

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**LIGHTING IN MUSEUM BUILDINGS
AND INVESTIGATION OF A CASE STUDY**

**M.Sc. Thesis by
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Programme : Environmental Control and Building Technology

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FOREWORD

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Feride ŞENER

Architect

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ABBREVIATIONS

CCT	: Correlated Color Temperature
CIE	: Commission Internationale de l'Eclairage
CIBSE	: The Chartered Institution of Building Services Engineers
CRG	: Color Rendering Group
DF	: Daylight Factor
HID	: High Intensity Discharge
HSA	: Horizontal Shadow Angles
HVAC	: Heating, Ventilating, Air- Conditioning
IASDR	: International Association of Societies of Design Research
ICOM	: International Council of Museums
IES	: Illuminating Engineering Society
IESNA	: Illuminating Engineering Society of North America
ISO	: International Organization for Standardization
LED	: Light Emitting Diode
PVB	: Poly Vinyl Butyral
VSA	: Vertical Shadow Angles
UV	: Ultra Violet
3D	: Three Dimensional

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LIGHTING IN MUSEUM BUILDINGS AND INVESTIGATION OF A CASE STUDY

SUMMARY

A museum is a permanent institution in the service of society and of its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment, for the purposes of education, study, and enjoyment" as defined by the ICOM, International Council of Museums. Artistic and scientific artifacts are exhibited in museums where interaction between generations and cultures are provided.

These buildings must also be carefully designed from lighting conditions points of view. Providing the right perception to visitors about exhibited works and minimizing the deterioration of objects caused by lighting are the main matters that should be taken into consideration in lighting of museum and exhibition spaces. Due to the facts mentioned previously, works and collections in museums should be exhibited and protected properly. Specifying the importance of lighting in museum buildings and investigating the approaches for the protection of the artworks is taken as a fundamental issue for museum lighting.

In this study, museum architecture and the spaces of a museum building are described and the lighting system of museum buildings are investigated from daylighting and artificial lighting points of view. As a part of this study, an investigation was made at Kunstmuseum Stuttgart from lighting condition points of view. Comprehensively investigating the selected museum galleries from natural and artificial lighting systems and the sort of artifacts taking part in the collection point of view; necessary determinations are held by supplying illumination level measurements and comparing the measurement results with the international standards. Selecting one case gallery area with the least proper conditions, daylight simulations are performed by using ECOTECH and RADIANCE lighting simulation programs.

MÜZELERDE AYDINLATMA VE ÖRNEK BİR BİNA İNCELENMESİ

ÖZET

Müzeler, Uluslararası Müzeler Birliği'nin tanımına göre, sanat ve bilim eserlerinin sergilendiği, kuşaklar ve kültürler arası etkileşimin sağlandığı yerler olarak nitelendirilmektedir. Sanatsal veya bilimsel açıdan önemli olan eserler müze binalarında saklanıp korunmakta ve sergilenmektedir.

Müze ve sergileme mekanlarının aydınlatılmasında başlıca dikkat edilmesi gereken konular, sergilenen eserlerin ziyaretçiler tarafından doğru algılanmasının sağlanması ve aydınlatmadan dolayı nesnelerde oluşabilecek bozulmaların en aza indirgenmesidir. Bu bağlamda müzelerde eserlerin ve koleksiyonların doğru olarak sergilenmesi ve korunması gerekmektedir.

Bu çalışmada müze mimarisi ve müze mekanları ile ilgili genel bilgiler verilerek müzelerdeki aydınlatma sistemleri, doğal ve yapma aydınlatma açısından incelenmiştir. Müze nesnelerinin korunmasına ilişkin genel kavramlara değinilerek bu konuda yapılmış olan çalışmalar tanıtılmıştır. Bu çalışma kapsamında Stuttgart Sanat Müzesi örnek bina olarak seçilmiştir. Aydınlatma kriterleri açısından ele alınan mekanlar, doğal ve yapma aydınlatma sistemleri ve koleksiyonda barındırılan nesneler açısından ayrıntılı olarak incelenerek mekanların doğal veya yapma aydınlatmasına yönelik gerekli tespitler yapılmış, aydınlık düzeyi ölçümleri gerçekleştirilmiş ve ölçülen sonuçlar uluslararası standartlarda verilen değerler ile karşılaştırılmıştır. Örnek galeri hacmi, ECOTECH ve RADIANCE aydınlatma simülasyon programları yardımı ile modellenerek gerekli günışığı simülasyonları gerçekleştirilmiştir.

1. INTRODUCTION

Museums look after the world's cultural property and interpret it to the public. As this is not ordinary property, it has a special status in international legislation and there are normally national laws to protect it. The collections of the museum are part of the world's natural and cultural heritage and may be of a tangible or intangible character. Cultural property also often provides the primary evidence in a number of subject disciplines, such as archaeology and the natural sciences, and therefore represents an important contribution to knowledge. It is also a significant component in defining cultural identity, nationally and internationally.

Museum collections reflect the cultural and natural heritage of the communities from which they have been derived. As such, they have a character beyond that of ordinary property, which may include strong affinities with national, regional, local, ethnic, religious or political identity. It is important therefore that museum policy is responsive to this situation (Url-1). Museums collect, preserve and display natural artifacts or examples of human achievement. These buildings sustain the historical and cultural heritage. The lighting design of such important institutions must be unique and integrated to the architecture.

Art gallery and museum architecture developed strongly during the 19th century. There are many kinds of museums that can be classified due to their collections. Each of them have some various specific lighting requirements. Artifacts are the objects that belong to a museum's collection for historical, scientific, artistic, scholarly and humanity reasons. Generally artifacts are sensible to light and radiation. Radiation differs in wavelength, also in the visible region, that are potentially harmful to materials used in art. Therefore, the limits of light exposure must be considered in lighting design. These values have recently been revised by the publications of CIE and IESNA depending on kinds of materials, which are divided into categorizations due to their sensitivity.

In the history, lighting was supplied by daylighting only. The architecture of the buildings were shaped with respect to using daylight in a great percentage. Since

then architecture and art itself have changed a lot. But the basic needs of lighting in buildings remained. As the technology developed, further systems for lighting of buildings varied.

When an architect designs an interior environment with respect to daylight, the opening on the façade or building skin carry major importance as they effect the view outside and also they interact the appearance of the building. When the typology is a museum, the designer must be aware of the daylight openings and their control in the early design steps of the design. As the harms that the daylight may lead are currently known today by the architects and the museum staff, necessary obligations must be obeyed.

Designing a proper lighting system does not end with providing the recommended illumination values for the task areas. Color and vision are other important parameters in museum lighting to see the correct forms, textures and colors of the artifacts. International guidelines must be followed in museum lighting and shaping the architecture. Presenting the ideal visual comfort conditions and designing the most suitable conditions of the lighting system within the museum environment, the museum spaces turn into a more pleasant atmosphere and the cultural heritage can be protected and sustained to the next generations.

In a contemporary approach to design the interior by considering the lighting system, several simulation tools guide the designer. Simulation tools have been developed in order to predict the effects of artificial and natural light sources on the built environment. Computational visualization with synthetic images is a strong development in order to help the architect's design in many ways. Among them, the possibility of understanding and optimizing the architectural proposal from the daylighting point of view is also necessary considering the prediction of the conditions for environmental comfort and energy efficiency optimization in architecture.

In this study, museum architecture and the spaces of museum buildings are described in Chapter 2, where examples from the museums are given about museum spaces or museum architecture. The definition of museums and historical explanation of museums are made in a chronological order from architectural points of view in this chapter. As museum objects are exceedingly sensitive to any kind of

damage, lighting of a museum building needs additional skills when compared to other building typologies. In this study, main considerations about museum lighting are given in Chapter 3. The preservation of museum objects is considered to be another important parameter for museum design so it is essential to develop a lighting conservation strategy based on overall exposure lighting values for artifacts. There are many ongoing researches about artifact conservation and also many international guidelines exist in order to provide the artifacts from harmful portion of light. Chapter 4 discusses about light and its effects on museum objects giving examples about the conservation strategies. In Chapter 5, the investigations performed at Kunstmuseum Stuttgart from lighting condition points of view are described. In this chapter, lighting simulation tools that are used in this study are described. ECOTECT simulation tool and RADIANCE simulation engine were used in order to calculate the daylighting conditions of the gallery. This evaluation was performed in order to supply the most appropriate conditions from visual comfort conditions point of view and protecting the artifacts at the same time. The case study chosen for this thesis is a modern museum, but the same approach can be applied to other galleries or traditional museums in order to predict the time period when daylighting is to be controlled due to the reasons of conservation standards and visual perception.

2. GENERAL INFORMATION ON MUSEUMS AND MUSEUM ARCHITECTURE

Museums are one of the most desirable commissions for architecture acting as the triggering points of the regions that they are built to. Museum architecture can be seen as a distinguishing emblem for a city and in many cases as a landmark for the environment. The design of a museum carries great importance as they can act like a catalyst for their environment.

In this chapter, the definition and historical explanation of museums are made in a chronological order from architectural points of view. The spaces that a museum building might have are introduced by giving examples throughout the world about museum architecture.

2.1 Definition and Historical Development of Museums

A museum can be defined by the International Council of Museums as a permanent institution in the service of society and of its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment, for the purposes of education, study, and enjoyment (Url-1). Artistic and scientific artifacts are exhibited in museums where interaction between generations and cultures are provided. Museums and art galleries collect, preserve, analyze and display natural artifacts and examples of human achievement and their impact on people.

