illuminance levels.

Figures 7-9 and 7-10 illustrate the difference between results obtained with physical modelling, Radiance simulation and the readings taken in the existing building. These are presented across a longitudinal section through the centre of the playing area (Fig. 7-9), and section B-B' (see chapter five section 5.3.4). In both sections, the highest DF values are found in the middle grid points that appears logical due to the geometry of the roof with its concave shape and the symmetrical building blocks that surround the playing area.

However, results from scale modelling in Figure 7-9 show little difference between the central points and the points located at the boundaries of the section, in comparison with results from the field study and radiance simulations. This indicates that the buildings adjacent to the playing hall with low reflectance factors did not have much influence on the results obtained, probably due to the size of the sensors with respect to the physical model dimension.

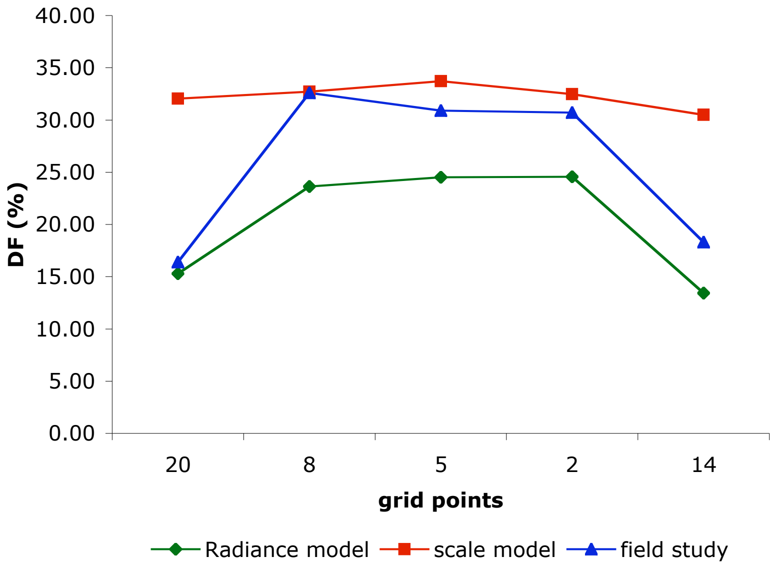

Fig. 7-9 Predicted and measured DF, comparison between Radiance simulation, scale model and field readings, across a long section of the playing hall.

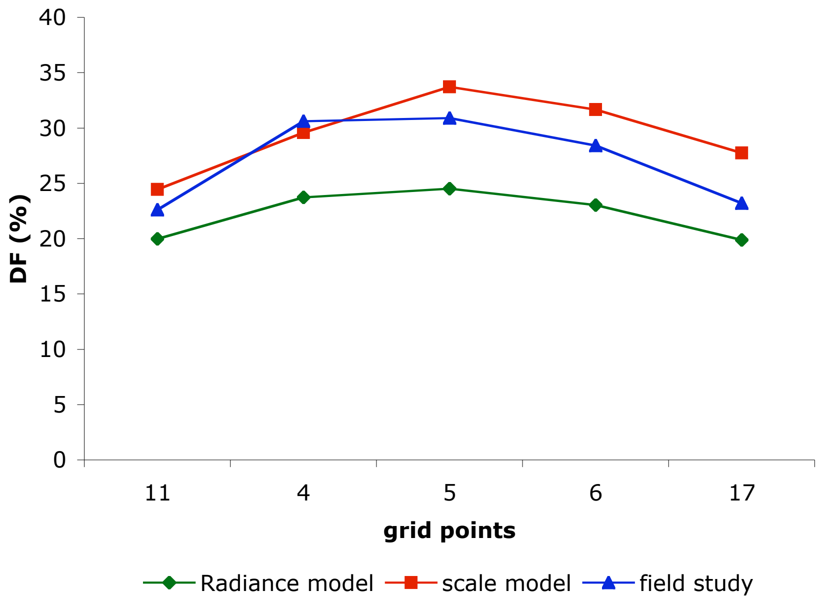

Fig. 7-10 Predicted and measured DF; comparison between Radiance simulation, scale model and field readings, across section B-B′.

The radiance model was recalculated for different –ab parameters, from 2 ambient bounces to 7 ambient bounces. Results show that calculation times did not vary much, only between eight and eleven minutes respectively. The average DFs obtained are: -ab=2, DF=18.53%; -ab=3, DF=21.51%; -ab=4, DF=22.70%; -ab=5, DF=22.84%; -ab=6, DF=22.98%; -ab=7, DF=22.98%. From these results and Figure 7-11 it is possible to see that the Radiance daylight factor calculations approximate to each other when setting –ab to six and seven ambient bounces; therefore, it is possible to say that six ambient bounces are enough to obtain more accurate results. With a DF of 22.98% the relative error between the radiance model and the field measurements are reduced to –4.25%.

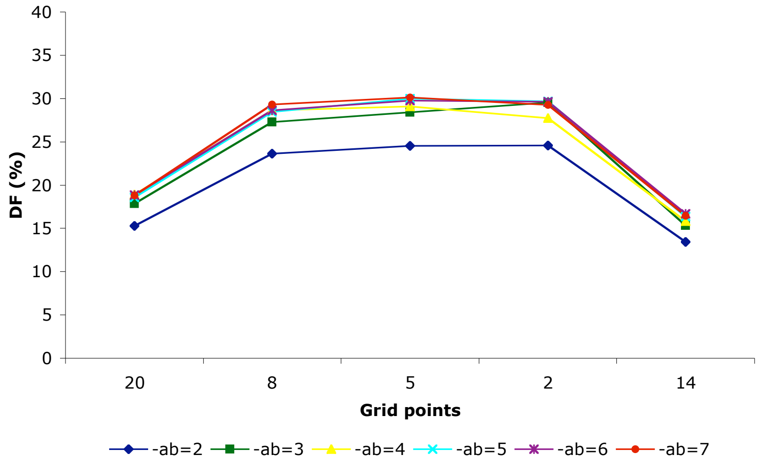

Fig. 7-11 DF% through one section of the IRAB for different –ab values

Table 7-6 shows the final daylight factors, illuminance uniformity ratios and relative errors obtained with the performance analysis of the existing building and the daylighting predictions carried out in this research.

Table 7-6 Comparison of DF, uniformity ratio and relative error of field measurements, scale modelling and computer simulation for case study 3.

BUILDING	**FIELD STUDY**		**SCALE MODEL**			**RADIANCE MODEL**		
	DF	UNIFORM. RATIO	DF	UNIFORM. RATIO	RER	DF	UNIFORM. RATIO	RER
Amenity Building (-ab=2)*	24%	0.29	27.6%	0.79	15%	18.5%	0.62	-23%
(-ab=6)*			26.7% ^	-	11%	22.9%	0.63	-4.25%

* -ab are the number of light ambient bounces set for Radiance calculations.
^ This figure resulted using a correction factor (3.18%) for sensor size error.

The following Figure shows a comparison between daylight factor contours maps obtained with measurements taken on site, and simulations with scale and Radiance models.

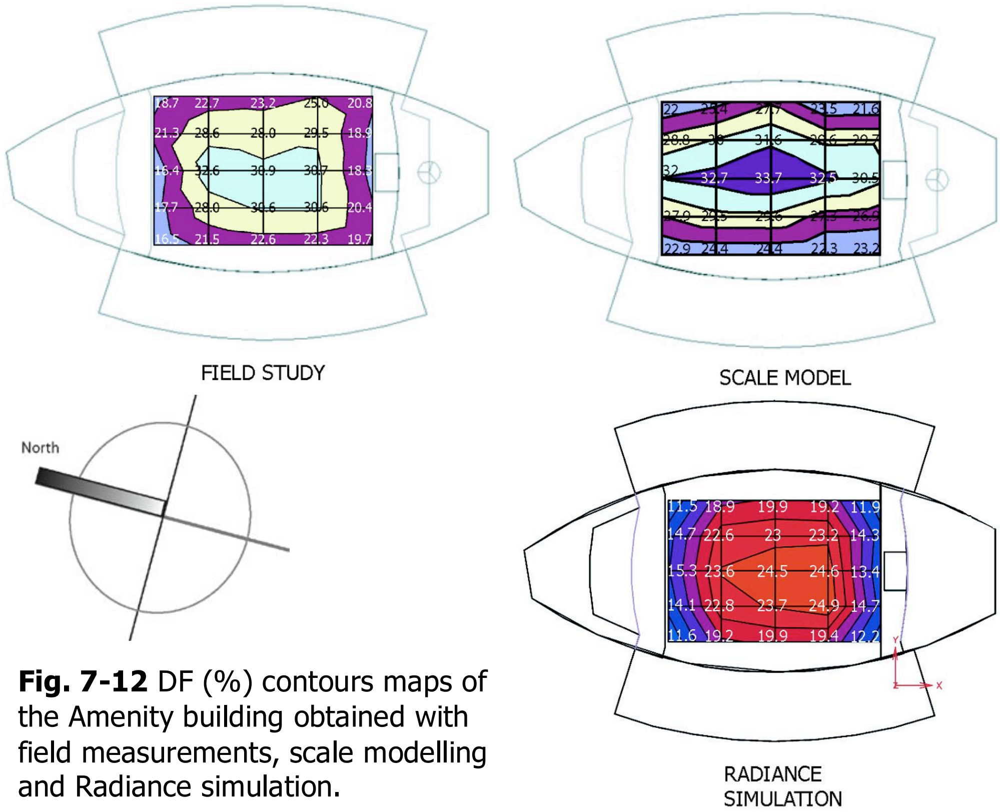

Fig. 7-12 DF (%) contours maps of the Amenity building obtained with field measurements, scale modelling and Radiance simulation.

In the three daylighting scenarios shown above the highest values are found in the centre of the building, decreasing towards the long sides. The field study measurements and Radiance results display a higher influence on the lighting maps of the building block that contains the crèche (opposite the main entrance: left side of plans), and the reception partitions and first floor corridor located above the reception area at the right side of the images. All these walls have low reflectance, which absorb daylight reflecting little light back into the playing area, producing an obvious decrement on illuminance levels at playing level.

The illuminance contours map originated from the scale modelling results does not seem to have taken into account the crèche building block and the reception, which were modelled, thus creating longer contours along the building. Again, this error could be caused by the small scale of the physical model in comparison with the size of the light sensors, but mainly due to the fact that the panel windows located on top of the crèche (closing this first floor creating a sitting area), were not modelled.

Although a glazing correction factor was applied to the physical model results, it seems that simulating the real window material with its transmission factor and exact location in the building, provides more accurate results.

7.2.4 Discussion

7.2.4.1 Field measurements

During the stage of field measurements developed for this investigation there were potential errors that made necessary to repeat the measurements several times in each building to have a consistent set of data. Some of these errors included changing sky conditions; because of this some measurements were discarded when clouds disappeared allowing the presence of clear skies.

Another potential error is the position of the light sensors; it was necessary to put some Velcro and blue tack to fix the sensors to the floor surface in a horizontal position. Some data presented non-expected results and it was deduced that some people were curious about the sensors and put themselves close to the equipment obstructing the light reaching the sensors.

A further source of errors during field measurements is changes made after construction to the building, including different space layout, extra rooms, different surface materials or colours, changes in geometry, and modifications to the natural and built contexts (trees, adjacent buildings). In addition, maintenance could be another potential error especially if the building evidently suffers from lack of maintenance. The accumulation of dirt can cause important alterations to the light transmittance of translucent or transparent materials, and although correction factors for dirt have been considered for the physical and computer models, it might be possible that those factors do not represent the reality of the case study building.

7.2.4.2 Physical modelling

In all three case studies physical models overestimated the buildings' lighting behaviour. This tendency of models has been previously acknowledge by some researchers; among them, Cannon-Brookes[3] has demonstrated the high sensitivity of the model's performance to small changes in the model's physical representation of the building. Errors pointed out by the author have also been detected in this study, among the most important are:

- **Accuracy of photometric properties.** The representation of reflectance and transmittance properties of surface materials was found to be extremely important for the performance of the models. Although several paper cards were tested to match the required reflectance properties and real surfaces' colours, the results showed that it is advisable to model surface materials using neutral colours such as different hues of grey, avoiding any influence of the materials' colours into their reflectance factors.
- **The small scales used to construct the models**. This was dependant on the size of the testing table and the dimension of the artificial sky; considering also that the case studies are large and complex buildings. Using small scales in the models means that less detail can be represented especially when modelling fenestration or structural elements. A compromise has to be done between the level of detail in the model and the investment required regarding time and cost of materials. In chapter five of this thesis, it was found that detail in the representation of fabric louvres in case study one did not represent a significant difference on the results obtained; unlike case study two where a 2% difference in daylight factor was found. It seems that smaller scale models, such as case study two, are more sensitive to dimensional and representation changes than larger scale models such as case study one.
- **Instrumentation**. The size and location of light sensors are important to obtain realistic results. An advisable sensor size for horizontal

illuminance measurements is when the sensor's head reaches a task plane height. If only one size of sensors is available then, they can be placed under the floors of the models letting sensors' heads come out through holes drilled on the floors' surfaces. A 3% error in the measurements was caused by sensors height in two models, and a 14% error was found in Lord's model. The calibration of sensors must be verified; for this investigation the calibration was tested under the artificial sky where three measurements were taken with all the six lux sensors located in the same position. A 5% difference was found between the readings taken under the artificial sky by the six sensors used in this study. Though they were calibrated by the manufacturers, there seems to be a slight difference caused by the calibration of the equipment.

- **Transmission characteristics of glazing and membranes**. The designers of the buildings and materials manufacturers provided the light transmission properties and thickness of the glazing used for windows and skylights (polycarbonate). In the case of the computer models each characteristic was attached to the actual surface; on the other hand, in the case of the physical scale models glazing was not modelled and the holes for the windows and openings were left open. Then, the results obtained were multiplied by a correction factor accounting for transmission losses due to glazing and dirt. According to the findings of this investigation, it is evident that using the real transmission characteristics of glazing during the lighting simulations provides more realistic results.

7.2.4.3 Radiance simulation

Radiance closely simulated the lighting environment of the Cricket school at Lord's Ground. However, the simulations of case studies two and three underestimated the real buildings' performance. Apparently, Radiance is a powerful lighting software very sensitive to ambient parameters set for the simulations as well as to photometric properties of materials.

After creating and running Radiance models and simulations it became evident that the default number of two ambient bounces had to be replaced by higher numbers for case study 2 and case study 3. These changes resulted in Radiance considering more light inter-reflections between surfaces making calculations more realistic and producing higher levels of illuminance in the buildings' interiors. Building 2 provided more accurate results with –ab=7 (number of ambient bounces), and building 3 with –ab=6.

Radiance simulations predicted accurate illuminance distributions proving that with the right settings, geometry and materials, Radiance can produce realistic calculations and images of daylit sports buildings with membranes used as daylighting control systems.

In the Radiance models the real reflectance factors of materials were attached to specific surfaces (walls, floors, etc) trying also to match the colour of each surface; though, for white surfaces Ecotect used a range of grey hues that looked rather dark at the moment of modelling the buildings, but provided good results in the calculations and images rendered by Radiance.

Two different daylighting simulation techniques have been evaluated against physical measurements taken in three existing buildings. Computer simulation using Radiance has proven to be a more accurate and reliable daylighting simulation tool of membrane sports buildings. Results presented in this thesis show that scale models overestimated by a factor of 2 the lighting performance of two very similar case studies. The physical model of the third case study best predicted the performance of the building. In this case the geometry of the physical model was very similar to the real building, all the building blocks were included in the model.

Based on the findings of this work, it can be said that scale models are an useful tool for being a three dimensional object that allows designers and clients to visualise the general lighting behaviour of the building, possible sources of glare, the building geometry and layout, and the effect of exterior obstructions on the lighting performance of the building. However, in order to obtain accurate lighting simulations using this tool, it is necessary to carefully construct the model following as close as possible the geometry of the building (checking for post-occupancy changes if the intention is to compare results with an existing building), materials reflectance, glazing type and transmittance and exterior obstructions if present. If lighting measurements and simulations are cautiously done within the model, then the resulting data can be helpful when analysed during the design stage of a building but not for making important design decisions.

When accurate results are needed for an architectural project in the final stages of design, or to persuade clients or building regulators about the daylighting performance of a sports membrane building, a computer model and daylighting simulation made with Radiance are advisable. If there are specialised human and technical resources on computer modelling and Radiance simulations available, accurate and relatively fast results can be expected. Photo realistic images can be produced with Radiance and changes to geometry or materials characteristics can be done quickly; however, simulation times depend on the accuracy of the calculations required and the ambient parameters set for the simulations. In order to simulate the lighting performance (obtaining illuminance or DF values) of the three case study buildings with their degree of complexity, it took approximately 30 minutes to run the lighting calculation in Ecotect for each model, and between 10 and 15 minutes each Radiance simulation. This calculation times are not too long allowing the researcher to try different parameters, output data or camera views.