Collections of objects brought together as they have personal or collective associations occurring in remote antiquity. Grave goods found with Paleolithic burials provide evidence of this fact. However, development towards the museum idea occurs early in the second millennium BCE at Larsa in Mesopotamia where copies of old inscriptions were reproduced for educational use in the schools. Archaeological evidence from the sixth century BCE levels at Ur suggest that not only were the kings Nebuchadrezzar and Nabonidus collecting antiquities at this time, also, about the same time, there was a collection of antiquities in a room near the temple school

which was associated with a tablet describing earlier brick inscriptions found locally. This could be considered to be a museum label.

The grouping together of precious objects has gone on since antiquity: Egyptian tombs, ancient temples, medieval church crypts, royal treasures, and all sheltered collections. But the attractive presentation of these pieces, including art, as opposed to their secretive storage, marked the beginning of what the museums are. At the beginning of 16th century, in English country houses and French castles, painting collections at first confined to portraits, were shown in long, connective corridors.

Despite the classical origins of the word ‘museum’, neither the Greek nor the Roman empires provide examples of a museum, as we know them today. The votive offerings housed in the temples, sometimes in specially built treasuries, were normally open to the public, often on payment of a small fee. They included works of art, natural curiosities as well as exotic items brought from far-flung parts of the empire but were primarily a religious provision. The veneration of the past and of its personalities in Oriental countries also led to the collection of objects while relics were being accumulated at the tombs of early Muslim martyrs of which those dedicated to Imam-Reza at Meshed in north-west Iran is today housed in a museum near the tomb. The idea of al-waqf, involving the giving of property for the public good and for religious purposes, also resulted in the formation of collections. In medieval Europe, collections were mainly the prerogative of princely houses and the church. Such collections had an economic importance and would be used to finance wars and other state expenses. (Monater, J. M., 1990).

Other collections took the form of alleged relics of Christendom. With the resurgence of interest in its classical heritage and facilitated by the rise of new merchant and banking families, impressive collections of antiquities were formed in Europe. Outstanding among the collections was that formed and developed by the Medici family in Florence and eventually bequeathed to the state in 1743 to be accessible ‘to the people of Tuscany and to all nations’. Royal and noble collections were also formed in many other European countries. (Greub S., Greub T., 2007).

By the seventeenth century, increasing interest into human as well as natural history led to the creation of many specialized collections by the intelligentsia of the day. This is also the period when the first scientific societies were established; and a in

Florence (1657), the Royal Society of London (1660) and the Academie des Sciences in Paris (1666). By this time systematic classifications for the natural and artificial world were available to assist collectors in ordering their collections. This reflects the spirit of system, rational enquiry and an encyclopedic approach to knowledge now emerging in Europe (Monater, J. M., 1990).

The museums of eighteenth and nineteenth century were expected to simply provide spaces for the permanent exhibitions. The design was only needed to supply the fundamentals of the museum environment. As the exhibitions of the collections were held in magnificent spaces of the big palaces, such buildings were seen as the architectural precedents of museums. Because of it, museum buildings with neoclassic style in Germany, America and England began to be built since the beginning of 1800. As new collections were put together in the 19th and 20th centuries, private individuals also began to commission architecture for them. In the twentieth century, a wide variety of functions were added to the museums and the main design parameters of this typology changed. In addition to exhibition areas, museums required considerable spaces for storage, conservation and restoration of the works. With the increase in population of visitors to cultural buildings, museum activities combined with other activities so they turned into conceived centers of educational facilities and consumption with the needs of shops, restaurants, auditoria and spaces for temporary exhibitions (Greub S., Greub T., 2007).

2.2 Museum Architecture and the Spaces of a Museum

They also carry out a city centre function connecting the citizens. Rundown areas of a city can be developed with the linkage of cultural spaces like museums containing diverse facilities. Guggenheim Museum in Bilbao designed by Frank O. Gehry and Georges Pompidou Centre designed by Renzo Piano and Richard Rogers and Sue Rogers are two of the well-known examples. Both of these famous buildings were first designed in order to develop the areas that they are constructed to. In Figure 2.1 and Figure 2.2, the images for these museum buildings can be examined.

The architecture combines the typology of a museum with the typology of an urban meeting point. A museum building can also act like a catalyst for economical revival in an urban area or in a city. In previous times, it was only the exhibition that saliented in a museum building but now, the building itself is seen like an important

prestige element. The architecture of a museum building must function in the dialogue between building and art, architecture and user. In the recent museum buildings that were designed after 2000, five tendencies can be examined in the architecture of the buildings which are classic modesty, new transparency, new missions, new symbolism and new body reference (Greub S., Greub T., 2007).



Figure 2.1 : Guggenheim Museum in Bilbao (Url-2)



Figure 2.2 : Georges Pompidou Centre in Paris (Photo by Şener, F., 2008)

Today's museums are built so that the building itself can be the message for the subject it involves. They can be built as prestige elements for the commissions that they symbolize. Mercedes Benz Museum Building in Stuttgart, Germany can be given as an example for this situation. As can be seen from Figure 2.3 and 2.4, the museum building is designed so that the building itself symbolizes the developing technologies and is a demonstrative element of the Mercedes Commission. This building does not only contain the collections of old or recently developed industrial

designs by Mercedes Benz, but also gives the message of a changes in technology, culture, and its integration with transportation.



Figure 2.3 : Mercedes Benz Museum Building in Stuttgart (Photo taken by Şener, F., 2008)



Figure 2.4 : An interior from the Mercedes Benz Museum where the collections are exhibited in a chronological order in the circulation system supplied by ramps (Photo taken by Şener, F., 2008)

2.2.1 The categorization of the museum buildings

The categorization of the museum buildings may be done due to the subjects of the museums or branch of the knowledge that the museum involves. Museums can be categorized into general museums, specialized museums and special museums. Special museums are also called theme museums with that displays on a specific

subject. Some examples to theme museum categorisations can be given as social history, transport, military, history, agricultural and so on (IASDR07, 2007).

Museum typologies can be investigated under the following headings from architectural sight:

- Cultural Complexes,
- National Museums and Galleries,
- Museums of Contemporary Art,
- Museums of Science, Technology and Industry,
- Civic and Single- Theme Museums,
- Galleries and Centres of Contemporary Art (Monater, J. M., 1990).

As the museums of the recent generations have many facilities inside, the typology has turned into great cultural complexes communicating the public. These types of spaces are generally connected to each other under a huge shell letting the visitors to use different kinds of activities. Federation Square Building in Melbourne designed by LAB Architecture is an example to complex museum buildings involving cultural institutions, art galleries, city visitor information centre, retail spaces, and civic spaces like shops, restaurants and cafes. In Figure 2.5, one image from the Federation Square Building in Melbourne is given.



Figure 2.5 : Federation Square Building in Melbourne (Url-3)

National Galleries are another kind of museums where the collections belong to a country. These buildings express the idea of a nation charged with political and

ideological degrees. They can explain the monumental architecture housing collections under an administrative structure. British Museum is an example to types of national museum kinds (Monater, J. M.,1990).

Contemporary art museums are the spaces where the artworks of contemporary art are collected and exhibited. As these buildings are the symbols of new design approaches, the architecture of them also reflect the changes brought by new technologies. The artworks are intended to be exhibited in an entirely new building or in the extensions of historical buildings constructed because of the increase in the need of spaces.

Museums of Science, Technology and Industry are places where the collections may differ in scales. This effects the space requirements of the interior. These buildings can be designed as neutral, flexible containers housing collections. The recent examples of them present an extremely high level of technology from the technical details of the building to the sophistication of the equipments. Civic and single theme museums are the sorts of museums where the design is based on compartmentalization of space and supporting elements spesifically for each of the collection or artwork. In this kind, the building itself is not of great importance while the interior space only defines the character of the exhibition (Monater, J. M., 1990).

The remained last group of museums are named as galleries and centres of contemporary art. This typology is similar to contemporary art museums but the difference is that they are commisions which are private (Monater, J. M., 1990).

2.2.2 Spaces of a museum building

The main activity of the museums is exhibition of its displays. Beside this today museum designes have different spaces for various functions. Some examples to museum spaces can be given as exhibition halls, shopping and dining areas, circulation areas which can also be a part of the exhibition areas, educational areas for performing workshops, lectures, entrance foyers and service areas. Stated below, the design fundamentals of museum spaces can be seen in different titles can be seen.

2.2.2.1 Design of circulation areas

Circulation areas are the ways that the connecion between other spaces can be supplied. The architectural characteristics of facilities play an important role in

determining circulation patterns. Museums can act as spaces designed for circulation of the public so design of the circulation axes, corridors, vertical and horizontal connections, ramps, stairs are of great importance in these buildings. Transparency is an important factor for the design of circulation areas in order to create an elegant and attractive atmosphere. The glazed roof on the British Museum is given as an example in Figure 2.6 for using transparency effects for the circulation areas.



Figure 2.6 : Circulation areas of the British Museum, London (Photo taken by Yener, A., K., 2008)

The idea of positioning exhibition galleries designed at different levels around one central court and connecting these spaces by means of circulation systems is a common used feature in museum architecture. This method can be based on an early approach by Le Corbusier's design called Mundaneum where design of different routes lead to the exhibition spaces. This solution is employed by Frank Lord Wright in the Guggenheim Museum where the central ramp is used as a connection to the exhibition levels which is also the most dominant part of the museum building. In Figure 2.7, one section from the museum is given.

There are three major elements for circulation in museums which are conceptual orientation, wayfinding, and circulation. Conceptual orientation includes an awareness and understanding of the themes and subject matter organization of the facility. Although visitor expectations and prior experiences play a key role in conceptual orientation, the most important factor appears to be on-site orientation systems. Wayfinding, involves being able to find or locate places in a facility. Orientation devices such as maps and direction signs are critical for wayfinding in

museums (Bitgood S., 1988). Today, innovative technologies can also guide the visitors in wayfinding in the circulation areas.



Figure 2.7 : Section of Guggenheim Museum in New York showing the connection of the ramps to museum spaces (Url-4).

Several stairways can access to different parts of the museum building. An alternative access for disabled must also be considered when stairs are used in museums. Additional lighting systems can be recommended to prevent accidents caused by insufficient visual conditions. An example for stair lighting is given in Figure 2.8.



Figure 2.8 : Lighting of steps in the staircase of Mercedes Benz Museum, Stuttgart (Photo taken by Şener, F., 2008)

2.2.2.2 Design of exhibition areas

The task for an exhibition area design is, in most cases, to bring form and content of the exhibition together into a synthesis of content, communication and aesthetics.

These components must support each other, to give the visitor an optimal experience. The design of exhibition areas change due to the kinds of collections. They may vary in size as there are different kinds of objects in the exhibitions.

The architecture is recommended to control the environment to enable both display and conservation. Environmental control in case of museums involves the regulation of lighting and HVAC systems in the interior.

2.2.2.3 Shopping and dining areas

As the museums turned into spaces of commissions, these kinds of spaces are added to museum functions. These spaces can be run by special commissions or may also belong to the museum or the gallery. The shopping areas of the museum buildings, several goods about the exhibition may be found. In Figure 2.9, the shopping area of Neue Staatsgalerie in Stuttgart is given.



Figure 2.9 : Shopping area of Neue Staatsgalerie in Stuttgart (Photo taken by Şener, F., 2008)

2.2.2.4 Spaces of education and innovative technologies

The education function of museums is about enabling people to learn of all ages and cultures. It embraces learning from museum buildings, sites, documentations published by the museum, research and collections that they house. An important opportunity that museum use to fulfil their education function is to produce effective exhibitions that respond to audiences learning needs (Url-5).

The technology lets interactive experiences to be used in general benefitting from natural interactions, compelling communication. These technological features are also common for museum buildings as they faced with the challenge of designing exhibitions, handling large volumes of visitors, and conserving precious artworks. Contemporary museum buildings require diverse spaces suitable for developing functions.

Using interactive techniques embedded in the physical space of museums can present a large variety of connected material in an engaging manner within the limited space available. They can also enrich and personalize the visit with computers, which act as a visual and auditory storyteller that guide the public through the path of the exhibit. The presentation tables can be used as a playful interface for the public to access and explore the body of facts, content, and stories of the exhibit. (Sparacino F., 2002)

Interactive spaces in museums attract the visitor's attention and guide them in an educative and enjoyable way. These spaces require technological connections. In Figure 2.10, an example to an interactive area designed for Unbuilt Ruins Exhibition at Compton Gallery is given. Placing the active cursor on the map visitors can supply information about the project and display its views.

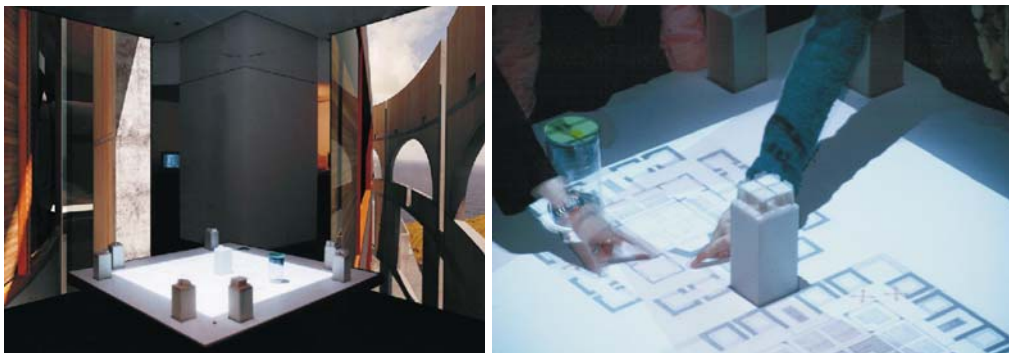


Figure 2.10 : Images of the Unbuilt Ruins exhibit taken at the Compton Gallery at MIT (Sparacino F., 2000)

3. LIGHTING IN MUSEUM BUILDINGS

Museums are institutions that collect, safeguard and make accessible artifacts and specimens, which they hold in trust for society. Museums enable people to explore collections for inspiration, learning and enjoyment, defined by the UK Museums Association (Url-6). Such institutions must also be unique in their lighting design. As museum objects are exceedingly sensitive to any kind of damage, lighting of a museum building needs additional skills when compared to other building typologies.

Light is a primary element in architectural design. Architect Le Corbusier clearly identified the importance of light in architecture when he expressed the point that, “Architecture is the masterly, correct and magnificent play of volumes brought together in light.” emphasizing that the history of architecture is the history of the struggle for light (Le Corbusier, 1985).

Lighting design for a museum or an art gallery is a collaborative art and science at the same time. The design must be considered from the early steps of the project and must also include all the necessary information about the international lighting standards. The lighting designer or the architect of a building must take the lighting system of the building into consideration while designing the building elements. The integration of lighting systems to the building skin can be seen in the early design sketches of the Sainsbury Visual Arts Centre Building designed by Norman Foster in Figure 3.1.

The lighting design process must involve input from many individuals. Discussions with the curator and the museum educators will help determine how the objects should appear when exhibited, how to direct the visitor through the exhibition and how to direct the visitor’s eye in viewing individual objects. Discussions between the conservator and the lighting designer should focus on the light sensitivity of the objects, the illumination limits for the objects, the exposure duration limits or wavelengths. Close work with the exhibition designer will enhance the appearance of the

exhibition. Working relationships with the maintenance staff will determine its ability to sustain the design before it is implemented (IESNA RP 30, 1996).

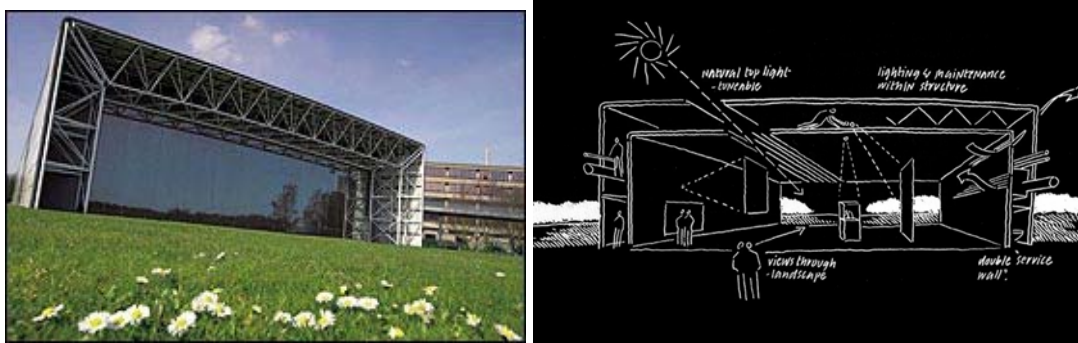


Figure 3.1 : Sainsbury Visual Arts Centre Building and the sketches showing the integration of lighting design to a museum building (Foster N., 2004)

3.1 General Aspects of Lighting Design and Visual Comfort in Museums

Light is one of the tools to shape the built environment visually and emotionally. Lighting design is a synthesis of light and shadow, color, form, space, rhythm, texture and proportion. The lighting design of spaces is a creative process for developing lighting solutions to have safe, productive, and enjoyable use of the built environments (IES DG-7, 1994). The flowchart for designing a lighting system for a museum buildings is given in Figure 3.2.

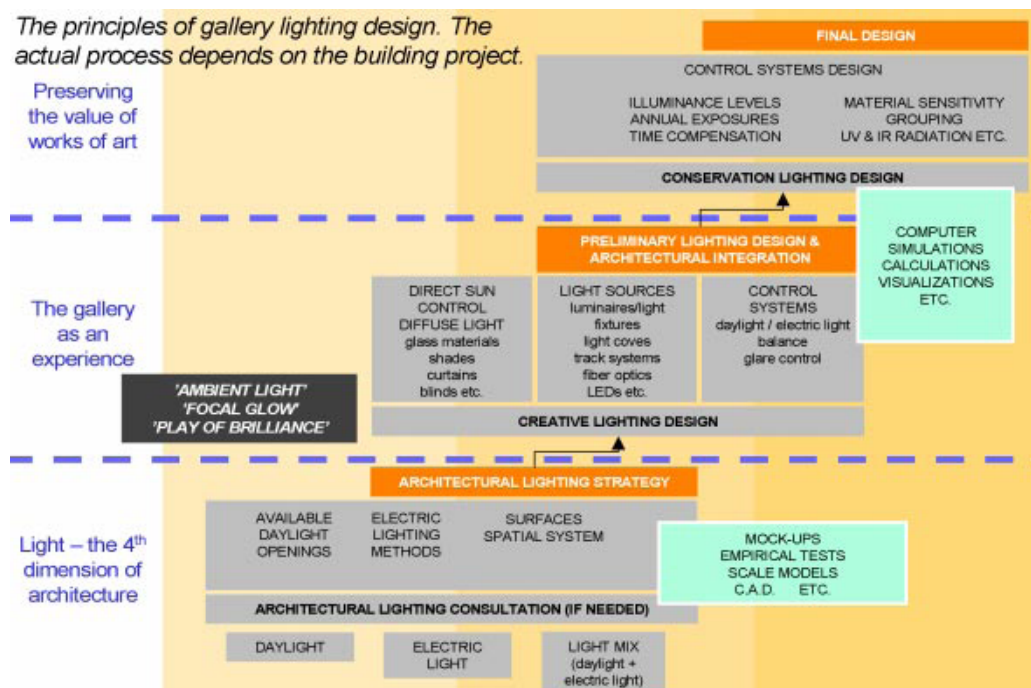


Figure 3.2 : The flowchart of design in museum buildings lighting (Oksanen J., Norvasuo M., 2002)

In the past, there has been an emphasis on assuring that an appropriate quantity of light is delivered into the task or working surfaces. Quality of light has been considered mainly in the limited sense of controlling direct glare from luminaries or reflected glare from the surfaces and objects. Lighting design must ensure both of these mentioned aspects of light.