Finally, both scale models and computer models with Radiance simulations created during this research work can be improved to provide more reliable results, converting these tools into accessible and common daylighting prediction techniques to be used by building researchers and designers. In order to achieve this, it would be necessary to follow a precise modelling and monitoring methodology. As a consequence of the experience acquired while developing the work presented in this thesis, possible improvements to the adopted methodology for daylighting simulation of sports membrane halls have been included in the following section.

7.3 POSSIBLE IMPROVEMENTS TO THE ADOPTED METHODOLOGY

Nowadays, the use of daylight in buildings is almost required in any architectural design due to the growing concern among people of the importance that saving as much energy as possible within the construction and operation of buildings has. Therefore, the development and use of daylighting simulation tools have become essential for building engineers and architects. Currently, there are many lighting simulation computer programmes with different characteristics and limitations.

During this research work, two widely used daylighting prediction tools have been evaluated: small scale modelling and Radiance ray tracing software. Results from both tools have been compared to a set of lighting information gathered through field measurements of three existing sports buildings that have incorporated fabric membranes as daylighting control systems.

This section aims to present improved researching and modelling methodologies, based on the methodology used to carry out this work and the results obtained. Together with recommendations to better use these simulation tools, they intend to help the designer or researcher to obtain more accurate and reliable results that could help extending the integration of natural light in buildings.

7.3.1 Field measurements

Daylighting assessment of existing buildings can have some advantages for the researcher or lighting designer, but it could also present some disadvantages or problems. In order to better face these possible problems, it is essential to be aware of them before starting the analysis.

When monitoring an existing building with the aim of modelling it and comparing results it is essential to consider that the building could have suffered changes throughout its operating life, mainly in its geometry, layout, finishing materials, lighting systems, and exterior obstructions (trees can have been planted after the construction of the building, or other buildings could have been built adjacent to the evaluated room or construction). It is therefore recommended to conduct a survey of the existing building checking for any possible discrepancies with the original drawings, and updating the information of the building.

The following points summarise the approach followed during this research work, which could ensure a more reliable and faster data gathering process.

1. Before starting any monitoring it is essential to test the lighting measuring equipment. This can be done under an artificial sky where light is constant.
2. A chronological programme of the measuring or monitoring process must consider extra time for any contingency, to corroborate readings taken or to complete a further study.
3. If the aim is to obtain daylight factors, it is necessary to take all readings under standard overcast sky conditions, preferably under a maximum exterior horizontal illuminance of 10,000 lux. Simultaneous measurements have to be taken inside and outside the building in an unobstructed area.
4. Record with photos or drawings any alteration made to the building after construction. This can include changes to structural elements, interior layout of the space, surface materials, glazing and surroundings (new buildings, vegetation, etc.). This is important if results are being compared with previous studies of the building, or with any lighting simulation tool.

5. If possible, it is advisable to integrate the survey/measuring team with at least two people making the process more reliable and faster to conduct.

The following figure is a diagrammatic representation of the adopted field measuring methodology.

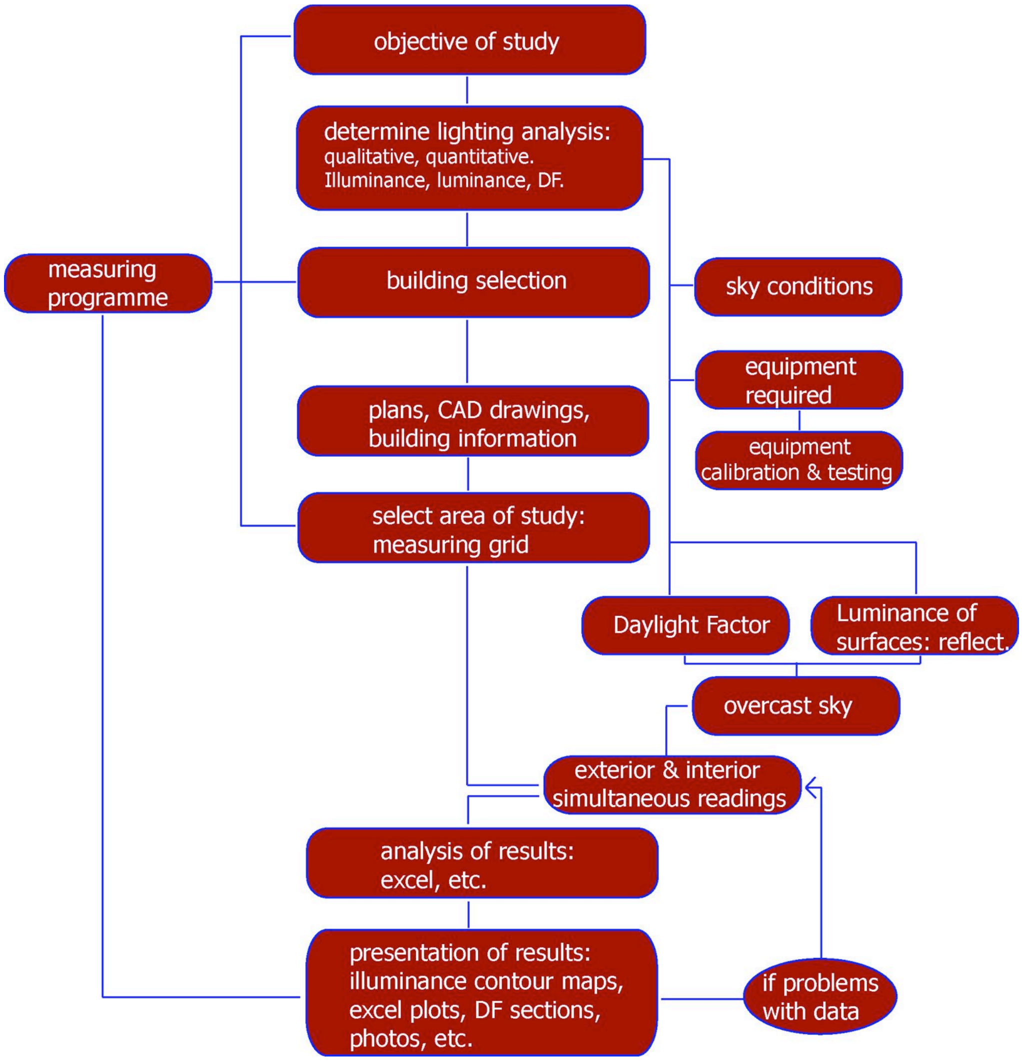

Fig. 7-13 Adopted methodology for field daylighting studies in real buildings

7.3.2 Scale modelling

Scale modelling is a common tool among architects, usually used during the design process, or for marketing purposes. Their use for lighting studies has been analysed for a long time[4] usually obtaining higher results than the real building's performance. However, scale models still have an advantage over computer simulations: their qualitative representation of space and light is in three dimensions, helping designers to understand the lighting performance of the space or the lighting systems in a faster and comprehensive way than looking at a flat screen.

The use of physical models to represent translucent membrane buildings is widely used due to the complexity of simulating these structures with computers. In addition, they make easier to understand the structural and aesthetics performance of these structures becoming an important aid during the design process. Still this tool has not been previously used to study the behaviour of daylight in this type of buildings.

Findings obtained in this work indicate that scale modelling can be a useful tool to simulate daylight distribution in sports membrane buildings, at least during the design process. However, it has been found that it is very difficult to obtain accurate lighting values using physical scale models of membrane buildings.

More precise results than the ones presented in this thesis can be achieved if some factors of the model construction process are improved. Improvements to the adopted methodology are pointed out in the following points together with the general methodology:

1. It is essential to test the equipment verifying its calibration and configuration before starting any simulation. This can be done under an artificial sky with uniform lighting conditions.
2. Information regarding the building to be modelled must include photographs and notes registering any type of changes occurred after construction, especially alterations in geometry or surface materials.
3. The selection of the scale to construct the model is based on different aspects, such as: dimension of the area of study, dimension of the artificial sky (if it is the case), size of light sensors. For large buildings a recommended scale is 1:20 or 1:50.
4. The location of the camera has to be selected according to specific views needed for the study.

5. The materials for constructing the model have to be opaque; these can be plywood, card, paper, cloth, etc. Reflectance of each material has to be measured with a luminance meter under an overcast sky; preferably using an artificial sky to ensure all materials are measured under the same lighting conditions. The selected materials have to match as close as possible the photometric properties of real materials. The use of materials with neutral colours is recommended to avoid any influence of colours on the reflectance of the surface.
6. It is advisable to obtain a sufficient amount of materials selected to construct the scale model, especially if unplanned modifications have to be made.
7. It is desirable to construct the full geometry of the building, including all interior spaces, structural elements, sculptural objects, adjacent buildings or vegetation.
8. Based on the analysis of the data obtained in the pilot study, changes of materials' reflectance or further detailing of the geometry (interior obstructions, furniture, etc.) of the model have to be undertaken.
9. A correction for glazing and dirt is applied to results when the windows are left open. Real transmittance factors of glazing can be used to lower error; however, if this information is not available, some authors have recommended correction factors according to the location of the building (non-industrial or dirty industrial areas), inclination of glazing (vertical, sloping, horizontal) and type of glazing (single, double or triple)[5,6,7]. Nonetheless, it is recommendable to always model glazing in windows or skylights with the real materials or at least with similar optical properties.

Figure 7-14 is a diagrammatic representation of the modelling process followed for this study.

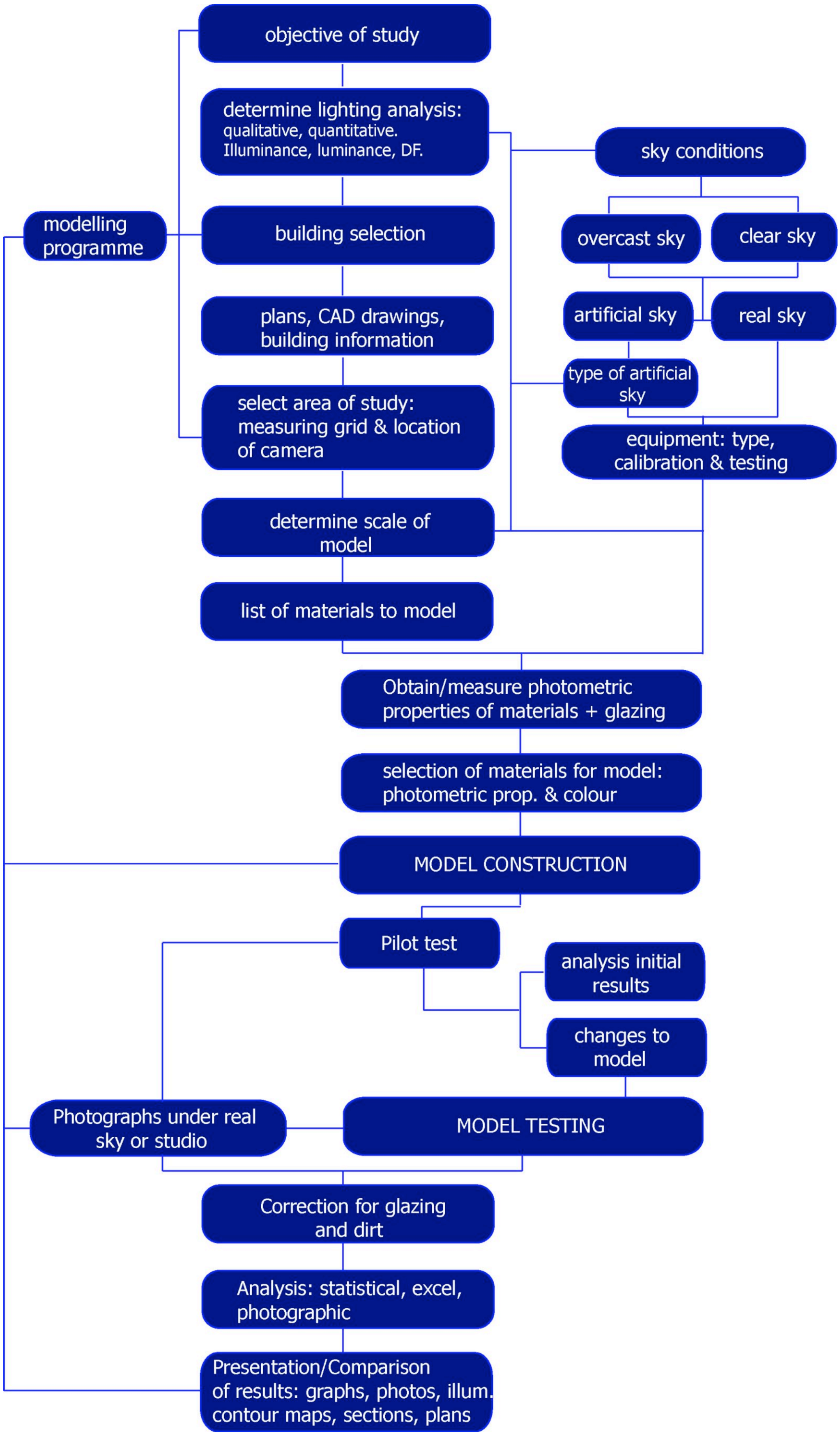

Fig. 7-14 Adopted methodology for scale modelling

7.3.3 Computer modelling

The development and expanding use of lighting simulation software has allowed researchers and designers to simulate the lighting performance of complex buildings in little time and with the possibility of making quick changes allowing, for instance, to test different innovative daylighting control systems. However, becoming an expert using such kind of software (like Radiance) is a hard and time-consuming task. These computer packages usually require a detailed and accurate representation of the building geometry, photometric properties of materials and appropriate settings in order to obtain correct data from these simulations.

Some advantages and limitations of using computer modelling for daylighting simulation of sports membrane buildings are mentioned in the following points.

- Nowadays, it is likely that the designers have 3D CAD models of the building. If these are available for the lighting simulation, then an important part of the computer modelling is already done.
- Once having a 3D model, it is easy to make changes to geometry.
- Using CAD software allows the designer or researcher to simulate complex buildings and daylighting systems. Usually, lighting simulation packages can support AutoCad drawings.
- Materials' photometric properties can be attached and changed easily, providing the possibility of testing their accuracy.
- Software such as Radiance can offer photorealistic images, which can be used to carry out a qualitative analysis of the evaluated building.
- Illuminance and Daylight Factor contour maps can be output from the software.

Some limitations of daylighting computer simulations include:

- The time and effort of learning the software can be exhaustive; taking several months before some coherent results are drawn. Because Radiance, for instance, is continuously developing and constantly improved by its creators and users, it also means that there are always different ways of simulating daylit buildings. Therefore, manuals do not always have the solution to specific problems. Internet discussion groups have been established to support users of this software.

- Although Desktop Radiance is freely available on the Internet, its installation requires having AutoCad already installed, and sometimes the installation is not a straightforward process. Therefore, previous computer knowledge is required for installing and using this software.
- The output obtained with lighting simulation software is only possible to see it on a flat screen, never in real three-dimensional volumes. This makes visualisation a limited process, where lighting designers have to use some imagination to appreciate the results.
- Radiance is very sensitive to ambient parameters. These parameters have to be carefully selected if accurate results are desired. In order to achieve this, a simulation has to be run several times trying different parameters and once the results are stable then those parameters are probably appropriate. Setting ambient parameters depends on the desired calculation accuracy and time.
- Some simulations can take several minutes or hours depending on the computer characteristics and the simulation settings.

Despite of the disadvantages mentioned above, computer modelling for daylighting analysis is a useful tool for assessing daylighting performance of complex buildings, such as tensile membrane structures. The fact that translucent materials can be modelled and recognised as such by the software, makes an enormous advantage when modelling fabrics and membrane buildings.

The adopted computer simulation methodology is presented in Figure 7-15. The following points are fundamental to consider when creating a model for daylighting simulation:

1. If the case study is an existing building, a survey will be essential to register changes made to the building after construction and during its lifetime. These changes can include interior divisions, adjacent buildings or extensions, furniture, different surface materials or colours,

fenestration type or glazing, different use of the spaces, and different surroundings (trees, other buildings).

2. The location of cameras must match the physical modelling and/or field study's views, if a comparative analysis is to be developed.
3. Then, materials' photometric properties are attached to the layers created. Translucent materials are best simulated by Radiance if the material is created especially for that software. This can be done as explained in chapter six, creating the material in a *.rad file. However, it is also possible to create all materials following Radiance's *plastic* material type for opaque surfaces. Whether is more convenient to use Radiance materials or Ecotect materials is beyond the findings of this work, but a further study on this topic would be a valuable contribution for future research projects.

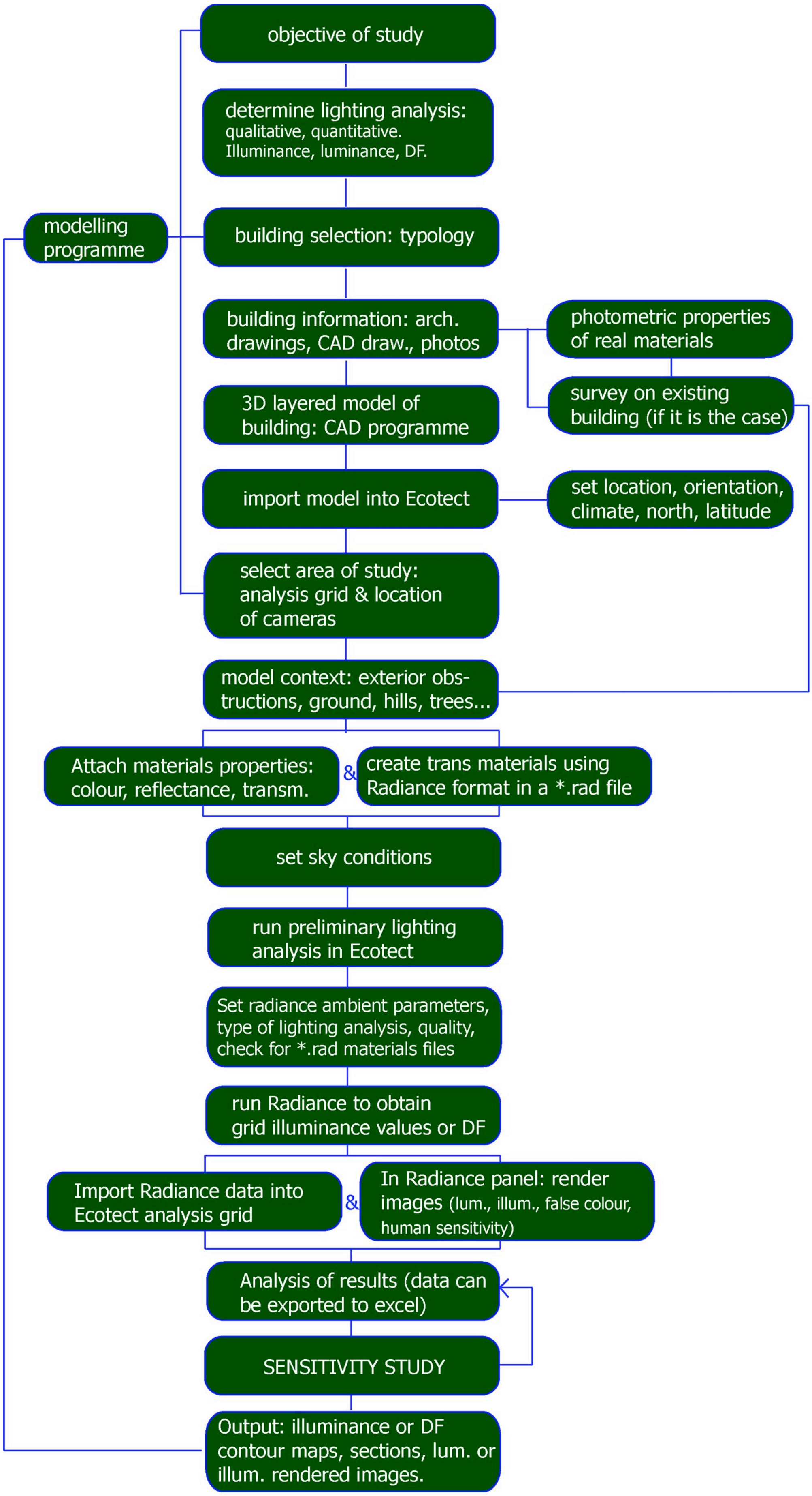

Fig. 7-15 Adopted methodology for daylighting computer simulation

7.4 DAYLIGHTING IN SPORTS BUILDINGS

Lighting design in enclosed sports buildings have always been a major concern of designers, clients and users. Good performance of any sport practiced indoors greatly depends on the lighting environment. Some sports such as cricket or tennis need high and uniform levels of light in the building so players can practice properly. The fast speed and small size of the balls can make difficult for players to follow the action, and sometimes could also be dangerous if a ball travelling at 90Mph, in the case of cricket, hits a player.

In northern latitudes cold weather conditions oblige some sports to be played or practiced indoors. Traditionally, sports buildings were designed with artificial lighting systems only allowing designers and managers to control the interior lighting environment. This fact plus the high levels of light constantly required have made sports halls highly energy consuming buildings during their operational life. Every year the UK's sports sector buildings spend £700 million on energy, resulting in huge annual emissions of carbon dioxide contributing to climate change[8].

During the past decade growing environmental concern has turn architects and building designers into researching for new methods of reducing energy consumption in buildings while still fulfilling their lighting requirements. A common way of doing this is introducing natural light into buildings, while reducing their electrical lighting consumption and creating a more natural and comfortable interior environment. Controlling daylight inside a building can be a difficult task; problems of overheating, glare, veiling reflections, etc., may arise. Nonetheless, saving energy and providing a comfortable environment are obviously worthwhile.

In addition, extensive studies have demonstrated the importance of providing daylight and outside views in buildings[9,10]. These factors can provide higher work productivity and comfort of occupants. Research has shown that people prefer daylight to artificial light because of its variability, which together with variable luminances in the field of view make the space bright, radiant and visually warm[11].

The following Table shows comparative figures of electricity consumption of the case study buildings plus the electrical consumption of the University of Nottingham Sports Centre, which is a completely closed building lit with artificial lighting only. Basketball, volleyball, cricket, badminton, netball, trampoline and aerobics are sports practiced in that building.

Table 7-7 Energy use in sports buildings

	Indoor Cricket School, Lord's	**National Cricket Academy**	**Amenity Building, Inland Revenue Centre**	**Sports Centre, Nottingham University**	**BRECSU typical^**	**BRECSU good practice^**
Building area (m^2)	2,664	3,115	3,000	2,739	1,400	1,400
Annual consumption (£)	7,820	3,710.7	32,828.7	27,775.72	12894	7,126
Electricity Rates for business (p/kWh)*	6.97	6.97	6.97	6.97	-	-
kWh/year	112,195.12	53,238.16	471,000	398,318	147,000	89,600
kWh/m^2/ year	**42.12**	**17.09**	**157** predicted in IRC: 94	**145.42**	**105**	**64**
Electricity cost (£/m^2)	2.94	1.19	10.94	10.14	9.21	5.09
Lighting approach	Daylit	Daylit	Daylit	Artificially lit		
	GOOD	**FAIR**	**POOR**			
Annual energy use◊	**<75**	**75-85**	**>85**	kWh/m^2/year		

(1) *Information supplied in April 2005 by London Energy, Business Team ADMAIL 1025, London, WC1V 6LA.

(2) ^ Type 1 building: Local dry sports centre. Energy Consumption Guide No. 78 'Energy use in Sports and Recreation buildings', Best Practice Programme, pp. 18, 19. Available at http://www.energy-efficiency.gov.uk

Note: Data of case studies 1, 2 and the University of Nottingham Sports Centre was obtained from the buildings' managers. Data of the Amenity Building was obtained from M. Hopkins & Partners office, and it corresponds to figures of the whole Inland Revenue Centre; therefore, the energy use of the Amenity building alone may vary, but it was not available from the designers or the building manager.

(3) ◊ From: "Sports facility without a pool. Energy Consumption Guide No. 51, Energy Efficiency in Sports and Recreation buildings: a guide for owners and energy managers". Best Practice Programme, p. 2. Available at http://www.energy-efficiency.gov.uk

From Table 7-7 it is possible to see that the two cricket schools are good practice buildings according to their annual energy consumption, and particularly in the National Cricket Academy the designers achieved to create a low energy building. This cricket hall is the best performing building in energy terms and compared with Lord's building provides better daylighting conditions (both quantitatively and qualitatively); it is obvious that the designers have learnt from their early experience designing Lord's Indoor Cricket School.

The operation of buildings is also important to save energy. For instance, artificial lighting in the cricket schools is turned on only when it is needed and players have to ask for it if they feel they need more light. In addition, the layout of these buildings also help to use electric light as less as possible since the playing areas are divided into different playing lanes, which could be not all of them in use at the same time, therefore, it is possible to turn on only the lamps necessary to lit one lane while the other lamps stay off.

It is possible then, to conclude that daylighting sports buildings can be designed and operated in such a way that the interior lighting environment is controlled and light levels are high enough to play sports at amateur and professional level while saving energy. The use of membrane structures is a good alternative to control daylight access efficiently and aesthetically offering many design possibilities to architects and sports associations. Nonetheless, care must be taken when designing with such environmentally sensitive materials in order to avoid excessive heat loss in winter (increasing the energy consumption of the building by using heating systems), and overheating in summer. In summary, other environmental design aspects, apart from lighting, have to be considered for the efficient design of sports buildings in terms of energy savings, functionality and users' comfort.

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7.5.1 Figures and tables

Eight

8. POST-OCCUPANCY EVALUATION STUDY: USERS' RESPONSE

8.1 INTRODUCTION

The main objective of post occupancy evaluation (POE) studies in buildings is to systematically assess their performance once they have been occupied and used. One type of POE methodology is to obtain subjective reporting by the occupants, where they have to evaluate whether the building's environment is comfortable and suitable for the activities they perform. In order to carry out a POE study of the three daylighting case study buildings analysed in this thesis, a questionnaire has been designed to collect the responses of the buildings' occupants.

The evaluated buildings include the Amenity Building of the Inland Revenue Centre in Nottingham (IRAB), the National Cricket Academy in Loughborough, and the Indoor Cricket School at Lord's Ground in London. The common features of these buildings are their function, sports centres, and their innovative environmental approach maximising the use of natural light.

In addition, a similar questionnaire was distributed among users of the University of Nottingham Sports Centre. This is a completely enclosed building totally illuminated with artificial lighting. Results from this survey are compared with the responses obtained in daylit sports halls.

Daylighting performance of buildings can be determined under two different approaches: quantitative measurements of daylight levels and quality of daylight. According to Fontoynont[1] there are two main differences between the performance of daylighting and artificial lighting systems: natural light is variable, it continuously changes in colour and intensity; and the attractiveness of views towards the outside, which tends to produce higher users acceptance even under low luminous environments than with artificial lighting systems. This has also been pointed out by Baker[2], people tend to tolerate much lower illuminance levels of daylight than artificial light, especially under diminishing daylight conditions when people continue to read at levels as low as 50 lux.

Several authors have mentioned daylight quality as an important factor when assessing daylighting systems and user preferences. Fontoynont[1] has mentioned that occupants perceive daylight quality in a room through a mixed sensation: daylight is expected to fulfil required illuminance levels at task, without generating glare; and they also expect the space to be 'visually' agreeable.

Nabil and Mardaljevic[3] have summarised the findings of several authors regarding occupant preferences and behaviour in the following points.

1. Daylight illuminance values of less than 100 lux are generally considered insufficient to be either the only light source or to contribute significantly to artificial lighting;
2. Daylight illuminance between 100-500 lux is considered effective;
3. Daylight illuminances between 500-2000 lux are perceived as desirable or at least tolerable;
4. Daylight illuminance levels higher than 2000 lux are likely to produce visual and thermal discomfort.

The above points are based on studies mainly carried out in office spaces where task planes are not very big and usually minimum illuminance levels of 500 lux are required, which is not always the case in sports buildings because the task plane usually comprises a large area and higher illuminance levels. However, this information provides a general view of user preferences towards daylight.

Parpairi et al[4] have mentioned the lack of field studies where user preferences in relation to real sky, weather and working conditions are recorded. The authors assessed how daylighting quality affects the users of a space. This research was conducted in three daylit libraries in Cambridge, where 26 students in each library were asked to record their feelings of the space through a questionnaire while local daylighting conditions were simultaneously monitored. The authors concluded that several parameters affect daylighting quality; these can be divided into three sections: quantifiable parameters, architectural parameters and personal parameters. A schematic representation of the parameters is presented below.

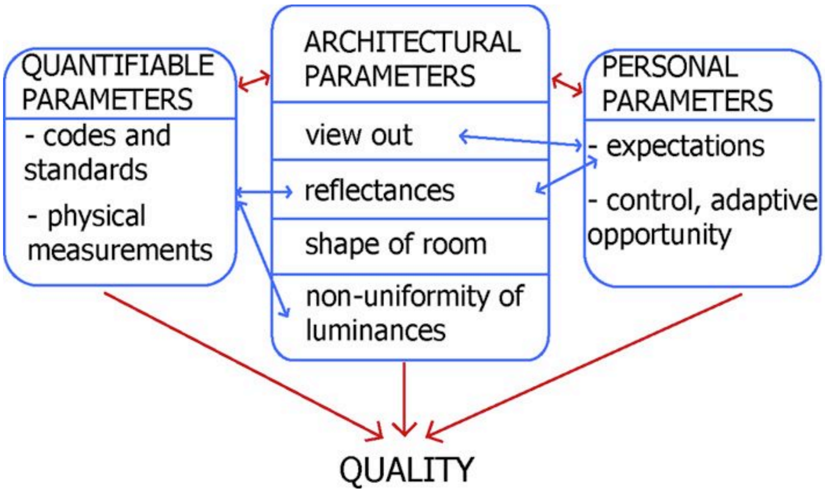


Fig. 8-1 Schematic representation of parameters affecting daylight quality (reproduced from Parpairi et al, 2000)

Furthermore, Velds[5] carried out a user acceptance study to evaluate discomfort glare in daylit rooms. The author recorded the views of 23 participants towards discomfort glare from windows while they were working at a horizontal task and with a computer, using an electronic questionnaire. An identical testing room was used to monitor vertical illuminance. Participants were asked to record luminance levels while answering the questionnaire. Velds concluded that minimum required quantities to monitor visual comfort under intermediate or overcast sky conditions are vertical illuminances or average sky luminances. In addition to taking those measurements in real buildings, the author suggested the use of a questionnaire installed at the user's own computer in order to obtain subjective evaluation of visual comfort in field studies.

Unfortunately, carrying out that kind of study in existing sports halls is not feasible. Users of sports buildings rarely stay in the building more than the time they spend playing (an average of two hours per day approximately); they usually play, get changed and leave the building. Due to the limited playing space of these buildings, they usually work with a booking system; consequently people have only certain period of time to play. Because of this system it was difficult to directly approach the occupants asking them to spend ten minutes of their time answering a questionnaire or responding to an interview. In addition to this, the buildings' managers were reluctant to allow the researcher to stay for long periods of time inside the buildings trying to get some questionnaires answered (except for the Sports Centre of the University of Nottingham where the only restriction was the short time students spend in the building). The most viable possibility was to design a questionnaire leaving several copies of it in the buildings' entrances or with the managers so users could take one and return it at the end of their playing session. Therefore, it was not possible to record the lighting conditions when each questionnaire was answered.

A basic questionnaire was designed, then additional questions were included and some changed according to the different features of the case studies that were part of the evaluation. In addition, the questionnaires were also adapted according to the sport practiced in each building. The questionnaire applied in the Sports Centre of the University of Nottingham had some questions removed due to the lack of daylight coming inside the playing areas. A copy of the basic questionnaire can be found in the appendix of this thesis.

8.2 BRIEF DESCRIPTION OF THE BUILDINGS

8.2.1 Building 1

The first building is the Indoor Cricket School at Lord's Ground in London. It was completed in July 1995. The innovative design of the MCC Indoor School includes the use of natural daylight achieving uniform lighting. The architect tried to reduce the amount of artificial lighting needed to illuminate an indoor cricket centre. The building was oriented in a way that allowed glazed areas to take advantage of the uniform lighting conditions from the northeast. This orientation avoids the evening sunlight available during the summertime. The roof of the cricket school is formed from a series of aluminium-clad vaults with half of them facing north containing a double-glazed transparent polycarbonate unit.

The lighting solution allowed maximum penetration of daylight. Sunlight penetration is diffused by a series of curved fabric (acrylic coated polyester) blinds located beneath the glazing and fixed to the main steel structure. Essentially the fabric louvres avoid the penetration of direct sunshine into the playing area.

8.2.2 Building 2

The National Cricket Academy is located in the campus of the University of Loughborough. It was designed by David Morley Architects and opened to the public in October 2003. The building includes an area of 70m by 25m: six lanes of playing area, fitness centre, changing rooms, office accommodation for the National Academy staff, a performance analysis suite, seminar rooms, bar and viewing balcony.

The lighting objective in this construction was to achieve a minimum of 1500 lux in the playing area. The design has included a combination of both natural and artificial lighting. The fabric louvres designed for the National Cricket Academy are made of polyester and were tensioned with steel battens and brackets located at one end of each section. This solution tends to diffuse daylight creating a steady lighting environment, which is necessary to play cricket.

8.2.3 Building 3

The Amenity Building of the Inland Revenue Centre was designed by architects Michael Hopkins and Partners in 1994; and Ove Arup & Partners designed the structural solution for the building. The architectural project aimed to be a green ecological design with maximum use of natural ventilation and light, suitable for construction in a short period of time.

The amenity building contains the staff restaurant, a nursery and sports facilities, which are located at the centre of the complex. The building is closed at one end by the reception area and on the other by a crèche; both sides of the building are fully glazed. The amenity building is covered by a PTFE coated glass fibre membrane, which is separated into two different levels enhancing all the activities that take place in the building, one encloses the sports hall and the other covers the cafeteria and gym areas located at both sides of the sports area. The main roof form is generated by four elliptical glazed ladder trusses located at the top of the membrane. These trusses provide a combination of diffuse and direct light captured from the sky[6,7]. The sports practised in this building include: badminton, basketball, volleyball and five-a-side football; all of them at amateur level.