The main criteria in museum lighting can be defined as the protection of the artifacts and at the same time providing the right perception for the objects. In 18th century when the first modern museums were established, the main function in the building was only to exhibit the artworks and because of this fact, the museum buildings designed in these periods had basic spaces with rectangular plan shapes with toplighting using all the walls as exhibition areas. In the beginning of 20th century, educative functions were also included in the museum programs and this led changes in the alteration of museum spaces and their lighting designs as well (IESNA RP 30, 1996).

As described in IES, the main characteristics for lighting design of interior spaces must include owner and design team preferences, visual and perceptual needs, security issues, architectural opportunities and constraint, photometric considerations, budget, energy limitations and maintenance considerations. In museum spaces an addition to these criteria is the protection of artifacts while designing the lighting system (IES DG-7, 1994).

In the design development phase, the lighting concept is generally refined, and the further documentation before the design period is initiated. Mounting details are developed and lighting layouts are firmed up. Selection of light sources and luminaries requires an understanding of photometric reports. Initially the designer creates the lighting effects by using some techniques named as enlarging the space by light, making smaller spaces, grazing, wall washing, framing, accent, ambient and visible fixtures.

When the deteriorative effects of daylighting were figured out, artificial light was preferred for lighting, both to create a light effect and to prevent exposure to harmful elements in natural light, but it sometimes provides an unnecessarily theatrical presentation or creates an artificiality that can inhibit the visitor's appreciation and enjoyment of the work. Much greater use is now made of controlled indirect natural

light. Tate Gallery, London is a good example to using indirect lighting systems as integrated to building design that are used in the exhibition spaces. In the section of the Tate Gallery building, the artificial lighting system is integrated to the specially designed roof in order to increase the effect of daylighting when it is insufficient (Kılıç H., 1985). In Figure 3.3 the images from the toplighting can be examined.



Figure 3.3 : Interior and exterior images from Tate Gallery, London showing the controlled toplighting and solar control system (Wilson M.,2006)

In museum buildings, visual tasks are of great importance. When obtaining daylight in the interior, the visual problems caused by daylighting must be controlled. Glare is the visual sensation produced by bright areas with the field of view and may be experienced as either discomfort glare or disability glare. Glare may also be caused by reflections in specular surfaces usually known as veiling reflections or reflected glare. It is important to limit the glare to avoid errors, fatigue and accidents.

Disability glare is a common met situation in exterior lighting but it may also be experienced from spotlights or large bright sources such as a window in relatively poorly lit spaces. In the interior spaces, discomfort glare usually arises directly from bright luminaries or windows. If the discomfort glare limits are met, then the disability glare is not usually a major problem.

Glare is caused by excessive luminances or contrasts in the field of view and can impair the vision of objects. It should be avoided by suitable shielding of lamps in the artificial lighting design of spaces (CIE, 2001). The minimum shielding angle of lamp luminances shall not be less than the values given in Table 3.1.

Table 3.1: Lamp luminance and minimum shielding angle for luminaires (CIE, 2001)

Lamp luminance (kcd/m ²)	Minimum Shielding Angle
1 to 20	10°
20 to 50	15°
50 to 500	20°
≥ 500	30°

Museum exhibits can be categorized into four main groups in which the lighting requirements change for each specific situation. This categorization is necessary for a better design in exhibition spaces. These groups can be named as flat displays on vertical surfaces, display cases, three dimensional objects and realistic environments (IESNA RP 30, 1996). For each of the groups, the lighting designers must deal with creative opportunities and different challenges. Each of these categorizations will be explained below.

3.1.1 Flat displays on vertical surfaces

Flat displays are defined as the paintings or two-dimensional art objects. These kinds of collections require flat vertical exhibition places. From lighting point of view, uniform lighting of the flat displays on vertical surfaces is a common lighting dilemma in museums. Paintings, prints, documents, explanatory labels can be counted in this category of artifacts.

The uniform lighting of the flat surfaces can be illuminated from the ceiling by using spotlights or wallwashers. Another method to illuminate them is using luminaires integrated to the floor when possible. Schematic illustrations for flat display lighting can be seen in Figure 3.4.

When a surface with a high reflectance value is used to protect the artifact surface, some reflection problems occur. This situation can be defined as one of the most often met visual problems in the display. The positioning of two high reflectant surfaces in a space can cause mirror effect, which is an unwanted situation for flat displays on vertical surfaces. In Figure 3.5, an example to this situation can be found.

One of the most famous paintings in the world, portrait of Mona Lisa, is illuminated by using a ceiling mounted lighting system, but the glass protective layer causes reflection on the exhibition surface.

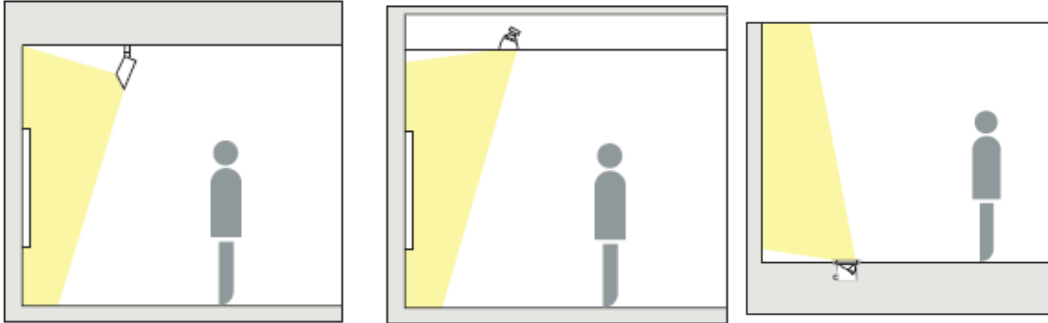


Figure 3.4 : Schematic illustrations for flat display lighting (Url-7).



Figure 3.5 : Reflection on the protective glass layer of Mona Lisa (Photo taken by Şener, F., 2008).

Generally the lighting should provide uniform intensity over the entire surface. There are two good methods for reaching uniform lighting levels when lighting a vertical surface. Wall washing and spotlights are the commonly used techniques for artificially lighting the flat displays. Wallwashers are integrated to walls to evenly diffuse light which is the most important aspect in this kind of lighting. Spotlights are used in lighting of small or medium sized pictures or label panels mounted on a wall. The mounting diagram for a vertical surface can be seen in Figure 3.6. Average viewing distance for the flat displays on vertical surfaces is defined as 1050 mm.

This distance is directly proportional to the sizes of the paintings. Average adult eye height is 1550 mm. Luminaires positioned so that the beam center axis is 30 degrees from the vertical, which is also illustrated in Figure 3.6, helps to produce minimal shadows and glare free viewing. This situation also allows the visitors to approach the artifact closely without casting their shadow. The mounting distance of lamps (x) is given in Formula 3.1. in this context (IESNA RP 30, 1996).

The mounting distance of lamps (x) = (Ceiling height- Eye level) x 0.577 (3.1)

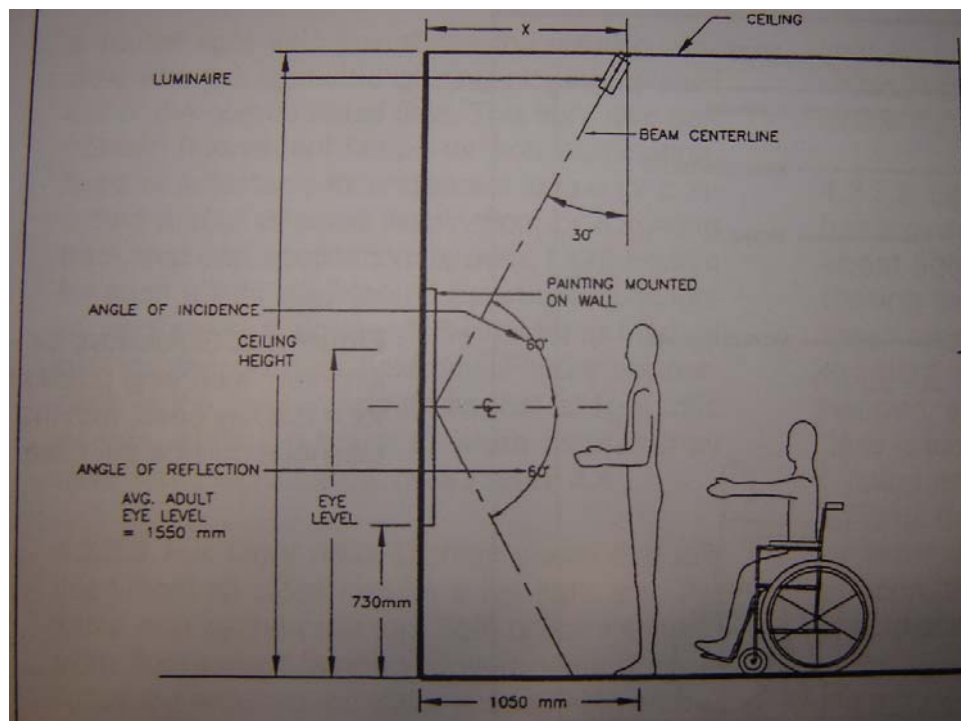


Figure 3.6 : The mounting diagram for a vertical surface (IESNA RP 30, 1996).