8.2.4 Building 4

The Sports Centre of the University of Nottingham is located on the University Park Campus in Nottingham. The building was constructed in 1969, and provides shelter for a variety of sports practised there, including: badminton, basketball, cricket, netball, trampoline and aerobics. The building is part of a complex that also includes squash courts, gym and swimming pool. The sports centre is completely closed, there are no windows to the outside, and it is illuminated only with electric lighting. The lighting objective is to maintain 400 lux on the playing area. The building is divided into a large hall (35m x 38m) with 42 lamps, a small hall (35m x 19m) with 24 lamps, and lower and upper practise rooms (12m x 12m each). The operation time of the building is from 7am to 11pm.

The following Figures are interior views of the four buildings where questionnaires were distributed.

Fig. 8-2 Interior views of case studies
Fig. 8-2a IRAB, Nottingham **Fig. 8-2b** National Cricket Academy
Fig. 8-2c Cricket School, Lord's **Fig. 8-2d** Sports Centre, Nottingham Univ.

Table 8-1 illustrates the main characteristics of each case study and their lighting approach.

Table 8-1 Case studies' features

BUILDING	BUILDING FUNCTION	PARTICULAR FEATURES	LIGHTING APPROACH
B1. Indoor Cricket School, Lord's Ground, London.	Cricket practice (professional level)	Vaulted roof: transparent Polycarbonate + opaque aluminium. Interior fabric louvres.	- Diffuse daylight penetration, - Uniform light levels - High lighting levels
B2. National Cricket Academy, Loughborough.	Cricket practice (professional level)	Inverted 'V' shape vaulted roof: transparent Polycarbonate + opaque aluminium. Interior fabric louvres.	- Diffuse daylight penetration, - Uniform light levels - High lighting levels
B3. Amenity Building, Inland Revenue Centre. Nottingham	Sports Centre (amateur level) + gym, nursery, and cafeteria.	Main structural roof: Tensile membrane structure + glazed trusses.	- Combination of direct and diffuse daylight.
B4. The University of Nottingham Sports Centre	Sports Centre (basketball, badminton, cricket, etc.)	Brick building with no openings to the exterior	- Completely enclosed building: only artificial lighting.

8.3 METHODOLOGY OF THE POE STUDY

The post-occupancy evaluation study carried out within this research project has been developed as a complement to the analysis made of the daylit sports halls and their lighting performance, included in chapters three to seven of this thesis.

POE studies generally aim to evaluate the environmental performance of buildings once they have been occupied, in order to assess environmental control systems, usage of the building and satisfaction of its occupants. POE studies can be divided into different categories[8]:

- Objective observations of the physical environment
- Objective observations of the occupant behaviour
- Subjective reporting by the occupant

Physical measurements were taken in the buildings recording illuminance levels and reflectance of surface materials. It has been found that buildings 1, 2 and 3 are mainly daylit sports halls; while building 4 is completely artificially lit. Illuminance measurements were recorded in 32 points across the main hall of building 4, and an average of 327 lux was obtained. This hall is eventually divided into two areas to allow people to play different sports at the same time; the division is made with a huge dark blue curtain that cuts the space into two sections, and it probably reduces the amount of light in the playing areas.

Since buildings are designed for people, it is very important to achieve a level of satisfaction and acceptance of the user towards the building. For instance, when designing energy efficient buildings with innovative daylighting systems, the user has to experience them as efficient and useful systems in order to accept the building. Therefore, it is essential to know the attitude of occupants towards the architectural design, functionality and interior environment of the building, if one wishes to evaluate it integrally. This can be done through a subjective report by the users.

A questionnaire was the selected method used in this study to collect subjective responses from the occupants. The method was chosen based on the type of occupancy of sports buildings where users spend just enough time to play (one or two hours per session), and usually this time is regulated by their coaches in the case of the cricket buildings. In addition, as it was mentioned before, the managers of the buildings (except building 4) were reluctant to allow the researcher to approach the users directly. Therefore, it was decided to design a questionnaire leaving several copies of it at the entrance of the buildings, and with the managers and coaches, so the occupants could answer it when best suited them.

A between-person design of POE study[9] was carried out due to the impossibility of having the same group of people using all four buildings because of the distance between case studies, the different sports practised in those buildings and the fact that only members of each building are allowed to use them.

8.3.1 Questionnaire Aims

The main aim of this POE study is to obtain the users' perception towards the interior environment, particularly the lighting environment of the buildings and its performance over time. The intention of this is to have a reasonable picture of the environmental conditions in the building and the daylighting systems performance during different periods of time, trying to avoid any influence on the users opinion by the conditions at the time of answering the questionnaire. In addition, it was also aimed at investigating the influence of the lighting environment on users' performance and mood in sports halls.

Other objectives are:

- To identify users' perception of environmental factors in indoor spaces
- To analyse the impact of daylight on people's mood and playing performance
- To explore how users perceive aesthetically fabric membranes as part of the interior environment of the building
- To obtain users lighting preferences in sports halls

- The overall comfort or acceptability of the environment from users' point of view in relation to the activities they perform.

As Parpairi et al[10] have pointed out, with this type of survey it was expected to know the level of satisfaction that users experience with the daylighting environment as a whole, without asking them to determine specific lighting conditions that find acceptable or intolerable, since they are not lighting experts.

8.3.2 Questionnaire design

Although the questionnaire designed for this study is mainly focused on the lighting (and daylighting) performance of sports buildings, in order to have a more holistic approach towards the effect of the presence of (or lack of) daylight in the space, questions regarding the physical environment as a whole were included. Ventilation, temperature, colour of finishing materials and noise are aspects of the environment that were evaluated by the buildings users.

The questionnaire has been designed based on a survey of questionnaires for users' subjective responses regarding environmental aspects of buildings: the questionnaire designed for the Daylight Europe Project[9], and a questionnaire for daylight evaluation proposed by Baker and Steemers[11]. The questionnaire has 39 questions including some fixed-choice questions, and some attitude scales with a Likert-type scale[12].

Variables

The different variables present in this study are the following:

- Building, sport practised in the building, perception of the quality of the lighting environment, environmental factors that influence playing performance, participants' mood, participants' playing performance, and presence of glare.

Type of questions

The questionnaire was divided into three sections:

1. **General information and playing experience:** gender, age, occupation, and eyesight condition. Experience as sports players and

type of venue where they have practised before (indoor or outdoor venues); and frequency of use.

2. **Environmental perception:** main environmental factors that according to the user have to be taken into consideration when designing Sports Centres in order to provide comfort. The participants are asked to choose between ventilation, lighting, temperature, acoustics, colour of surfaces, etc. They also have to answer questions related to sunlight, daylight presence, building preference (windowed or closed), and the interior environment of the buildings.
3. **Level of satisfaction regarding:**
   - The building's visual environment.
   - Light amount and quality.
   - Adaptive behaviour. How occupants cope with individual problems. Their behaviour aimed at improving the environment and how they feel about the situation.
   - Occupants' preference regarding: type of light, the presence of daylight and glare.

Participants are also asked about how the environment in the building influences their mood and their playing performance. In addition, questions regarding the users' perception of the fabric membranes and their purpose were also included in the questionnaire; together with the use of electric lighting in these buildings and a general impression of their architectural design.

8.4 USERS SURVEY: RESPONSES

8.4.1 Characteristics of the respondents

Although there are three types of people who use the buildings in different ways: sport players and instructors, administrative staff and visitors/spectators; the only areas covered by fabric membranes (buildings 1,2 and 3) are the playing courts which are generally used by players and instructors. A total of 101 questionnaires were answered: 12 from the IRAB, 16 from the Indoor School at Lord's Ground, 16 from the National Cricket

Academy in Loughborough and 57 from the Sports Centre of Nottingham University. Among the participants 51 were male and 40 female, from which 80% of the women belonged to the Sports Centre of the University of Nottingham. Moreover, 17 participants are members of the English and Welsh Cricket Board (ECB), while the rest are staff, cricket instructors, members of the MCC at Lord's Ground, amateur players, students and visitors.

Most of the respondents' ages varied between 16 and 21 years old (60%), followed by people between 22 and 35 years old (23%).

All participants were users of the evaluated buildings at least during a period of six months prior to the moment of answering the questionnaires.

8.4.2 Analysis of the information obtained

The analysis of the answered questionnaires was carried out using the Statistical Software SPSS v.12.0.1, which allowed us to carry out a non-parametric analysis of the data and some frequency figures. However, some of the questions regarding users' satisfaction towards the lighting environment, the architectural design and how occupants respond to problems in the buildings were open questions. Hence, responses from these questions will be mainly presented as notes and comments from the researcher based on the answers provided by the occupants of the four case studies.

Section 1 General information and playing experience

The following Table shows results regarding participants' training experience in the sport practised in the building and type of venue where they have practised before.

Table 8-2 Sports experience and type of former sport centre.

Experience	**< 5 years**	**> 5 years**
Participants response	26%	72%
Sport venue	**Indoor**	**Outdoor**
Participants response	66%	32%

Although the age of the majority of participants ranges between 16 and 35 years old, their experience as sports players is quite extensive, most of them answered more than five years. The question regarding the type of venue where they have practised before shows a bigger number of people practising in indoors sport centres; this is probably because of the wet and cold winters in the UK and the extended usage hours that these type of venues provide during evening-night times.

Even though users of building 4 practise a large variety of sports, the questionnaire was distributed among the people who play the same sports as in the other three buildings. Nevertheless, the sports practised by the respondents varied among the following: basketball, cricket, badminton, netball, softball, football, karate, circuit training and trampoline. Along with these sports, badminton, basketball and cricket are the sports played by 73% of participants.

Section 2 Environmental perception

Building users were asked to rank in order of importance a series of environmental factors that they feel should be considered when designing a sports hall. The Kendall coefficient of concordance W was used to test the significance of the results and the degree of agreement among the participants in their judgements[13]. The obtained W value is 0.219, which was compared with the average value of the Spearman rank-order correlation coefficients,

$$ave(rs)= 0.21$$

In order to test the significance of W, a table of critical values of the chi-square distribution was used[14]. Here the distribution of W under Ho (which is the assumption that the set of rankings are independent) has been worked out, and equation 8.1 determined chi square with N-1 degrees of freedom and then determining the probability associated with as large a value of X^2 by referring to the table. This will show the probability associated with the occurrence when Ho is true of any value as large as W.

$$X^2= k(N-1)\ W; \qquad (8.1)$$

Where k is the number of sets of rankings (101)

N is the number of objects or factors being ranked (6)

Then, X^2= 110.59 and referring to Appendix Table C from Siegel and Castellan[14], we find that $X^2 \geq 110.59$ with df= N-1= 6-1=5, has probability of occurrence under Ho of $p< 0.001$. Therefore, it can be concluded with confidence that the agreement among the 101 respondents is high and this very low probability under Ho associated with the value of W allows us to reject the null hypothesis that participants' ratings are unrelated to each other. We can conclude that there is a significant correlation among respondents concerning the environmental factors that have to be considered when designing indoor sports halls, even though the value of W is a weak coefficient in this case.

A summary of the results obtained is shown in Figure 8-3, illustrating the most and least important factors that influence the performance of sports halls.

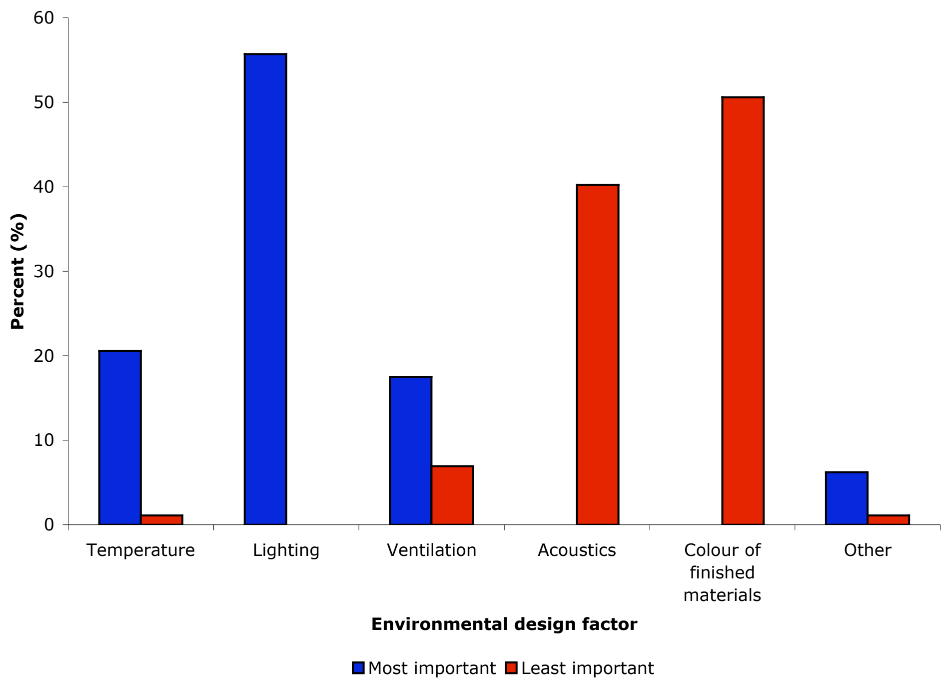


Fig. 8-3 Most and least important factors of the environmental design of sports halls

According to users' responses lighting is the most important design factor of the interior environment in all four buildings, 55% of respondents ranked it on first place followed by temperature ranked by 20% of the participants as the first most important factor. It seems important to mention that all the people who ranked 'other' as the most important design factor specified 'other' as floor surface quality.

On the other hand, the colour of finished materials and acoustics are the least environmental design factors in sports buildings according to users of the four case studies.

Figure 8-4 illustrates the amount of people separated by sport and building who think lighting is the most important environmental design factor. From a total of 31 respondents who play cricket, 28 believe lighting is the most important design factor, and from a total of 24 badminton players, 16 ranked lighting again as the most important environmental design factor. This information indicates that users' perception of the importance of environmental factors is determined by the requirements of the sport they practise.

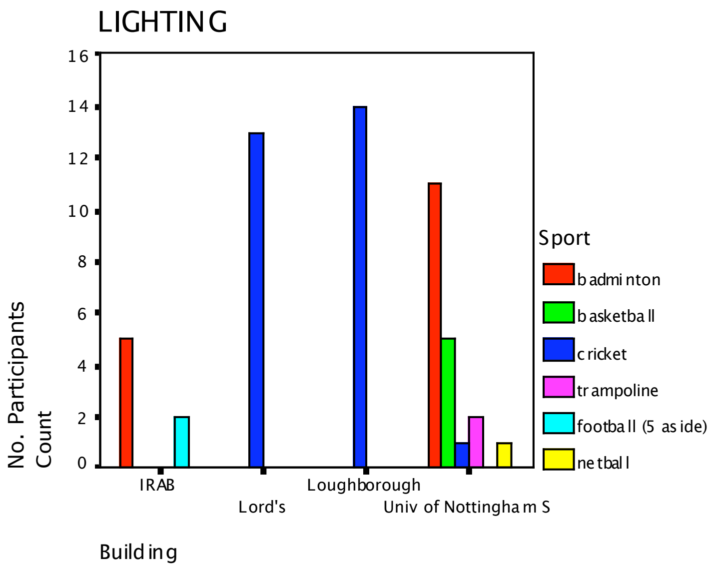


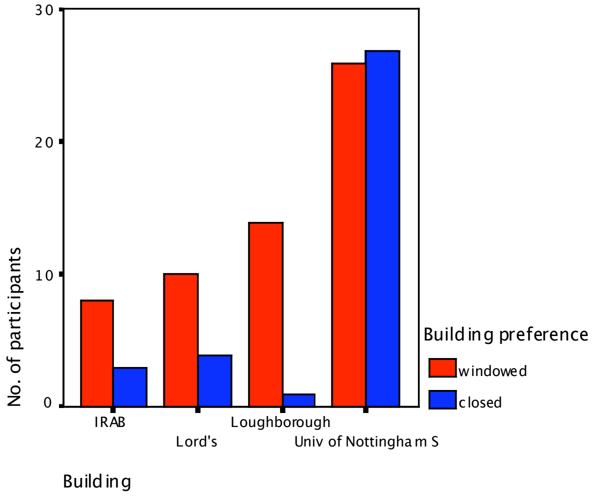
Fig. 8-4 Number of people by sport practised and building who think lighting is the most important environmental design factor

Preference of participants regarding the type of building, closed or windowed, they would prefer to practise in was also investigated. Results show that 62% of participants chose a windowed building whilst 38% chose a closed one as a better space to play. Preference of participants who play in daylit sports centres against participants who play in case study 4 (closed building) are as follows: from the daylit group, 80% prefer windowed buildings and 20% closed buildings; and 49% of users of the artificially lit building selected windowed as the preferred building type, whilst 51% selected closed (Figure 8-5a).

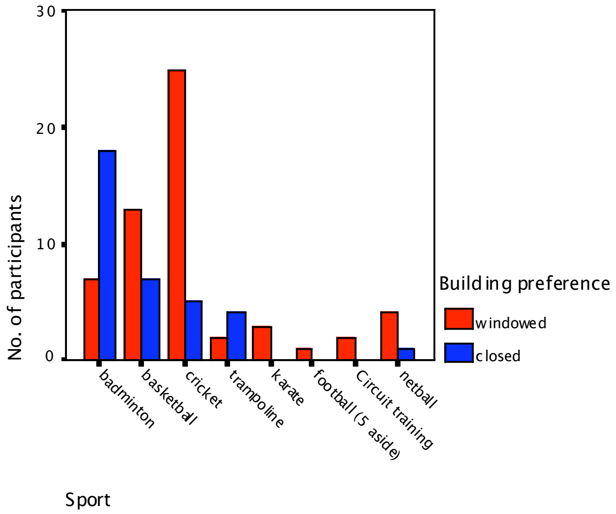
It is clear that people who have experienced daylit sports buildings believe that this type of lighting strategy is appropriate for their playing performance and comfort; while people who is used to play in a closed building think that daylight can cause problems such as glare, and some of them explained that they do not like to be seen from the outside when playing. Users of the closed building may have thought about traditional openings in buildings because no examples of daylighting sports halls showing other ways of including daylight in a building were referred to at the moment of applying the questionnaires. The fact that every one of the participants is only exposed to one building is a limitation of this study.

There is a correlation between building preference and sport practised. Most cricketers (25 out of 30 participants) and basketball players (13 out of 7 participants) prefer windowed buildings, while most badminton players (18 out of 25) prefer closed buildings (Figure 8-5b).

The number of users who selected lighting as the most important environmental design factor discussed in Figure 8-4, can be summarised as follows: 32 people (65%) out of 49 preferred a windowed building, whereas 17 people (35%) selected a closed building.



a



b

Fig. 8-5a Building preference according to users of each case study
Fig. 8-5b Building preference according to sport practised

Participants pointed out some reasons for choosing a windowed enclosure rather than a closed one, such as: natural light availability and reduction of artificial lighting, a windowed building allows natural ventilation and a feeling of outside while keeping a controlled environment. Most respondents commented that it is more 'pleasant', 'warmer' and 'gives a good feeling because is less claustrophobic'. In contrast, people who preferred a closed building pointed out some advantages: temperature and light are easier to control, it is more difficult to get light reflections, avoids distractions from outside and direct sunlight can be blinding and may cause hot spots around the hall. With this information we are looking at general trends due to the number of participants and the non normal distribution of the data.

Sunlight presence on the playing area has been experienced by 74% of all participants of the daylit sports buildings. Users of the Sports Centre of the University of Nottingham were not considered for this analysis since the building is completely closed. The following figure (Figure 8-6) shows the percentage of people who have seen sunlight on the playing area in all three case study buildings.

From that information it can be deduced that Lord's users have perceived more sunlight (29%), than users of the Indoor Cricket School at Loughborough (21%) or the Amenity Building of the Inland Revenue Centre, where 24% of respondents observed sunlight on the playing area. This response might be influenced by the architectural design of the buildings and/or the time of the year and day when this survey was carried out (the weather conditions). Unfortunately, it was not possible to record the exact circumstances at the moment of answering questionnaires. However, it is possible to know the general climatic conditions of the months where questionnaires were distributed and answered[15]. This information is included in the following points:

1. Questionnaires of building 1 (Lord's cricket school) were answered in July 2004. The weather in England during this month was changeable with some thundery rain. At the end of the month there was some warm and humid air. The mean temperature in Central and South England was 16.5°C, with 188.7 hours of sunshine and 53.1mm of rainfall.

2. Building 2 (National Cricket Academy). These questionnaires were answered in September 2004. At the beginning of the month the weather was warm, but after the 10th some showers and wind were experienced. Mean temperature in the Midlands reached 14.4°C, with 158.8 hours of sunshine and 51.5mm of rainfall.

3. Building 3 (IRAB). Questionnaires were answered in June 2004. The first two weeks of the month were warm, but turned much cooler with some wet and windy weather during the second half of June. Mean temperature in the Midlands was 15.2°C, with 195.4 sunshine hours and 51.8mm of rainfall.

4. Building 4 (Sports Centre of the University of Nottingham). Questionnaires in this building were answered in February 2005. In general, the weather in England was mild during the first half of the month, but after the 18th the wind turned to a north or easterly direction bringing snow to many places. Mean temperature in the Midlands was 3.9°C, with 68.3 hours of sunshine and 44.6mm of rainfall.

Clearly, people in IRAB and Lord's school were experiencing warmer temperatures and more hours of sunshine than people in buildings 2 and 4, who responded questionnaires during autumn and winter months respectively. This fact may have influenced the users' responses towards sunlight presence and temperature conditions.

Moreover, 74% of respondents reported that bright sunlight on the playing area interferes a little with their training, and the remaining 26% admitted a moderately degree of discomfort caused by sunlight when practising (Fig. 8-7).

Even though people have little interference of sunlight when playing, most of the participants still believe that lighting quality and quantity are important in sports buildings. Results presented in Figure 8-8 show that people are concerned about the lighting environment in the playing areas. Mainly people who play cricket and badminton made these comments. These are sports that require high and uniform levels of light, and also demand the players to look towards the ceiling in order to hit the ball or shuttlecock.

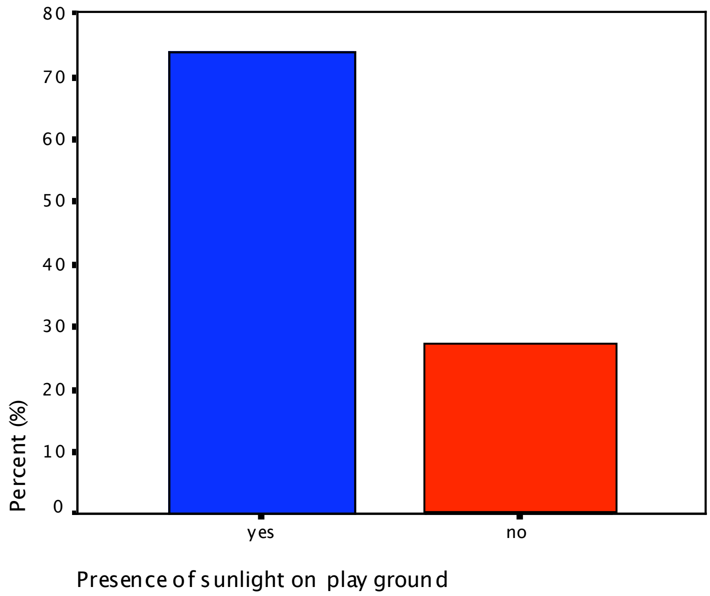


Fig. 8-6 Presence of sunlight experienced by users of the daylighting sports halls

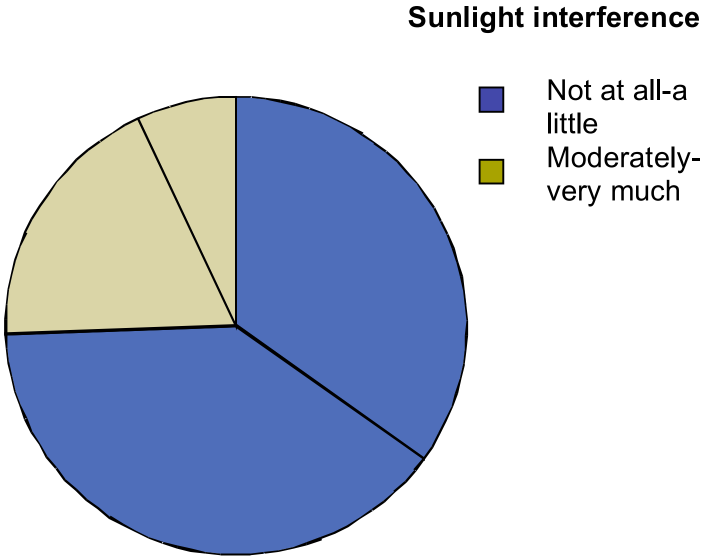


Fig. 8-7 People's response to sunlight interference in their playing

Section 3 Level of satisfaction

Participants' level of satisfaction regarding the lighting performance of the specific building was assessed in this survey. Responses regarding the importance of the quality and amount of light to play sports were influenced by the nature of the sport practised. For instance, cricket is traditionally played outdoors and players' eyesight is adapted to the daylight changing levels, and in reality most of them enjoy playing outdoors and avoid playing under artificial light (Table 8-3). Therefore, after analysing the results of this survey, it has been found the importance of carrying a user-group analysis since the responses of our participants are clearly influenced by the sport practised and the architectural design of the building. Figure 8-8 illustrates these results according to sport practised; it can be noted that for people who play badminton, cricket, football and netball, the quality and quantity of light are important.

In general, 90% of respondents of the four buildings think that the type and amount of light is important for their performance. Some of the reasons reported include: sunlight on the court impairs vision, when having poor light or too bright it makes difficult to see the direction of the ball (or shuttlecock) and especially playing cricket could be dangerous when the batsmen hit the ball at 90MPH. In addition, participants explained that it is important to constantly maintain a high standard of lighting for the appropriate performance of their training.

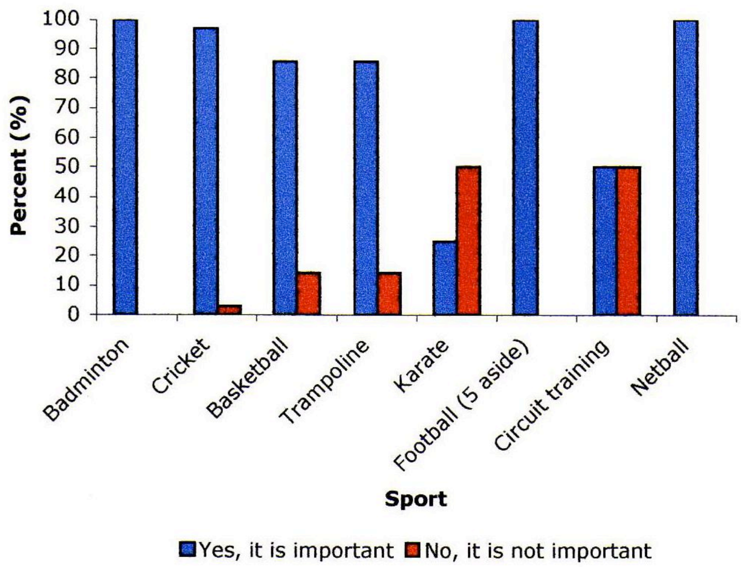


Fig. 8-8 Importance of light quality and amount according to sports players of the four case studies

The following Table shows the preference of respondents regarding the type of light they prefer to play in. As it was said before, cricket players prefer daylight or a mixture of artificial and daylight, rather than only artificial lighting. Nonetheless, people playing at IRAB prefer both daylight and a mixture of daylight and artificial light; and only one person (a badminton player) chose artificial light. In this building five out of six people who selected mixture of both as their preference are badminton players. Respondents from Nottingham University chose a mixture of artificial and daylight as their preferred light, but an important number of people chose only daylight and almost 25% chose artificial lighting.

Table 8-3 Preferred type of light adequate for playing

BUILDING	DAYLIGHT	ARTIFICIAL LIGHT	MIXTURE OF BOTH
IRAB	41.7%	8.3%	50%
LORD'S	93.8%	-	6.3%
LOUGHBOROUGH	81.3%	-	18.8%
SPORTS CENTRE NOTTINGHAM	35%	24.6%	40.4%

According to respondents from both Cricket Schools (Lord's and Loughborough), daylight is the type of light they prefer when playing, while an artificially lit space would not be so appropriate. The total data is presented in Figure 8-9; where 52% of all participants chose daylight as their preferred type of light, followed by 15% who chose artificial lighting and finally 33% of users said they prefer a mixture of both.

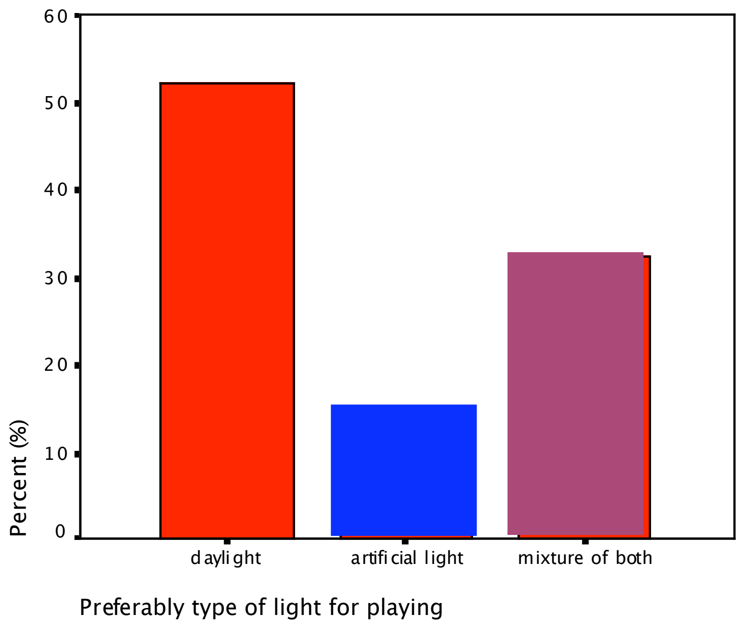


Fig. 8-9 Type of light preference for adequate performance of players

Table 8-4 Number of participants and selection of light preference

	DAYLIGHT			DAYLIGHTING ENVIRONMENT	
Building	**Sunlight**	**Diffuse light**	**Mixture of both**	**Bright light**	**Dull light**
IRAB (12)	5	3	-	6	4
LORD'S (16)	13	2	1	12	3
LOUGHB. (16)	12	1	-	12	4
SPORTS CENTRE NOTT. (57)	15	16	-	41	13

Table 8-4 shows the number of participants that selected the type of light that is best for their playing. People from Lord's and Loughborough buildings clearly prefer playing under sunlight rather than diffuse light, and they prefer a bright environment than a dull one. Responses of participants from the Amenity Building were not as clear; from the table we can deduce that they like better sunlight and bright light. Users of the Sports Centre of Nottingham University clearly expressed that they prefer to play under bright light rather than dull light; in addition, an almost equal number of people selected sunlight and diffuse light as their desired type of daylight.

The following frequency Table and Figure 8-10 illustrate how much people enjoy the presence of daylight in the playing area. The more frequent response indicates that people generally enjoy very much the presence of daylight in the playing area (42%); followed by participants who said they enjoy it moderately (35%). This behaviour was similar in all case studies.

Table 8-5 Enjoyable presence of daylight in playing area

	NOT AT ALL	A LITTLE	MODERATELY	VERY MUCH
Participants	11% (11 partic.)	11% (11 p)	35.4% (35 p)	42.4% (42 p)

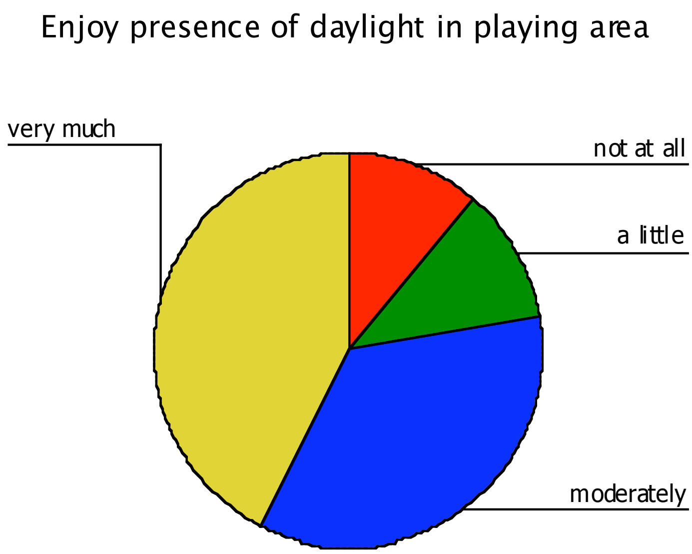


Fig. 8-10 How much people enjoy the presence of daylight in the playing area

As it was said in the introduction, this research studies how daylight influences the environment and users playing performance in sports halls. The three daylit buildings selected as case studies have included fabric membranes in their architectural design, these have been used to control daylight penetration diffusing light that comes through the membrane creating a bright atmosphere and reducing energy consumption for artificial lighting. Each one of the designers of these buildings had a different design approach and hence, the resulting environmental performance of each case study is different, and so is the perception of the buildings' users.