It is also possible to use optical projectors to frame the object but this can cause an artificial appearance. In this kind of situations, it is recommended to soften the light in the display space to prevent a transparent looking image. The uniformity of the illuminance is the ratio of the minimum to average value. The illuminance shall change gradually. The task area is recommended to be illuminated as uniformly as possible. The uniformity of the task illuminance should not be less than 0,7. The uniformity of the illuminance of the immediate surrounding areas should not be less than 0,5 (CIE, 2001).

Generally, the lighting should provide the uniform lighting situations for the two dimensional exhibitions. In order to avoid uniformity problems for the display of two-dimensional objects, international guidelines must be followed. In Figure 3.7, there is an image from Istanbul Naval Museum showing an often met lighting problem during the exhibition of two dimensional artifacts on the walls. As the illumination of the exhibited works is not supplied in a homogenous way, there is a great difference in the lighting levels on the walls. A proposal to solve the uniformity problem in Istanbul Naval Museum can be seen in Figure 3.8. In order to have uniform lighting distribution on the walls, wallwashers were selected so that the maps on the walls can be stressed.



Figure 3.7 : Uneven distribution of artificial light at İstanbul Naval Museum, Borealis Gallery (Photo taken by Şener, F., 2007).

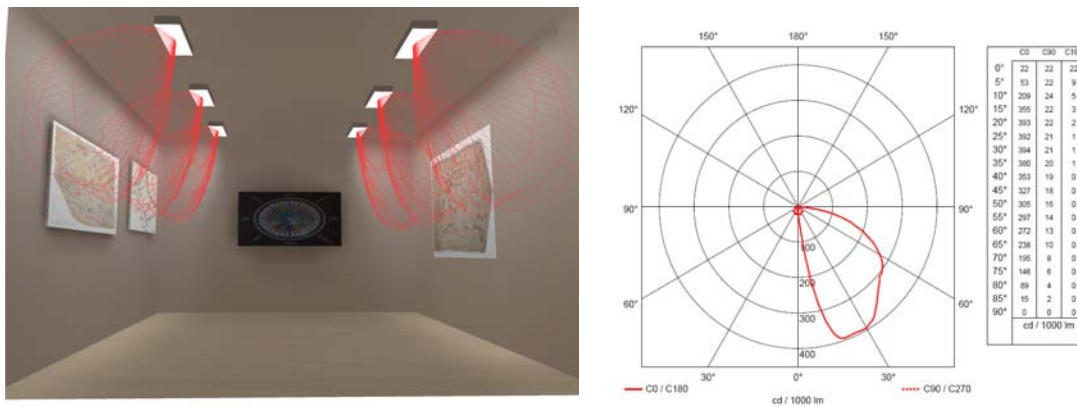


Figure 3.8 : A proposal for Istanbul Naval Museum Maps Room prepared by Relux Simulation Tool by using wallashers (Şener F., Yener A. K., 2007)

The placement of windows and the two dimensional objects at the same wall is not a recommended situation because of the change in the illumination level rapidly on the same surface. The adaptation of the eye to these kinds of changes is always difficult. An example to these kinds of problems can be found in the Louvre Museum, where both the windows and the paintings can be seen on the same wall in Figure 3.9.



Figure 3.9 : Two dimensional artifacts and daylight openings which are on the same surface, Louvre Museum, Paris (Photo taken by Şener, F., 2008).

3.1.2 Exhibit cases

Museum exhibit cases allow visitors to approach rare and delicate artifacts closely while maintaining a barrier against degradation, vandalism, or theft. These cases usually contain small, delicate and valuable artifacts and this protection is supplied by the usage of vitrines.

A vitrine can be explained as a transparent enclosure around an artifact, usually the top of a display case. It is essential that showcases are constructed with care and attention to detail as they form an essential barrier to the conditions within the galleries, but can also be used to provide a contrasting micro-environment. All materials used in the manufacture of both cases and case fittings should be inert, preferably metal and glass. The outer shell of the case must be made from laminate glass, toughened glass should not be used. Float glass may be used for shelving within a case. The possible loading of the shelf must be checked and a suitable thickness of glass should be used (Url-8). The vitrines may be designed so that they

can act like a part of the interior. Vitrine design in Jewish Museum can be given as example to the integration of vitrines with the designed spaces.



Figure 3.10 : The integration of vitrines and the lighting system to the design, Jewish Museum (Url-9).

Lamps should be housed in a separate compartment and it should be possible to direct the light from the source to the object. All case lighting must be easily controllable, using dimmers. Vitrines may have internal or external lighting, with different lamp alternatives. It is recommended in the international standards that the light source can be placed in any plane except directly behind the viewer.

When designing the most appropriate conditions for vitrine lighting, the designer must consider the advice taking place in the international lighting standards. The most often met problems with display case lighting are the reflections in the glazing caused by daylight or luminaries and shadows caused by the viewers or the displayed artifacts on the vitrines. The solution to avoid these problems is to place the luminaries and the glass surfaces of vitrines in the most appropriate way. Reflections caused by luminaries make the exhibition in vitrines hard to see and result in an unpleasant museum atmosphere for the viewers. An example to this situation can be seen in Figure 3.11 from Württemberg State Museum in Stuttgart. On glass surface of the vitrines, reflections caused by the luminaries and the windows can be seen.



Figure 3.11 : Reflections on the glass surface of vitrines in Württemberg State Museum, Stuttgart (Photo taken by Şener, F., 2008)

3.1.2.1 External lighting for vitrines

When the vitrines are illuminated by using an external source, the lights should be above the front of the case and focused straight down. Figure 3.12 describes the guidelines about luminarie mounting position for a display case with the luminaries outside the case. Other placements of the luminaries might cause unwanted shadows even if there are no opaque supporting structures. Diffusing materials can be used to create a self-lighted effect.

The diffusion material will cause a reflection from the case top onto the ceiling. It is also recommended in the standards for these luminaries to be flexible because of the changes of the possibilities for the display areas. External light sources directed onto the vitrines may produce some unwanted heat within the case by the greenhouse effect. Using dichroic reflector lamps or heat filters may help to reduce such problems.

Externally lighted display cases usually employ one of the reflector lamps in various beam patterns. Mounting heavy lamps onto the vitrines can always cause risks for the protection of the glass, which may lead to severe damage. Reduction of this kind of hazard can be supplied by placing a clear safety barrier between the lamp and the vitrine or selection of less massive lamps can be made.

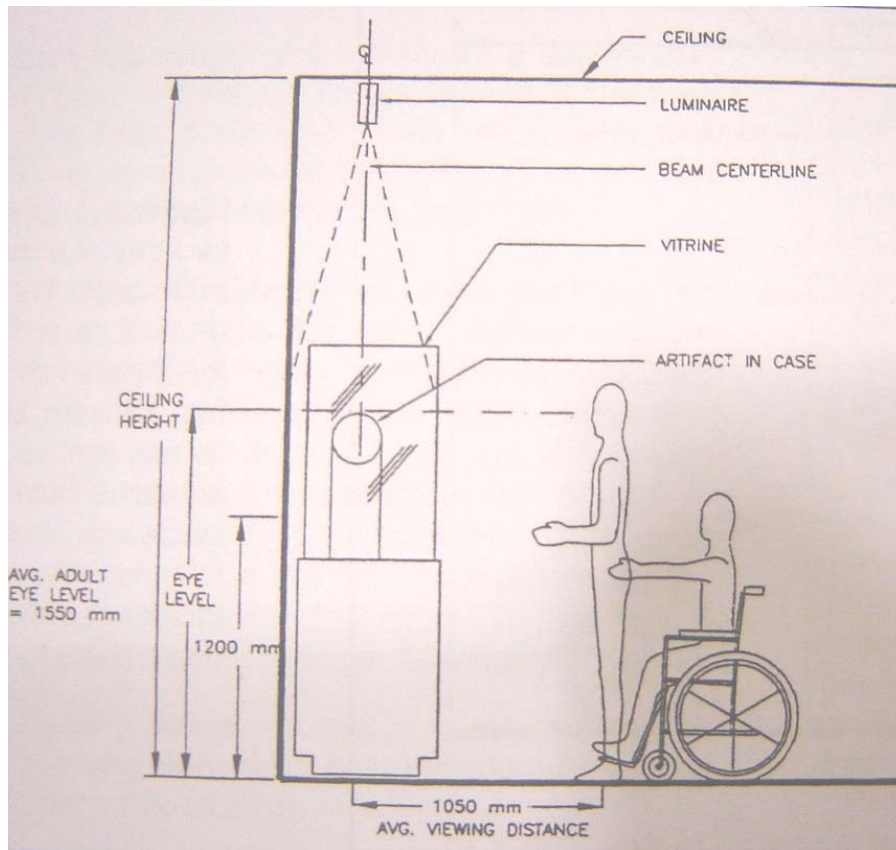


Figure 3.12 : External lighting for vitrines (IESNA RP 30, 1996).

3.1.2.2 Internal lighting for vitrines

Another method for illuminating the vitrines can be designed as internal lighting. The light sources for the vitrine can be placed onto the top of the case like a light box that can be defined as a light attic. Display cases that can only be observed from one direction can have a partial light attic above the viewing window with the light attic glazing sloping upward out of the normal visual field. These kinds of light attics can contain fluorescent lamps for soft illumination, fixed or adjustable lamps for controlled or indirect illumination. Luminaries must be simple, functional and easy to maintain.

For some occasions when the display cases are seen from all sides, it is possible to use a full light attic, which can be designed at the same size of the case top. Soft and uniform lighting can be supplied using fluorescent lamps in the attic. If the usage of spotlights is preferred instead of fluorescent lamps, it is recommended for the light attic to have a depth of 300 - 600 mm for the spots to be directed through small apertures in opaque materials or in a louver. Avoiding glare is another essential factor. Parabolic wedge louvers or lenses are the recommended choices for glare.