In order to have a clear idea of how the scale and character of the fabric structures or louvres are perceived by their occupants, they were asked to mention whether they have noticed or not the fabric structures in the building. Figure 8-11 presents the results: 100% of people from the IRAB have noticed the fabric; only 31% from Lord's Cricket School, and 44% from Loughborough. The membrane structure of the IRAB building is a single tensile membrane structure that covers the whole building and it is held by four big masts that pass through the fabric structure. The result is a dramatic lightweight building that looks modern and attractive both at day or night-time; therefore, there is no wonder why people have noticed the fabric structure.

On the other hand, the buildings designed for cricket training (Lord's and Loughborough) are a rectangular box with a steel roof structure. The fabric louvres are located inside the building underneath the roof and in between the white steel trusses. This characteristic together with the protecting nets located under the fabric louvres makes difficult to distinguish them, particularly when one only concentrates on practising cricket.

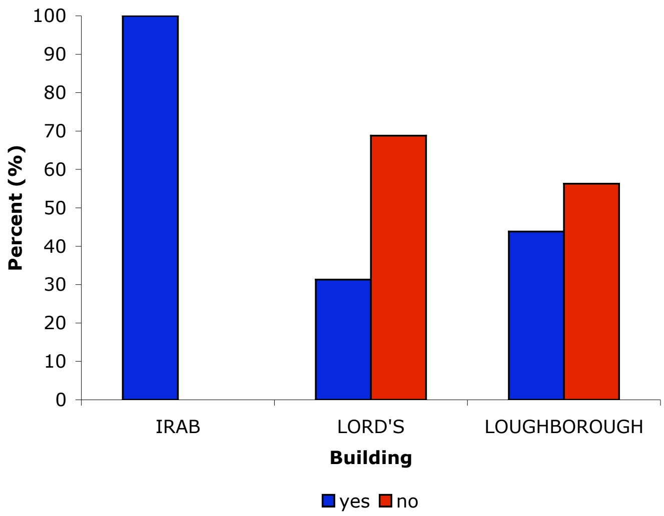


Fig. 8-11 Users' perception of the membrane structures (% of people who have noticed the membranes or not)

The following results (Table 8-6) show how users believe the environment of the building is influencing their mood. Their responses indicate whether or not the interior environment in a building influences peoples' mood, and how it differs from one building to another. Participants were provided with a series of positive and negative humour conditions, and were asked to select the ones they experience when using the building. In order to simplify the analysis, the mood states were divided into two categories: comfortable (positive, alert), and uncomfortable (negative, warm, sleepy, cold).

Table 8-6 Mood influenced by the interior environment

MOOD	IRAB	LORD'S	LOUGHBOROUGH	SPORTS CENTRE NOTTS.
Comfortable	45% (5 part.)	69% (11 part.)	81% (13 participants)	57.9% (33 part.)
Uncomfortable	55% (6 part.)	31% (5 part.)	19% (3 participants)	33.3% (19 part.)

From Table 8-6 it is possible to determine that the IRAB participants feel more uncomfortable than participants from Lord's School and Loughborough. In fact, is in the latest where most of the users who filled in the questionnaire stated their mood as being alert and comfortable (81%). This is probably due to the changing environmental atmosphere of the Amenity Building, where the fabric membrane allows an intense penetration of daylight, but is also very sensitive to the exterior environment. Therefore, the interior environment inside this building is dependant on the outside weather conditions; for instance, participants commented that this building is very cold during the wintertime and uncomfortably hot during the summer period. From the total of participants from the Sports Centre of Nottingham University, 57% expressed they usually feel alert and comfortable in the building, but a considerable 33% said they feel cold and uncomfortable mainly due to noise levels, echo, the temperature in the hall, bright light from lamps and the dim colour of interior surfaces.

In addition, the way light influences the playing performance of building users was also investigated. Participants' responses were again determined by the sport practised in these buildings. Cricketers answered that light influence their play because it could determine if they can see the ball clearly or not; and this quality greatly contributes to their playing performance. They also mentioned that proper lighting helps to distinguish net lanes and players positions.

A third of the IRAB respondents (4 people) commented that light positively influences their playing when looking for the ball or shuttlecock to hit it; and the same number of participants selected continuous changing light levels as the factor that reduces their playing performance (Table 8-7). The common response obtained in the Sports Centre of Nottingham University is that light allows the players to see the ball or shuttlecock clearly (53% of participants). Among these respondents there are 10 out of 17 badminton players and 13 out of a total of 21 basketball players. These sports require the player to look up for the ball or shuttlecock, therefore, for most players it is very important to have suitable light allowing them to see without any interference.

Table 8-7 Influence of light in playing performance

TYPE OF INFLUENCE	IRAB	LORD'S	LOUGHB.	SPORTS CENTRE NOTTS.
Allows to see the ball/shuttlecock clearly	33%	100%	73%	53%
Helps to distinguish net lanes and players positions	-	-	13%	17%
Does not influence/Other	17%	-	-	13%
Does not allow to see properly	17%	-	-	9.4%
Continuous changing light levels reduce the playing performance	33%	-	13%	7.5%

Glare is always a main topic when speaking about lighting and daylighting. It is difficult to avoid it and could cause serious interference with the activities developed in a building. Most of the participants from the Cricket Centres disagree regarding the presence of glare in the playing area; while, more than 65% of participants from the IRAB answered that there is glare in the building. In this sports hall and amenity centre the combination of fabric membrane and glass provide a bright environment, but at the same time it seems to cause problems with glare due to direct sunlight coming through the glass and overheating caused by the small thickness of the fabric. These problems are suffered mainly by people who use this building as a sports centre, especially those users who play sports like badminton where vision is very important. In addition, 27% of the respondents from the Sports Centre of the University of Nottingham stated that they have experienced glare in the building, whilst 50% of them said that there is no glare, and 22% (12 participants out of a total of 55) chose uncertain, which is probably due to the lack of understanding the concept of glare or because they just never have thought about it.

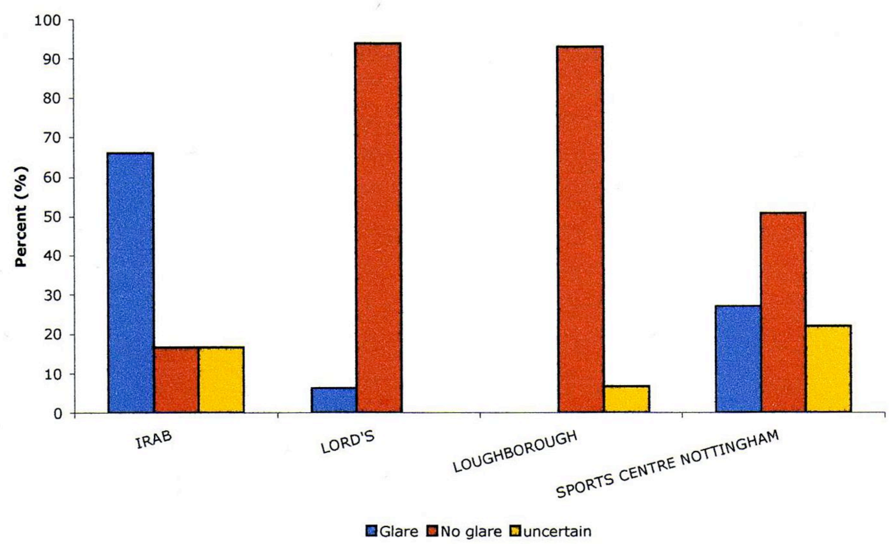


Fig. 8-12 Users' perception of glare presence in the buildings

Users of the buildings were asked to openly express their reaction towards glare. The most frequent comment made is trying to ignore it and continue playing since they can not do much about it; but some people also said they prefer to go outdoors or move elsewhere in the building when possible.

One of the main reasons for designing a naturally lit building is to reduce the energy consumption of electric lighting, which is part of the design strategies of sustainable buildings. Designers of the case studies of this research aimed to include daylight in order to reduce the use of electric lighting and energy, particularly in the cricket centres where constant high light levels are needed to practise. The survey included a question regarding the notion of the users towards the use of electric light in the playing areas. It has been considered that their responses are biased by different factors, such as: the lack of interest or attention paid to lighting, the time of the day when participants usually use the building, the season when the questionnaire was filled in and occupants (may be staff) usage and control of the lighting conditions of the buildings.

This question was only asked to participants of the three daylit buildings, since in the Sports Centre of Nottingham University it is necessary to have always the electric lamps on. Results obtained show that most of the participants are uncertain about the use of electric light in the three sports halls; and almost 50% responded that it is used frequently (all day) and often (some hours per day).

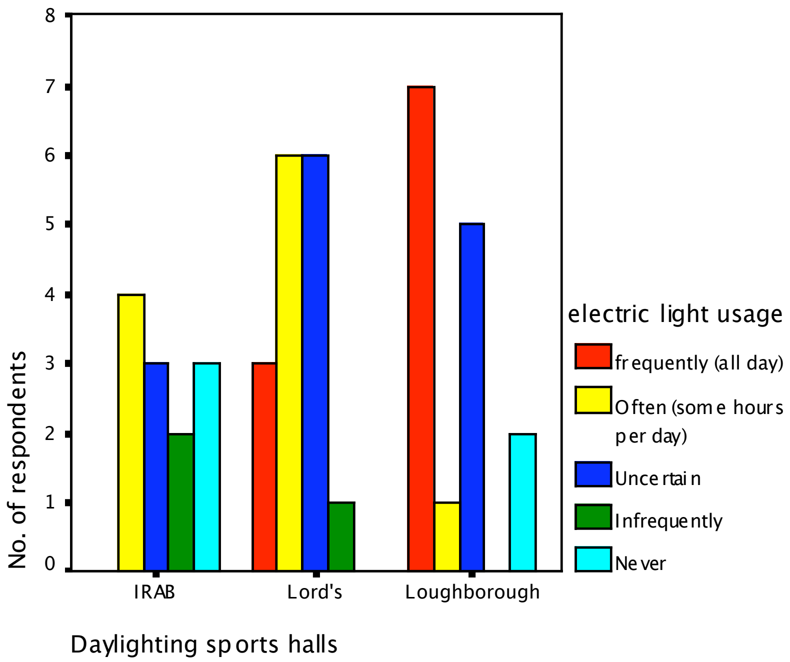


Fig. 8-13 Electric light usage according to users of the daylit case studies

Further comments and a comparison of figures regarding the electricity consumption of the four case studies are included in chapter seven of this thesis.

Table 8-8 illustrates the responses regarding the perception of the building users towards the architectural design and interior environment of the case studies. They were asked to rate how good or bad the architectural designs and interior environments are. According to participants from the Inland Revenue Amenity Building the architectural design of this building is quite good, whereas the interior environment perception is divided between people who think it is very good and people who think is poor.

In addition, participants from the Lord's Cricket School perceive both the architectural design and the interior environment as very good; but some other comments stated that the architectural design is excellent, quite good and a few people said it is poor. On the other hand, most of the Loughborough participants responded that the building is excellent, and the rest believe it is very good. Accordingly, responses about the interior environment were divided only between participants who answered excellent and very good. From these responses it can be said that participants from Loughborough considered the cricket centre as a very good architectural design with a very good interior environment.

Although both cricket centres (Lord's and Loughborough) were designed by the same architect, David Morley, and with a very similar lighting approach, it is believed that the actual performance of the buildings differs due to the improvement reached in the design of the National Cricket Academy in Loughborough, which was built almost eight years after the construction of the Cricket School at Lord's Ground and the architect's experience of designing other cricket schools in the UK.

Most respondents from the Sports Centre in Nottingham believe both the architectural design and the interior environment of the building are quite good which means it is acceptable for playing sports but not very good or comfortable. Both answers are consistent: similar percentage of people had equal opinion about the architectural design and the interior environment of the sports centre.

A chi-Square test on the answers about the Architectural Design of the buildings was calculated to know if the relation between the buildings and the category of architectural design is significant[16,17]. Hence, for a X^2= 64.36 and 15 degree of freedom, $p < 0.001$; this means that there is a probability of one chance in 1000 that the results occurred by chance, therefore, the level of significance of the relationship between each building and its architectural design is high.

Table 8-8 Perceptions of the Architectural Design and Interior Environment

ARCHITECTURAL DESIGN	**IRAB** 12 participants	**LORD'S** 16 participants	**LOUGHBOROUGH** 16 participants	**SPORTS CENTRE NOTTS.** 57 part.
Excellent	8.3%	25%	**68.8%**	1.8%
Very good	25%	**43.8%**	31.3%	19.3%
Quite good	**41.7%**	18.8%	-	**45.6%**
Neither good or poor	-	6.3% (1p)	-	26.3%
Poor	25%	-	-	5.3%
Bad	-	6.3% (1p)	-	1.8%
INTERIOR ENVIRONMENT	**IRAB**	**LORD'S**	**LOUGHBOROUGH**	**SPORTS CENTRE NOTTS.**
Excellent	8.3%	31.3%	**56.3%**	1.8%
Very good	**33.3%**	**43.8%**	43.8%	21%
Quite good	25%	25%	-	**49%**
Neither good or poor	-	-	-	21%
Poor	**33.3%**	-	-	5.3%
Bad	**-**	-	-	1.8%
VISUAL ENVIRONMENT (how appropriate is it?)	**IRAB**	**LORD'S**	**LOUGHBOROUGH**	**SPORTS CENTRE NOTTS.**
Not at all	8.3%	-	-	-
A little	25%	-	-	7%
Moderately	**50%**	4%	1%	**51.4%**
Very much	16.7%	**75%**	**93.8%**	31.6%

As in any building the architectural design of sports halls must fulfil the sports requirements (court dimensions, lighting, ventilation, colour of materials and surfaces, etc.) and the users' needs. For the purposes of this study participants were asked to evaluate if the visual environment of each case study is or not suitable for playing the sport they practise. Half of the respondents from the IRAB believe the visual environment is moderately suitable for their playing performance; followed by 25% who think is a little suitable (Table 8-8).

Due to their architectural and functional similarity, responses from Lord's and Loughborough are similar: both obtained higher rate at 'very much appropriate', and this tendency is clearer in the Loughborough Cricket Academy (Table 8-8). Almost 94% of participants selected the latter building as very much suitable for cricket training, and the rest selected moderately.

In general, it can be distinguished a clear trend which identifies the lighting solution (fabric louvres) of the cricket centres to be suitable for the visual requirements of this sport when is practised indoors. And in spite of the attractive shape and environment of the Amenity Building in Nottingham, it seems that in this case the roof solution of a tensile membrane structure is not the best one for a sports hall, and it can be discussed if the requirements of the sport area were appropriately considered in the proposals and final architectural solution of this building.

Respondents from the Sports Centre of the University of Nottingham clearly (50% of participants) believe the visual environment is moderately appropriate for practising sports. This figure is followed by nearly 32% of participants who think the visual environment is very much adequate. These results are included in Table 8-8. The following charts illustrate a comparison between the answers of participants from the four case studies, regarding their perception of the architectural design of the buildings, their perception of the interior environments and whether or not they think the visual environments of the buildings are suitable for playing sports.