Figure 3.13 shows the main parameters for internal lighting for vitrines (IESNA RP 30, 1996).

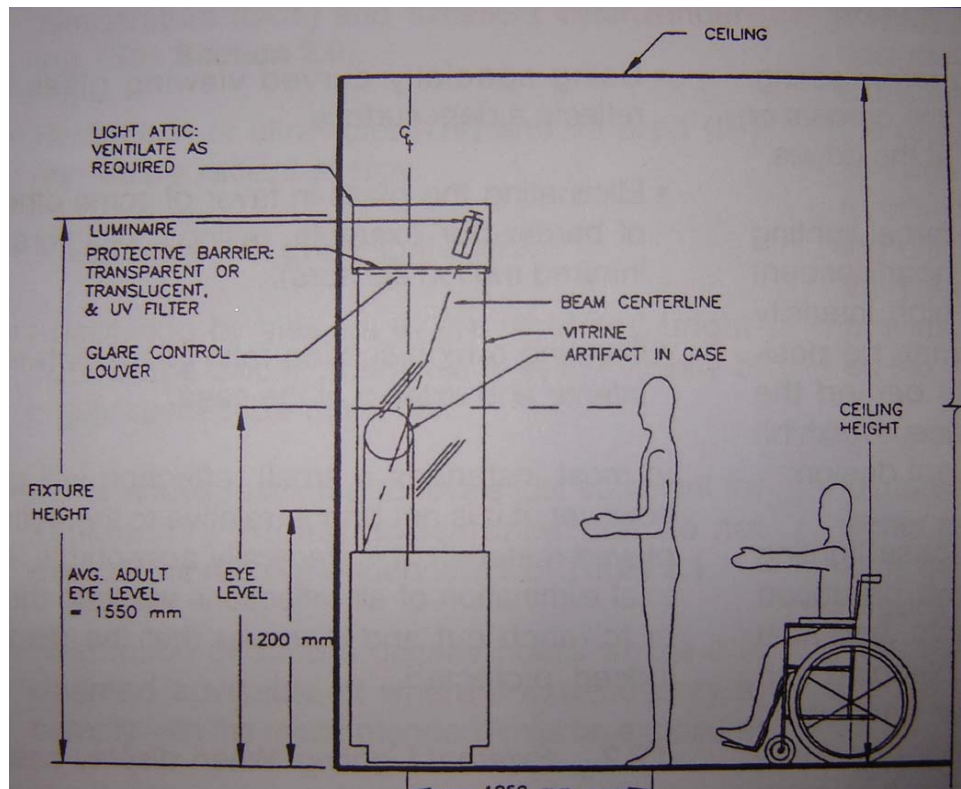


Figure 3.13 : Internal lighting for vitrines (IESNA RP 30, 1996).

Supplementary lighting from the side, back or bottom of the cases is practical in use and it can enhance the display object's dimensionality. This kind of lighting can greatly enhance ceramic, glass and polished- metal objects.

The main lighting problems met for vitrine lighting such as reflection on glass surfaces is a serious problem for showcases. An example can be seen from Stuttgart Museum where the luminaires mounted to the ceiling can cause reflections on the glass. In order to avoid these problems, anti-reflectant glasses can be used as a material choice. In Figure 3.14, the reflections on the glass surface of a vitrine caused by light sources is given.

Luminaries used for vitrines must be serviceable through a separate access door. Changing lamps should not jeopardize the display through accident, error or theft. The lamp chamber should be separated for the display case contents by a secured glazing material.



Figure 3.14 : Lighting of display cases causing reflections on the glass surface at Theodor Heuss Museum (Photo taken by Şener, F., 2007)

Internal lighting for vitrines has another kind of major problem about the protection of the artifacts exhibited, which can be explained as heat build up in the vitrine. Showcases should be as airtight as possible. In order to prevent the deterioration of the art works, there must be ventilation openings for convection cooling so that the heat can be dissipated by providing adequate airflow. These openings should also be filtered to reduce the dirt deposit on the luminaries and glazing (IESNA RP 30, 1996). Fiber optic systems do not cause heat build up in the showcases. As a result of this, they are commonly preferred in showcase lighting. An integration of fiber optic systems to vitrines can be seen in Figure 3.15.



Figure 3.15 : Internal Fiber Optic Lighting for Vitrines at Otzi Museum in Italy (Url-10)

Using UV filters on the surface of the vitrine glazing where light enters is one good method to protect the artifacts. UV filtering lenses can also be installed on the luminaries. Selecting fibre optic light sources provide distinct advantages for internally- lighted vitrines. Low level light can be piped directly into a case and focused at a specific object, while the case remains sealed. No ultraviolet light is transmitted through the fiber and the color of the fiber- conducted light can be changed by inserting a color wheel between the end of the fiber and the light injector.

3.1.3 Three dimensional objects

Three-dimensional objects exhibited in a museum building can be the sculptures or reliefs. A three dimensional art work must have some variation of illumination from several different directions to provide the essential highlights and shadows that define the object form and color. Daylighting is the most suitable kind of lighting for these objects but in many cases, daylight is not possible to use for protecting the museum objects. Light from various directions can help the designer to express depth by highlighting some areas while allowing others to fall in shadow that is a good indicator of surface forms and textures.

Illuminating a sculpture from only one direction is not a good solution to identify the forms and the textures of three dimensional artworks. All sides of a sculpture must be illuminated evenly so that the shape and the material of the sculpture can be experienced from different angles. The sculpture in Figure 3.16 takes place in front of a window and the artificial lighting system oriented to the artwork is in the same direction where the daylight is penetrating into the space. Proper distribution of light on the sculpture can not be supplied while glare problem is not avoided. This situation causes a visual problem called silhouette effect so that the artwork can not be perceived in details, texture and form. In this situation, little or none of the three dimensional quality of the form is exposed (CIBSE, 1994)

Minimizing glare at eye level is generally supplied when the beam axis of the luminaire should be 30 degrees from the vertical. For relatively small and low objects, luminaries may be steeply angled limiting the risk of glare for the observer on the opposite side. When the object is tall, some light may go past the display causing glare for viewers on the far side looking upward the artifact (IESNA RP 30, 1996). Solutions for this problem include:

- Angling the luminaries sharply down and relieving shadows with a high reflectance pedestal
- Keeping light beams entirely within the mass of the display
- Illuminating the objects from below as long as appearances are not distorted
- Using overall soft lighting in the exhibition space so that all the objects can be seen, while focusing a narrow beam on the important parts of each objects
- Lighting the background behind the artifact



Figure 3.16 : Sculpture silhouetted against the lighted background, Louvre Museum, (Photo taken by Şener, F., 2008)

3.1.4 Realistic environments

For some exhibitions, the concept of the display is designed in a whole way combining the environments, where the space itself becomes the message. For these kinds of spaces, the lighting system must be designed as the original lighting of the theatral space to give the correct message for that particular museum. Realistic exhibit spaces require compromises. The lighting designer can employ at least two techniques to achieve realistic lighting: concealed lighting positions and dual lighting systems. Deutsche Museum Pharmacy Gallery is an example to the realistic environment concepts used in museum spaces. In the gallery, the lighting system is a part of the gallery itself, emphasizing the science and technological developments in

the medical sector. Figure 3.17 belongs to the Pharmacy Gallery in Deutsche Museum.



Figure 3.17 : Realistic environment lighting in the Pharmacy Gallery at Deutsche Museum, Munich (Photo taken by Şener, F., 2008)

Another example to the museums with realistic environments can be given from Turkey, Ankara. The Atatürk Museum taking part in Mausoleum of Atatürk uses different kinds of realistic environments to express the feeling for the history of Turkish Republic and life of Atatürk. Fiber optic lighting systems were used in the design to stress the special points for the designed environment. In Figure 3.18, an image from the interior of the museum can be seen.



Figure 3.18 : Lighting of Atatürk Museum in Ankara with fiber optic systems (Url-11)

3.2 Daylighting in Museum Buildings

In the ancient times, the first and only way to lighten the interior spaces was only by daylight. The historical monuments were constructed and designed with respect to

the daylight. Daylighting of ancient Egyptian pyramids or the Greek temples are the two early examples that spring to mind when daylighting system in historical buildings is considered. An example to the daylight openings in the ancient history can be seen in Figure 3.19.

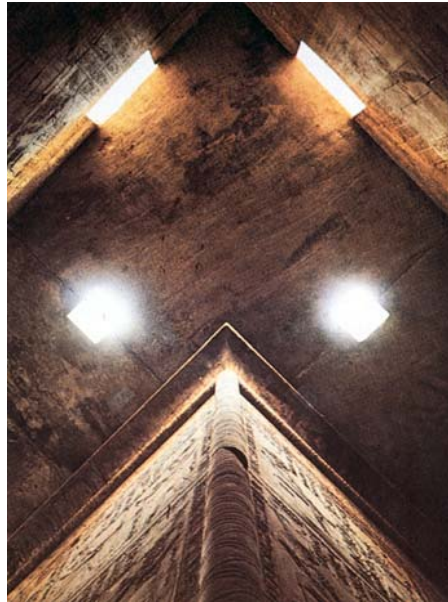


Figure 3.19 : Daylighting Chimneys in BaysHorus Temple, Edfu (Egypt) 237 BC (Scartezzini J, 2002)

The importance of daylighting is incontrovertible when its psychological effects are taken into consideration. The variable character of daylight in time and space creates a stimulating and dramatic effect as compared to artificial light. Daylighting does not only enrich the space by providing the right perception, it also minimizes the lighting load of the buildings and helps to save energy by diminishing the use of electricity for electric lighting while lowering cooling loads.