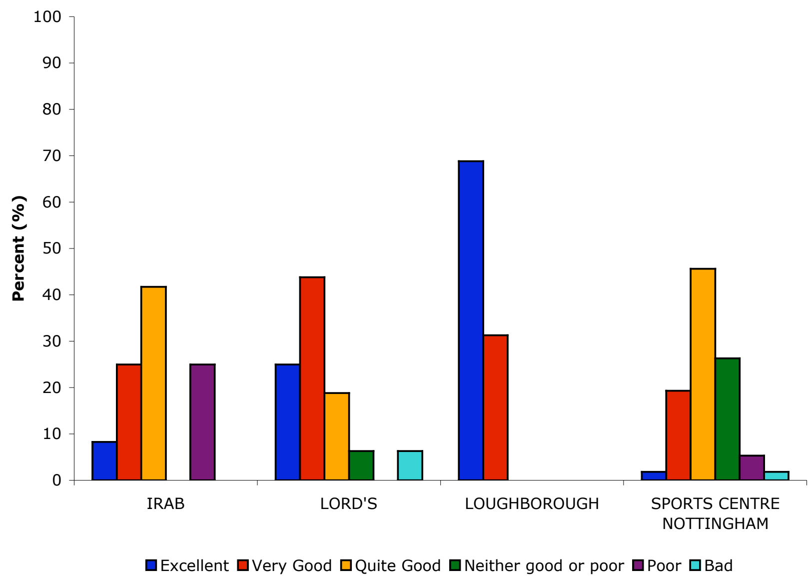


Fig. 8-14 Users' perception of the Architectural Design of each case study

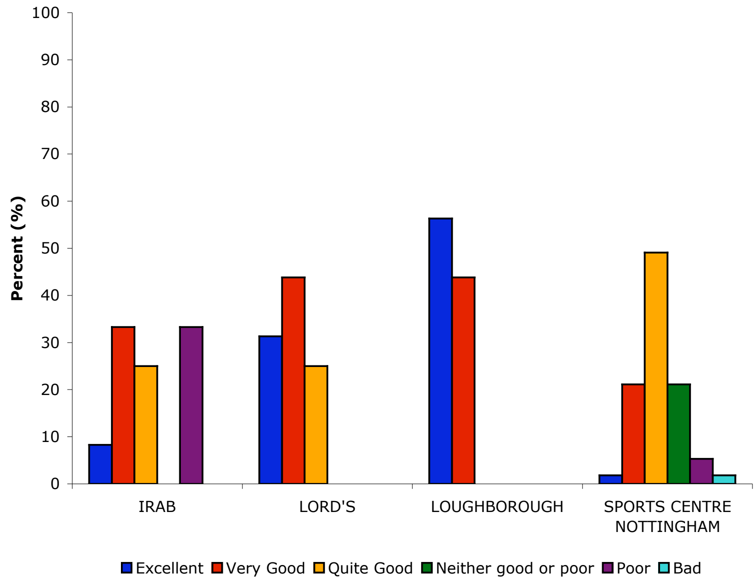


Fig. 8-15 Users' perception of the Interior Environment of each building

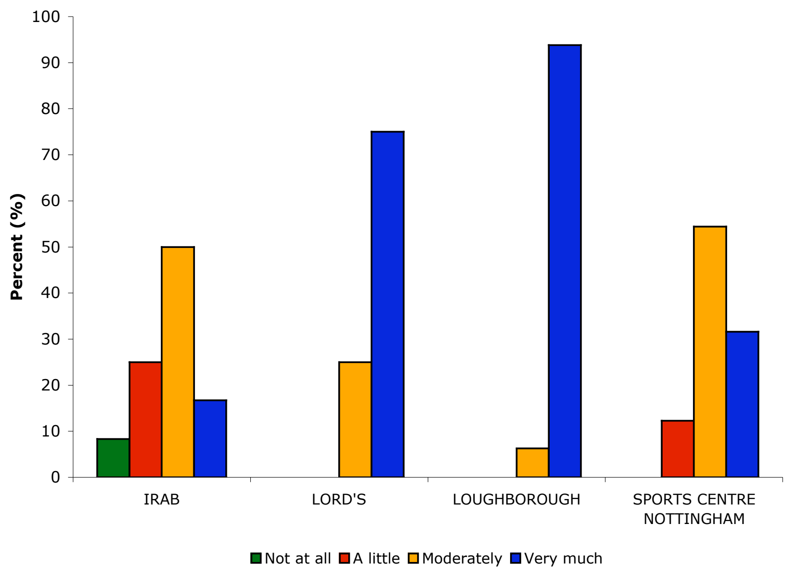


Fig. 8-16 Users' response regarding how appropriate the visual environment is for playing the sport they practise

8.5 DISCUSSION AND SUGGESTIONS FOR FURTHER RESEARCH

Although some limitations of time, users availability, geographical distance, buildings' admission policies and occupancy patterns were present in the development of this study, some interesting results have been drawn from this post occupancy evaluation survey. From the analysis of results some conclusions have been raised:

- The importance of the lighting environment in sports halls deeply depends on the sport practised in the building. The more lighting demanding sports in the four case studies are cricket and badminton; both sports require high levels of light and uniform lighting conditions throughout the visual field of the players. If these conditions are not met the performance of the players decreases, and in the case of cricket, participants were very concerned about the risk of getting hurt if lighting was not adequate. For the badminton players the difficulty arises when they to look up to hit the shuttlecock, and if the lighting (natural or artificial) is poor they cannot see it. One respondent from the Sports Centre in Nottingham stated that walls colour make difficult to distinguish the shuttlecock and that he gets blinded by the electric lamps when looking towards the ceiling.
- People are generally aware of the environmental conditions of the building since it influences their playing performance. Most of the respondents answered that lighting and temperature are the most important environmental factors in sports halls, followed by ventilation. These answers were probably responded under the influence of the environmental conditions at the time of filling in the questionnaire; unfortunately due to the impossibility of recording these conditions in the case studies it is not possible to know with certainty if there is any influence, becoming this a limitation of the study. The same situation happens with the users' perception of the interior environment, which could be influenced by the conditions at the moment of answering the questionnaire even though the question referred to the interior environment throughout the year. In any case, the answers and comments although subjective, have provided an idea of how users perceive a building and the factors that are important to consider when designing sports halls.

- Fabric membranes can be a good solution for allowing natural light in sports halls while reducing electricity consumption. However, their design, size, geometry, location, materials, coatings, maintenance and durability have to be considered and tested at a design stage in order to avoid glare, uncomfortable temperature and poor light quality. Some participants from the Amenity Building in Nottingham reported acoustics problems in the playing hall. In addition, membranes used as louvres to control daylight penetration in the cricket buildings have proven to be successful. Most of the respondents assured that these buildings, particularly the National Cricket Academy in Loughborough, have an excellent architectural design, an excellent interior environment and a very much appropriate visual environment for cricket playing.
- Sunlight presence on playing areas was reported by an important number of participants from the daylit buildings. In the Amenity Building of the Inland Revenue Centre, sunlight reaches the playing court through the glass openings located in the membrane roof and the eye-shape glass openings located at both sides of the long sides of the court at the edges of the central membrane roof. Through these openings under clear skies sunlight penetrates into the building with no restriction since the glass is transparent. Badminton players mentioned this problem particularly with the eye-shape openings, which are situated parallel to the badminton courts and to the players' eyes.

  The Indoor Cricket School at Lord's grounds have sunlight on the playing area when the lateral sliding walls are open. These provide natural ventilation during summer time, but they also leave the building completely open on its east and west facades under clear skies.

  This problem was solved in the National Cricket Academy (Loughborough) providing ventilation through the roof. However, in this building the architects designed a long window facing northeast mainly to visually connect the indoor Academy with the outdoor cricket pitch. Glass doors are provided to enter into the academy's playing area and changing rooms from the outdoor pitch. Though, in reality players are not allowed to enter into the playing area from these doors in order to avoid noise from outside and mud on the carpet. The positive response of the users regarding sunlight presence in the building (64%) may be explained by sunlight coming from this window. However, due to the orientation of the window it is difficult to have direct sunlight except with the sun's low angles of winter. Other explanation for getting sunlight in the building is through the transparent sections of the roof, where the membrane louvres are located. Perhaps the tilted angles of the louvres are not correct or precise and some sunlight is not diffused by the membranes. This could be a problem of either design or construction of the building.

- In general, people enjoy buildings with innovative environmental and aesthetic solutions; but above that fact, the participants confirmed that it is more important for them to play or practise in an adequate functional building designed according to the sports requirements, rather than having an impressive building where is uncomfortable to play. Hence, people prefer an efficient building than a 'nice' one. Moreover, comments from users of the Sports Centre in Nottingham University included their preference for having windows providing natural light, natural ventilation and views out. They also mentioned that it would be good to have space for spectators and a better layout; this is difficult to achieve due to the box-type shape of this building, and due to the different sports practised and their timetables.
- The use of a self-answered questionnaire demonstrated to be a useful method of gathering subjective responses from the users of the four case studies. Post-occupancy evaluation studies can provide helpful information to improve existing buildings or to design new ones; where users' perception and satisfaction regarding the space have to be taken into consideration, since the occupants' comfort is the final objective of an architectural design.

Designing sports halls could be an opportunity to develop creativity and new roofing systems, since the dimension of these buildings and the need to cover large span areas with no intermediate supports give designers the possibility to experiment with inventive solutions.

Nonetheless, priority must also be given to sports requirements, climatic conditions of the site, orientation of the building, users' comfort, building regulations, always bearing in mind that the solution must be an environmentally responsive design. In this sense, daylight can provide bright interior environments in sports buildings even under cloudy climatic conditions. Both energy savings and attractive architectural solutions can be achieved if the right parameters are considered when designing daylit sports halls.

Further research about users' preference of daylighting environments in sports buildings may include a larger number of participants who have experienced more than one of the studied buildings. Then, a comparative analysis of the findings can be made. In addition, it is suggested to record the lighting and weather conditions under which participants are experiencing the buildings at the moment of completing the questionnaire. It would be advisable to select different buildings that accommodate one type of sport (i.e. a swimming centre) and a group of people who have some experience practising such sport and who could experience all the chosen buildings. A comparative analysis can be carried out taking into consideration the knowledge and experience of participants, and their views towards different architectural solutions for the same lighting, environmental and functional requirements.

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8.6.1 Figures and tables

Nine

9. CONCLUSIONS

During the last two decades the application of membrane structures in permanent complex buildings have extended, particularly their use in sports buildings. Designers are using membrane structures to cover large-span buildings taking advantage of new durable membrane materials, the development of structural analysis methods and a growing demand for constructing low energy buildings.

A review of the existing body of knowledge demonstrated that, although aspects of the structural behaviour of membrane structures and materials technology have been developed since the 1950s, the lighting environment created under such structures has been hardly explored. Even though designers are aware of the advantages that a translucent material can offer in buildings with high lighting demand, there is still a need to assess existing lighting simulation tools used for the prediction and evaluation of the daylighting performance of membrane buildings.

The research presented in this thesis explored the daylighting performance of three membrane sports halls: The Indoor Cricket School at Lord’s Ground in London, The National Cricket Academy in Loughborough and the Amenity Building of the Inland Revenue Centre in Nottingham. Two daylighting simulation tools were assessed, physical scale modelling and computer modelling.

This investigation was carried out in the five following stages:

- Daylighting field measurements were recorded in three full-scale daylit membrane sports halls
- Physical scale models of the three buildings were constructed and their lighting performance was tested under an artificial sky

- Creation of 3D computer models of the case study buildings. The daylighting performance of these models was simulated using two computer software: Ecotect and desktop Radiance
- Assessment of the accuracy of both tools (physical modelling and computer modelling) comparing results with data obtained in real buildings
- Design and distribution of questionnaires for a post-occupancy evaluation study regarding users' satisfaction towards the interior lighting environment of each case study.

9.1 ABOUT THE LIGHTING PERFORMANCE OF MEMBRANE DAYLIT SPORTS BUILDINGS

Traditionally sports halls have been designed as enclosed buildings illuminated with artificial lighting only. In this way, it is possible to control the internal lighting environment, which is important for playing sports. In addition, sports halls often require high levels of light and long operation periods, particularly during wintertime in northern latitudes when people have to practice indoors.

In the last few years some attempts of introducing daylight into the lighting strategy of sports buildings have been carried out. Some of these buildings are the case study enclosures chosen for this investigation. These buildings have included daylight as part of their lighting strategy, using translucent membranes for daylighting control helping to maintain high but stable light levels.

The field measuring sessions in each building demonstrated that these sports halls could be illuminated only with daylight for important periods of the year, as well as complementing the artificial lighting during winter. Illuminance uniformity and daylight factors obtained on site under overcast skies showed the lighting performance of the playing areas.

The National Cricket Academy is the best performing building with a daylight factor of 5.9% indicating that it is a controlled bright daylighting building, and a uniformity ratio of 0.55 assures a steady lighting environment required to play cricket at a professional level. As it was shown in chapter seven (Table 7-7) the National Cricket Academy is also the best performing building in terms of annual energy use. It is clear that the architects learnt from their previous design of the MCC indoor cricket school at Lord's, which has a similar lighting solution. This solution has been improved in their design of the National Cricket Academy. The membrane type selected for the latter building (with higher light transmittance than the membrane used in Lord's), the tilt angle of the louvres, the shape and orientation of the roof openings and the reflectance characteristics of the interior materials have provided a well daylit and energy efficient building.

Even under overcast skies the three sports halls demonstrated a high responsiveness to variations of daylight and sky conditions. Above all, measurements in the Inland Revenue Amenity Building (IRAB) showed high levels of daylight particularly in the centre of the playing area. Visual observation and photographs illustrated the presence of sunlight on the floor, which penetrates through the glass openings located in the central membrane roof and in the lateral membranes during summer days. This was seen to potentially have an impact on occupants' comfort and playing performance, causing glare and possible overheating.

In reality, the translucent membranes of the studied recreation buildings work in different ways. In the cricket centres the membranes act as interior blinds protecting the interior environment from direct solar radiation while allowing the access of diffuse daylight. In the IRAB the function of the membrane structure is to enclose the interior space protecting it from the outside and allowing the penetration of natural light. Results obtained in this work show that the function of translucent membranes louvres as daylighting control systems performed better than the translucent tensile membrane structure of the Amenity building in Nottingham. The cricket centres have more uniformly distributed lighting environments and there is no presence of solar radiation on the practice nets. On the other hand, the IRAB is more exposed to external environmental conditions due to the dimension of the membrane structure and the glass openings.

It is important to consider a possible relative error in the field measurements caused mainly by three factors:

1. Instruments. Although the light sensors used for this study were brand new and calibrated by the manufacturers, during a test in the artificial sky the sensors showed a discrepancy among each other of around 5%.
2. The sky luminance distribution. Even though the site illuminance and luminance measurements were taken under overcast skies, it is possible that some results could have small variations due to the changing luminance distribution of the sky, particularly during the summer.
3. Possible changes of nets divisions in the cricket schools. During the field measurements it is possible that some players had moved the divisions of the practice nets causing some difference in the readings.

It is difficult to avoid this type of errors when monitoring or measuring data in existing occupied buildings. These risks can be avoided taking several sets of data during different days and seasons.

9.2 ABOUT THE ASSESSMENT OF SIMULATION AND EVALUATION TOOLS

The physical scale models constructed for this investigation included reflectance values of interior surfaces measured on site, the real membranes used in Lord's and Loughborough buildings, and a lycra fabric that simulated the light transmittance and reflectance of the real PTFE fabric. Illuminance measurements were taken inside the models located under an artificial sky (overcast sky); and daylight factors and illuminance uniformity values were obtained. The data was then compared against values measured in the real sports buildings.

Both physical scale models, Lord's and Loughborough overestimated the buildings' lighting performance. The measurements confirmed that the whole geometry, even adjacent areas, of a building has to be included in the scale model for obtaining accurate results. The scale model of the Amenity Building in Nottingham best represented the lighting environment of the building, in terms of light levels and illuminance distribution. The scale of the playing area against the height of the building was considerable higher in the latter, leaving more space between the roof and the lux sensors. Hence, the behaviour of daylight in the scale model was similar to the behaviour recorded in the actual building. This did not happen with the models of the cricket schools, where both roofs were very close to the sensors allowing only a few inter-reflections before the light rays reached them, recording then high levels of light.

Physical scale models for lighting studies of membrane buildings can be expensive and time consuming; their performance greatly depends on the accuracy of the geometry representation, reflectance of materials and scale. However, they can be helpful to visualise in three dimensions the geometry and general lighting environment of a membrane enclosure. According to the good results obtained with the IRAB model, it is feasible to obtain also good results if the other two models are constructed considering the potential errors pointed out in this thesis. Nonetheless, it is essential to consider the complexities of time and cost involved before deciding to use physical scale modelling as a tool to predict daylight in buildings with translucent membranes.

Nowadays, the 3d computer modelling of an architectural project including membrane buildings is almost compulsory in any architectural practice as part of the development and construction of a building. Once having an accurate computer model, the real optical properties of materials and glazing can be attached and the site context included. In this research, the fabric membranes used in all case study buildings were modelled using the Radiance language creating materials files that are read during the lighting calculations made by the software.

The accuracy of the daylighting performance of the buildings simulated with computer models was assessed against data obtained on site. It was found that Radiance best predicted the lighting levels and illuminance distribution of Lord's School with a relative error of +7% and the Amenity building with a relative error (RER) of -4.25%. On the other hand, scale physical models of buildings 1 and 2 provided big RER between +108% and +164% respectively; however, the scale model of building 3 closely simulated the real building with a RER of +11% (Table 9-1). Calculation times with computer models were not too long; it took approximately half an hour for the Ecotect lighting calculations and ten minutes for the Radiance DF or illuminance calculations including two renders of interior views. These times depend on the accuracy desired and the complexity of the models.

Although Radiance is not a user-friendly software and it takes a long time to learn it in particular if the user has no previous experience on computer programming, the software has proven to be a reliable tool predicting the daylighting performance of membrane buildings. In addition, once the computer model is ready, changes to materials characteristics, geometry, glazing, etc can be made quickly.

The following Table shows a comparison of the final results obtained in the real buildings with results from physical scale modelling and computer modelling.

Table 9-1 Comparison of DF, uniformity ratio and relative error of field measurements, scale modelling and computer simulations.

BUILDING	**FIELD STUDY**		**SCALE MODEL**			**RADIANCE MODEL**		
	DF	**UNIFORM. RATIO**	**DF**	**UNIFORM. RATIO**	**RER**	**DF**	**UNIFORM. RATIO**	**RER**
Lord's Cricket School	4.4%	0.37	9.16%	0.8	108%	4.71%	0.73	7%
National Cricket Academy (-ab=2)*	5.9%	0.55	15.6%	0.56	164%	3.6%	0.33	-38%
(-ab=7)*	-	-	-	-	-	4.4%	0.56	-25%
Amenity Building (-ab=2)*	24%	0.29	26.7%	0.79	11%	18.5%	0.62	-23%
(-ab=6)*	-	-	-	-	-	22.98%	0.63	-4.25%

*-ab is the number of ambient light bounces in Radiance simulations.