In museum buildings, using daylight is beneficial in better color rendering of objects and perception in details. It is also of significant importance to use natural lighting from sustainability and energy efficiency points of view in buildings. Using daylight is also preferable when a visual contact with the outside is necessitated. Daylight can be supplied to the buildings by using conventional or technological methods. The schematic ways to enter daylight into a space can be seen in Figure 3.20.

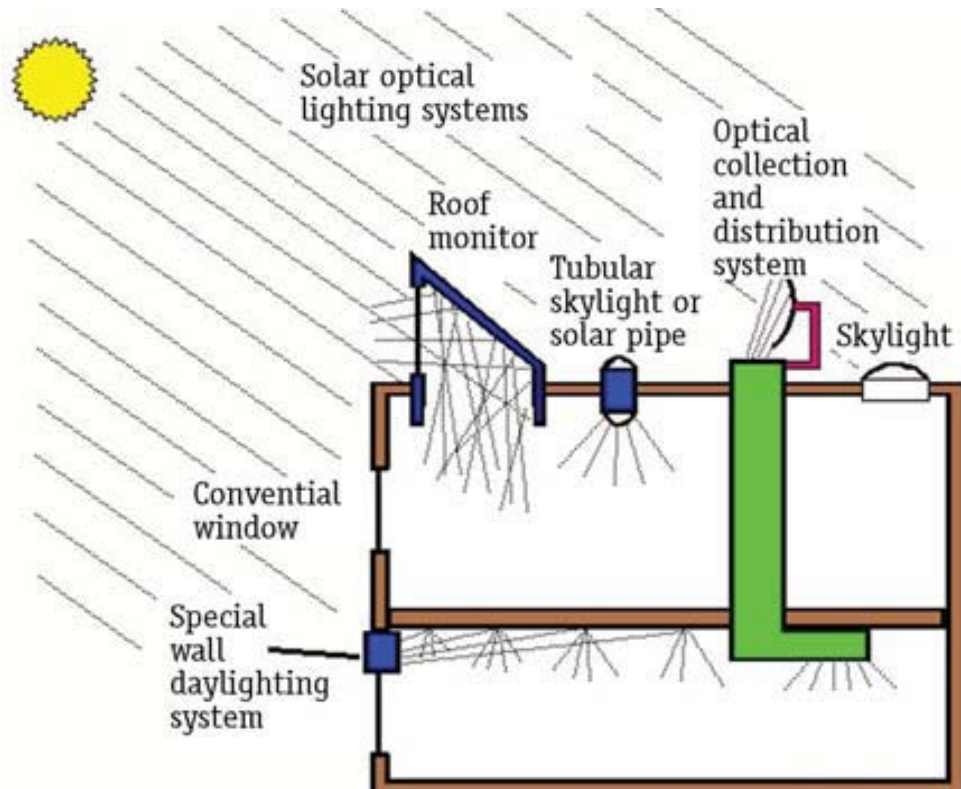


Figure 3.20 : Illustrations for gaining daylight into a space, (Kinney L, McClurey R.; 2006)

The building's form must modify the intensity and distribution of daylight to create appropriate luminous environments. The most critical decisions for a well daylit building come during the conceptual phase of architectural design, when the building's configuration and fenestration are formulated. The most critical decisions for saving lighting energy are taken during the design, specification, and commissioning of the electric lighting control systems (Leslie R.P, 2003).

For comfortable ambient lighting, the basic principles of daylighting are:

- Configuring the building so that most of the floor area occupied by people is within the daylight zone.
- Elongate a building along an east–west axis to avoid excessive solar heat gain in the summer months and to maximize north daylighting apertures (south apertures in the southern hemisphere).
- Locating critical visual tasks near the building's perimeter.
- Configuring the daylight openings in higher levels because of the fact that higher windows on the wall allow the light to penetrate further into the space.

- Admitting daylight from more than one side of a space if possible. Bilateral lighting, increases uniformity and balances the brightness within the room.
- Controlling the direct sun.
- Using light-colored interior surfaces as light surfaces reduce the luminance contrast between the windows and surrounding surfaces which will help to increase visual comfort.
- Locating workstations and computer screens perpendicular to the windows to reduce rejected glare in the screens or visual discomfort (Leslie R.P, 2003).

The principal method of admitting daylight into the exhibition spaces uses fenestrations, clerestories, or skylights. Glazed areas in the buildings have always been of major importance in determining the form and the character of buildings. The architect must be concerned with the way in which the solution to the lighting problem acts on other aspects of the building. The method of daylighting and the distribution of the glazed areas are directly related with the layout and form of the building both in plan and section. The Jewish Museum Building in Berlin, Germany designed by the architect Daniel Libeskind is a significant example to the architectural expression of a building with the design of the glazing both in the interior and exterior of the museum, see in Figure 3.21.



Figure 3.21 : Jewish Museum in Berlin, the effect of daylight openings to interior and exterior design (Photo taken by Şener, F., 2008)

In public circulation areas, the principal objective of the luminous environment is satisfaction of biological information needs. Sunlighting can be valuable for orientation and visual relief, particularly in very large institutions, where visitors experience will be pleasing. Luis Kahn is an architect who uses natural lighting in a great percentage in his design. An example that spring to mind among his museum

designs is Kimbell Art Museum where a special kind of toplighting is used. At the outset of the project, the Kimbell's first director, Richard Brow, required that the natural light should be an integral part of the museum program so that the visitors should be in touch with the ever-changing world outside the museum. At the Kimbell, natural light enters the space through the vaulted ceilings. The light strikes suspended convex, perforated-aluminum natural light elements, that prevents direct light from entering the space (Worth F., 2003). The shape of the ceiling and the daylight redirecting design can be seen in Figure 3.22. As the light is reflected onto the curved concrete, it indirectly illuminates the gallery. Through this unique design, the designer avoided many of the pitfalls inherent in a museum gallery where a primary source of illumination is natural light.



Figure 3.22 : Lighting of Kimbell Art Museum (Worth F., 2003)

Architectural forms and daylight affecting lighting in museums and art galleries should be analysed in terms of their impact on adaptation, orientation, and artifact preservation. Six factors affect the final illumination levels produced by architectural surfaces and daylighting:

- The area of operative glazing in relation to the floor area
- The room dimensions, especially the ceiling height and room depth
- The placing and spacing of available glazing

- Site location in terms of longitude and latitude and direction
- Obstructions, external and internal
- The reflecting characteristics of interior surfaces (IESNA RP 30, 1996).

Illumination criteria that influenced museum development in the 18th and 19th centuries maximized the collection of available daylight while minimizing windows. The criteria did not consider artifact preservation and centered on three typical solutions; clerestory windows, translucent skylights, and monitors. Due to the middle of the 20th century, gallery lighting criteria sought to prevent ultraviolet and visible radiation from modifying the organic composition of the artifact. This resulted in two major modifications of the architectural form of museum buildings; replacing daylight with electric light and strictly controlling the amount of daylight in a space. During the last two decades, energy conservation requirements and improved glazing materials have reviewed the use of daylight in museums. These advances have fostered creative solutions to the problems of good illumination, human comfort, and artifact preservation (IESNA RP 30, 1996).

3.2.1 Toplighting in museum buildings

Toplighting is one way to obtain necessary lighting levels in the museum space. It is only possible in single- storey constructions or at the top of a multi storey building. Usage of topleighting is more efficient than a side window because a rooflight transmits light more effectively when compared to side lighting. On the other hand, it can be difficult in cleaning, in the arrangements for sun blinds and blackout and in providing ventilation opening lights. Consequently, the economic advantages of the selection of top lighting need careful examination in relation to particular requirements. Some different alternatives for topleighting in buildings can be seen in Figure 3.23.

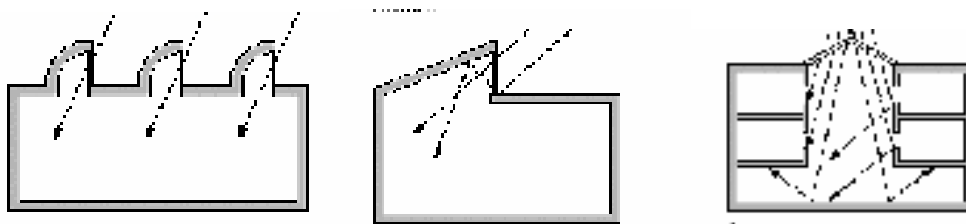


Figure 3.23 : Alternatives for topleighting in buildings (Url-12)

In museums, the choice of toplighting is often more preferable owing to the fact that the sidewalls are generally used as exhibition surfaces. By doing so, the homogenous distribution of daylight is provided and more space is gained for the exhibition areas. Two examples to this situation that spring to mind can be given from the old section of the Louvre Museum in Paris and the Pergamon Museum in Berlin, shown in Figure 3.24. In both cases, toplighting is used in the interior space to illuminate the two dimensional drawings and the three dimensional sculptures.



Figure 3.24 : Toplighting in Louvre Museum in Paris and the Pergamon Museum in Berlin (Photos taken by Şener, F., 2007)

3.2.2 Sidelighting in museum buildings

Sidelighting is not an often met situation in the museum lighting conditions. There are many methods of gaining sunlight by using sidelighting. In Figure 3.25, some of the ways for sidelighting is given. If a window is a source of both view and light, there is a great possibility of competence for display areas and it is not recommended to have a source of visual competition and artifacts on the same wall. Any windows located on the eye level can cause veiling reflections on facing walls parallel to them and the placement of objects and windows on the same wall is not recommended because the artifacts can not be properly seen because of glare.