Considering the variation of daylight even under overcast sky conditions, the standard deviation of the daylight factors obtained on site in all three case study buildings was calculated. Results are presented below as error bands that graphically show the divergence between field study, radiance simulation and scale modelling. Scale models of Lord's and the National Cricket Academy greatly overestimated the availability of daylight. However, results from the other analyses fall under the error band of the site measurements (Figure 9-1).

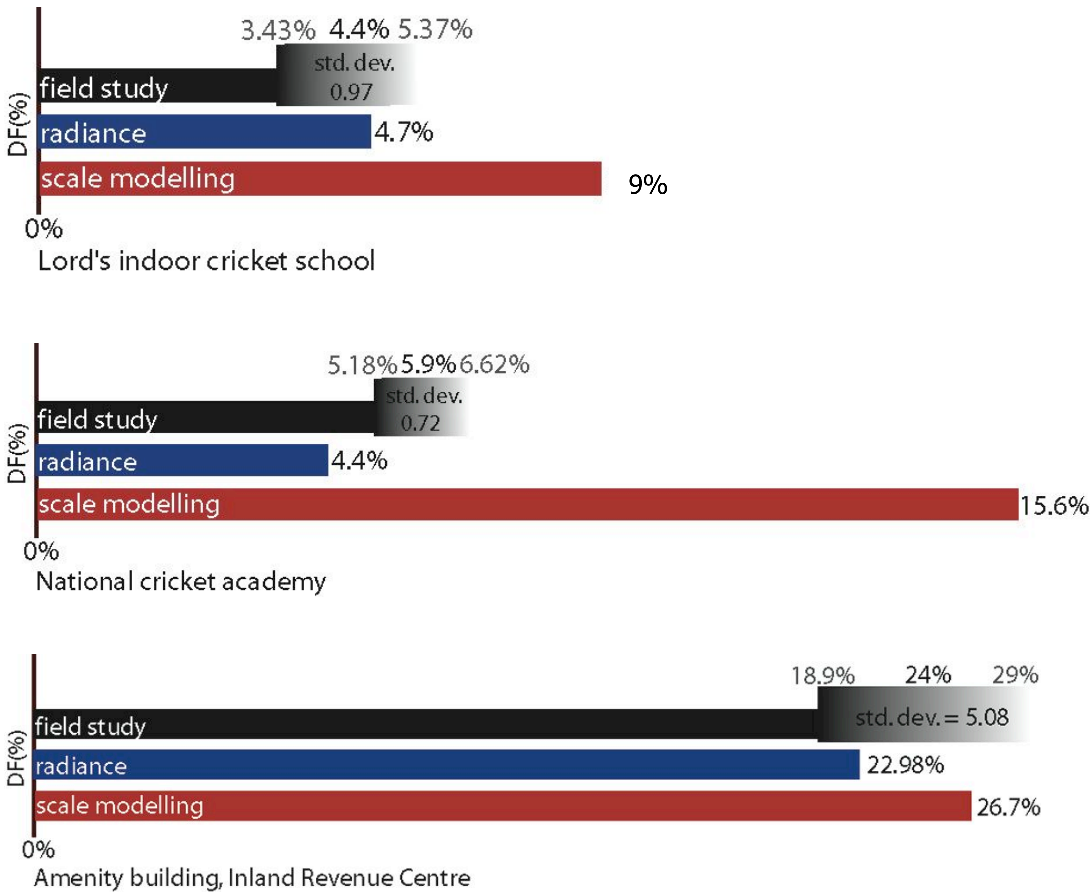

Fig. 9-1 Error band of field measurements and results from physical scale modelling and computer simulations of the three evaluated buildings.

Finally, taking into account possible errors in field measurements of Lord's school and the amenity building in Nottingham caused by distant obstructions to the sensor reading the sky illuminance, higher average daylight factors are then obtained. Final figures considering a completely unobstructed sky illuminance (USI) have reduced the divergence found between field measurements, scale modelling and computer modelling. In spite of that the physical scale model of the National Cricket Academy overestimated the real building performance by +62%, and the Radiance model of the same building underestimated its performance by -34%. Although computer simulations results of the National Cricket Academy are not very encouraging, it is important to bear in mind that changes and improvements to this model can be done within very little time. Table 9-2 presents final divergence results for the case study buildings.

Table 9-2 Daylight factors divergence between field studies, scale models and computer simulations

BUILDING	DF FIELD STUDY (*with correct. for USI)	DIVERGENCE: FIELD STUDY vs. SCALE MODELS	DIVERGENCE: FIELD STUDY vs. RADIANCE
Lord's Cricket School*	4.88%	+46%	-3.6%
National Cricket Academy	5.9%	+62%	-34%
Amenity building*	26.6%	+0.4%	-15.7%

9.3 ABOUT USERS ACCEPTANCE

In order to carry out a complete evaluation of the buildings studied in this thesis, a users satisfaction questionnaire was developed and distributed among occupants of the three daylit sports buildings evaluated in this thesis plus one more hall completely artificially lit: the Sports Centre of the University of Nottingham. The main aim of the assessment was to know the users satisfaction regarding the lighting environment of the buildings and its appropriateness to play certain sports.

A total of 101 questionnaires were answered by people who play badminton, basketball, cricket, five a side football, trampoline, netball and karate. From the data analysis it is possible to say that in general people prefer sports buildings with openings to obtain daylight and exterior views. Their interest on the lighting environment greatly depends on the sport practiced; badminton and cricket players stated that lighting is the most important environmental factor. Both sports require high levels of light to allow the player to see the shuttlecock or the ball. Direct sunlight must be avoided especially coming from the roof since players have to look towards the ceiling to hit the ball or shuttlecock and direct light can blind them. Because of this problem but caused by artificial lighting, badminton players complaint about the lamps in the Sports Centre of the University of Nottingham.

Occupants of the National Cricket Academy in Loughborough best rated the building in terms of visual environment, lighting and architectural design. This perception agrees with the evaluation of the building previously discussed in this chapter. Although users of the Amenity Building in Nottingham affirmed that they like the architectural design of the building, some of them believe the building is uncomfortable, too hot during summer and cold during winter. They also mentioned problems with the acoustics of the hall saying that noise travels too much. Some users of the Sports Centre of Nottingham University also made the same comments regarding noise in the building.

The information extracted from the questionnaires is to some extent limited by different factors:

- The limited number of participants (especially in the daylighting buildings)
- The short stay of the users in the buildings
- Due to the location of the buildings, their membership policies and the different sports practiced in each hall, it was not possible to do the study with the same group of people experiencing all the buildings
- It was not possible to record the precise weather conditions under which the occupants answered the questionnaires, since questionnaires were distributed by the buildings' managers and occupants answered them at different times during a month period. Therefore, it is possible that their responses are biased by the climatic conditions they experienced at the moment of completing the questionnaire.

Despite the factors mentioned above, questionnaires have represented a useful tool for approaching users and obtaining their subjective views towards the lighting environment and design of buildings.

9.4 FUTURE WORK

The ability to accurately predict the daylighting performance of translucent membrane buildings is significant for designers, practitioners and researchers interested in daylighting and sustainable architecture. Due to the increasing demand for low energy and sustainable buildings, the further use of translucent membranes to control daylight penetration can be anticipated. Therefore, having reliable daylighting prediction tools is very important.

An efficient solution for daylighting control is using membrane materials of different light transmittance, durability, colours, printed patterns and coatings, which have to be appropriately chosen according to climatic conditions, building function, architectural design and lighting requirements. Membranes can either be part of the main structural and roofing system, or be used as interior or exterior louvres.

Results presented in this thesis and the rapid development of technology point towards an increasing use of computer simulation for daylighting predictions. Radiance provides accurate quantitative lighting simulations that allow architects to make design decisions. The expanding use of this software among researchers and architectural practices and its freedom for adapting its programs to specific needs, means that Radiance is a powerful software and that future improvements and a user-friendly environment will soon be developed.

In order to continue exploring the performance of daylighting buildings and daylighting prediction tools, the following points present further work that can follow the research carried out for this thesis:

- A similar approach to the one presented in this thesis for daylighting simulation using Radiance can be developed in further studies with different types of membrane materials (i.e. PVC or ETFE cushions), different light transmittance and colours. A parametric study can be developed to assess the effect of such membranes properties on the daylight availability of naturally lit enclosures.

- Computer models of the case study buildings should be simulated under clear and sunny sky conditions during different times of the year.
- Computer simulations combining daylight and artificial lighting for the same buildings has to be further studied in order to have a complete analysis of these buildings.
- A further study must include the modelling of all materials with Radiance instead of attaching some material's properties in Ecotect. Results could assess the importance of simulating all details with Radiance for higher accuracy.
- The performance of other daylighting control systems and shading devices can be tested with Radiance under different sky conditions and for different climates.
- Following the method presented in this thesis a wider daylighting performance evaluation must be carried out for any other type of daylit buildings, such as museums, libraries, schools, etc.
- The physical scale models constructed for this research work ought be tested under real skies completing a quantitative and qualitative study of the buildings and assessing the performance of scale models to simulate daylight under different sky conditions.
- Further work with scale models should be improved if they are carefully constructed, which means modelling the full geometry of the building, structural details, lighting control systems and surfaces reflectance. It is advisable to collect a set of materials with their optical characteristics to elaborate a library of modelling materials ready to be used for constructing physical models for lighting studies. However, testing different lighting systems or complex geometries with physical models will always be time consuming and expensive.

It is hoped that increasing environmental concern continues putting pressure on designers and constructors to include environmental strategies in the built environment. In addition, closer collaboration between academia and industry is necessary to develop environmental strategies taking into consideration the climate, culture and social characteristics of the site.

9.5 Figures and tables

APPENDIX A

Questionnaire for the post-occupancy evaluation study

The University of Nottingham

School of the **Built Environment**
Faculty of Law and Social Sciences

September 2004

We are working in a study of lighting performance in sports halls, which is part of a PhD project currently developed at the School of the Built Environment of the University of Nottingham. We want to hear your views about how the building design, in particular the lighting design, influences your playing performance.

Therefore, we will appreciate if you could complete the following questionnaire, which has been divided into three different sections with a total of 39 questions. These will not take you more than 5 minutes to respond.

The first part of the questionnaire includes general questions regarding your occupation, age, visual condition, your experience as cricket player and the frequency of your visits to this building.

The second part is about the environmental perception of different factors inside the building, such as: ventilation, lighting, temperature, etc.

And finally, the third section includes questions regarding your level of satisfaction about the building's architectural design, the light quality and visual environment in relation to your mood and cricket training performance.

Your answers will be completely confidential and the results will be used only for research purposes. We are relying on you to complete and return the questionnaire so that we can know what people think of a building that has incorporated a daylighting design strategy.

Thank you very much for your help in this. If you have any queries about this study please feel free to contact me.

Yours faithfully,
Julia Mundo.

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University of Nottingham
University Park, Nottingham. NG7 2RD

T. 0115 9515151, ext. 14872
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Section 1: General information and playing experience.

1. What is your occupation?

___

Please tick one option in each of the following questions.

2. Your age:

- ☐ Under 16
- ☐ 16 - 21
- ☐ 22 - 35
- ☐ 36 - 45
- ☐ 46 - 55
- ☐ Over 56

3. Are you male or female?

- ☐ Male
- ☐ Female

4. How would you rate your eyesight?

- ☐ Excellent
- ☐ Good
- ☐ Bad

5. Do you suffer any visual condition or eye illness?

- ☐ Yes
- ☐ No

If yes, which one? (You may select more than one option)

- ☐ Myopia
- ☐ Strabismus
- ☐ Amblyopia
- ☐ Other ___
- ☐ Astigmatism
- ☐ Colour vision deficiency
- ☐ Cataracts

6. Why are you here at the National Cricket Academy?

- ☐ England & Wales Cricket Board (ECB) cricket player
- ☐ University of Loughborough Cricket squadís player
- ☐ Other Cricket Club player
- ☐ Cricket instructor
- ☐ Administrative staff
- ☐ Visitor or spectator
- ☐ Other: ___

7. For how long have you played cricket?

- ☐ Less than one year
- ☐ One year
- ☐ 2 to 5 years
- ☐ 5 to 10 years
- ☐ More than 10 years

8. Where have you played and/or learnt cricket before? (Please specify name of the school and geographical location).

___

___

9. Was it an Indoor Cricket School?

- ☐ Yes
- ☐ No

1

10. When did you join to the National Cricket Academy in Loughborough?

Month ______________________

Year ______________________

11. How often do you come to this building?

- ☐ Every day
- ☐ 3 - 5 days per week
- ☐ Twice per week
- ☐ Once per week
- ☐ Once per month
- ☐ Other

12. During what period of time do you usually come to this building?

- ☐ From 9 hrs - 12 hrs
- ☐ From 12 hrs - 16 hrs
- ☐ From 16 hrs - 22 hrs

13. How long do you usually use the playing area in each visit?

Hours ______________________

Section 2: Environmental perception.

14. Which of the following do you feel are the most important factors to consider when designing Indoor Cricket Schools? (Please rank the following in order of importance. Number them so that 1 = most important, 2 = next most important, through to 6 = least important).

- ___ Temperature
- ___ Lighting
- ___ Ventilation
- ___ Acoustics
- ___ Colour of finished materials
- ___ Other ______________________

15. Do you prefer a windowed building or a completely closed one?

- ☐ Windowed
- ☐ Closed

16. Why?

____

____

____

17. Have you ever noticed the presence of sunlight on the play ground?

- ☐ Yes
- ☐ No

18. When the sunlight is bright, how much does it interfere with your playing performance and training?

- ☐ Not at all
- ☐ A little
- ☐ Moderately
- ☐ Very much

19. Overall, what do you think about the architectural design of the National Cricket Academy? (Please tick only one option).

- ☐ Excellent
- ☐ Very good
- ☐ Quite good
- ☐ Neither good or poor
- ☐ Poor
- ☐ Bad
- ☐ Unacceptable

20. How would you describe the interior environment of the School? (Please tick only one option).

- ☐ Excellent
- ☐ Very good
- ☐ Quite good
- ☐ Neither good or poor
- ☐ Poor
- ☐ Bad
- ☐ Unacceptable

2

Section 3: Level of satisfaction.

21. From your experience, is the visual environment in this building appropriate for cricket training?

☐ Not at all ☐ A little ☐ Moderately ☐ Very much

Why? ______________________________

____

____

22. Do you think the amount and type of light are important for cricket playing performance?

☐ Yes ☐ No

Why? ______________________________

____

____

23. Under which type of light would you prefer to play cricket during the day?
☐ Daylight
☐ Artificial light
☐ Mixture of both

If you selected daylight please continue on question no. 24, if artificial light then continue on 25.

24. Would you prefer:
☐ Sunlight
☐ Diffuse light (e.g. cloudy skies)

25. At night time would you prefer:
☐ Fluorescent light
☐ White light (such as spotlighting)

26. Do you prefer to play cricket in:
☐ Bright light
☐ Dull light

27. How much do you enjoy the presence of daylight in the playing area?

☐ Not at all ☐ A little ☐ Moderately ☐ Very much

28. Do you think daylight penetration is adequate (functional) for cricket playing in this building?

☐ Not at all ☐ A little ☐ Moderately ☐ Very much

29. Have you ever noticed the fabric louvres located underneath the roof?

☐ Yes ☐ No

30. Do you think they fulfil their purpose of diffusing light creating a steady lighting environment? (Please circle one answer)

Strongly disagree Disagree Uncertain Agree Strongly agree

31. Do you think the environment of this building (playing area) makes you:
☐ Alert
☐ Warm
☐ Distractive
☐ Comfortable
☐ Sleepy
☐ Cold
☐ Attentive
☐ Uncomfortable

3

32. What do you think makes you feel like this (noise, temperature, light, etc.)?

33. In your experience, how often is electric lighting from the ceiling used in addition to daylight? (Please circle one answer)

Frequently (all day) | Often (some hours/day) | Uncertain | Infrequently | Never

34. Do you think the internal lighting environment in the building is influencing your mood?

- Yes
- No

Why?

35. How does light influence your playing performance? (Please tick as any as appropriate)

- Allows me to see the ball clearly
- Helps me to distinguish the net lanes boundaries and other players' positions
- Doesn't influence
- It does not allow me to see properly
- Continuous changing light levels reduces the quality of my playing performance
- Other

36. Do you consider this building to have problems with glare (high brightness) ? (Please circle one answer)

Strongly disagree | Disagree | Uncertain | Agree | Strongly agree

37. When the daylight is uncomfortable or interferes with your activity, how do you re sp on d? (e.g. Move elsewhere in the building, go outdoors for a while, try to ignore it)

38. In general, the National Cricket Academy in Loughborough is a good design solution for an indoor cricket centre. (Please circle one answer)

Strongly disagree | Disagree | Uncertain | Agree | Strongly agree

39. If you have any other comments to add about the architectural design of the National Cricket Academy, please provide them here.

You have reached the end of the questionnaire. Thank you for taking the time to complete this survey. Your responses will certainly make an extremely valuable contribution to our research.

4