Figure 3.25 : Alternatives for sidelighting in buildings (Url-12)

Designing of sidelit galleries must always involve some compromises and to avoid these compromises, the best way is to separate the functions of a window as view and as light source. Sidelighting design in museum buildings is recommended be kept out of visual field. Sunlight should be introduced into baffled clerestory windows and bounced to reflecting surfaces that are out of visual field for viewers. While illuminating the walls with these systems, excessive shadows should be controlled. An example to sculpture lighting with sidelights is given in Figure 3.26.



Figure 3.26 : Sidelighting in Louvre Museum in Paris and the Pergamon Museum in Berlin (Photos taken by Şener, F., 2008)

Daylight tubes can be a more energy efficient alternative to conventional skylights. They consist of a clear, hemispherical dome, a highly reflective tube and a diffuser at ceiling level as shown in Figure 3.27. As they require a smaller area of roof glazing than a traditional skylight, heat gain in summer and heat loss in winter are significantly reduced. Types with textured, flexible ducts can deliver significantly less light than those with smooth shiny light ducts. These alternative daylighting systems can be useful in museum environments where a re-directing system for daylight can be supplied and UV can be blocked.

3.2.3 Solar control in museums

The sunlight component of daylight is directional, intense, and sometimes causes harsh shadows and glare. Sunlight is often avoided as a source for daylight by use of solar control devices. Solar control is of great importance in museum buildings to protect the artifacts and prevent glare caused by direct sunlight. It can be seen as an essential factor for reaching the best visual and thermal comfort conditions in the interior. Some general ways of solar control can be seen in Figure 3.28.

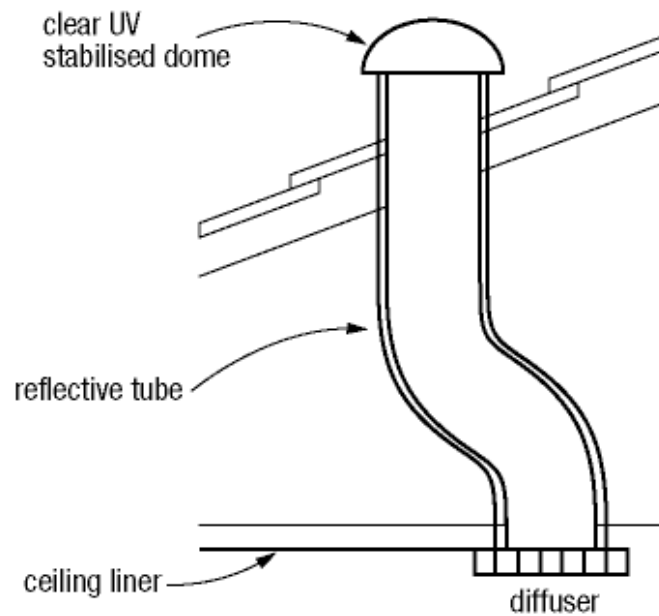


Figure 3.27 : Illustration of daylight tubes (Url-13)

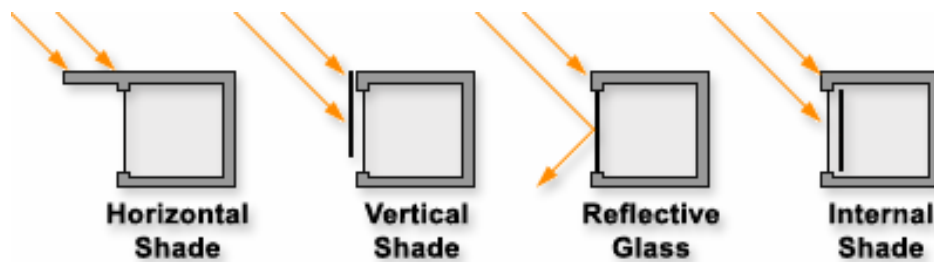


Figure 3.28 : General ways of solar control (Url-14)

Assuming the northern hemisphere, horizontal overhangs are the most appropriate towards the south orientation, where the sun angle is higher than the east and west orientations. Vertical projections flanking the windows are suitable for east and west orientations where the angle of the sun is lower. In Figure 3.29, schematic description of horizontal and vertical shading elements can be seen.

An alternative to the solar shading is the combination of louvers and screening on the facades that is effected from the sunlight so that daylight and view can be admitted and direct sunlight is controlled. There are also adjustable shading devices which can be pre-programmed or connected to outside sensors, responding to temperature, radiation intensity and to time or season. They also can be programmed by taking the sun's position and altitude and azimuth angle of the sun in its daily path into consideration. (Reid E., 1988)

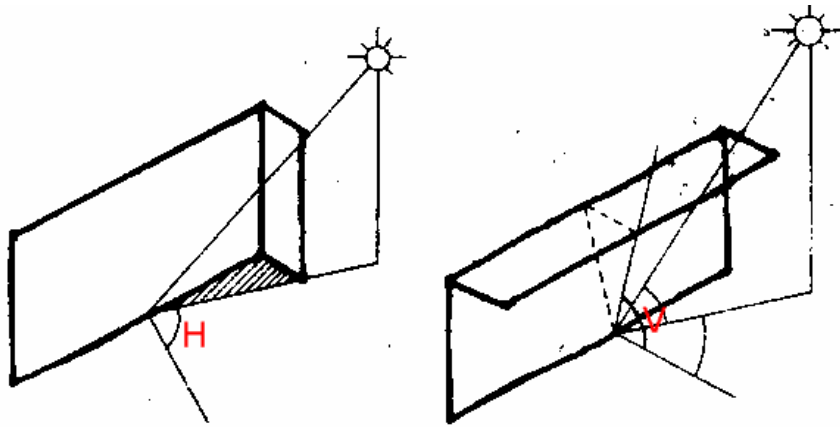


Figure 3.29 : Horizontal and vertical shading elements (Bansal N. K., Hauser G., Minke G.,1994)

There are several ways and recently developing technologies for controlling the direct sunlight and their integration to the design is under the responsibility of the architect in general. In Figure 3.30, the integration of solar control devices to the roof can be seen at one gallery in Atlanta High Museum as an example. The roof of the naturally illuminated gallery is covered with the solar control units and a uniform distribution of daylight is supplied in the space.

The solar control systems in the museum spaces can be examined under the following categories: Shading devices integrated to buildings, redirecting systems for having indirect light in the museum and precautions taken in the design of building skin. Generally louvers and curtains are most often used solar control technologies in museum environments to control direct sunlight penetration.



Figure 3.30 : Solar control devices in Atlanta High Museum, Solar Control Blinds, (Franks, M., 2005)

Louvers are composed of multiple horizontal, vertical, or sloping slats of various shapes and different surface finishes. Louvers and blinds may be external or internal. They are used to partially or completely obstruct the sun's rays, and can be used in any direction and latitude. Horizontal louvers utilize both direct and diffuse sunlight, as well as ground reflections, and can be used in south and north directions. In sunny conditions, louvers and blinds can increase penetration of daylight derived from direct sunlight. In overcast conditions, they may also contribute to more uniform daylight distributions. There are many types of louvers classified based on their materials and geometries, like translucent louvers, horizontal, curved, light-directed louvers and fish louvers (Freewan A., Shao L., Riffat S., 2008). In Figure 3.31, the integration of louvers to a museum's façade can be seen in Barcelona Museum of Contemporary Art, which is designed by Architect Richard Meier.

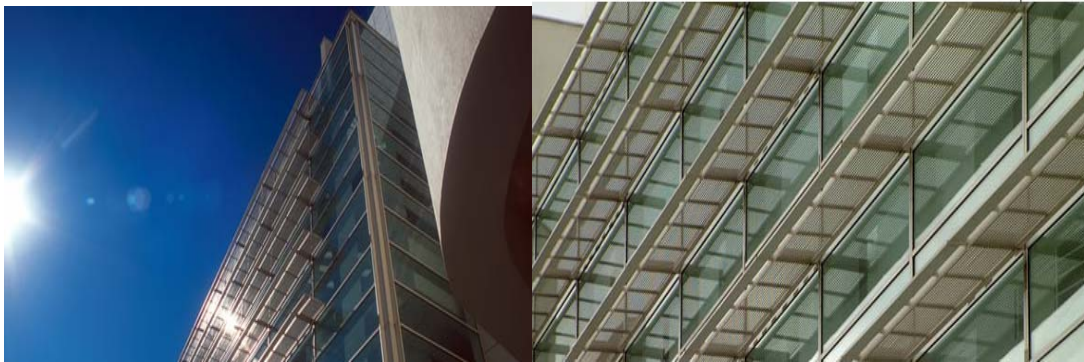


Figure 3.31 : Images from the south façade of Barcelona Museum of Contemporary Art (Url-2).

Solar control blinds are another shading system suitable for museums. Manually or automatically controlled blinds should be lowered in direct sunlight and adjusted in response to the sun. They should also be adjusted according to the light levels in the room. The blinds are usually made of a white or cream colored fabric which gives a diffuse light inhibiting the passage of direct sunlight. Cream colored blinds give a warmer light. Good quality blinds can be used for many years. One disadvantage is that they require frequent and rigorous adjustment to ensure effectiveness.

Curtains can be used to reduce light in situations where blinds are inappropriate for aesthetic reasons. Thicker material obscures more light. They should be well fitting to prevent shafts of light entering the building. Unfortunately, curtains must be completely closed when in use, preventing a view outside. One example can be seen in Figure 3.32. Careful positioning of furniture and other objects in the interior can

also help to minimize their deterioration. Placing them out of the path of direct sunlight is important because direct light causes far more damage than diffuse light.



Figure 3.32 : Solar curtains in Stuttgart Musical Instruments Museum (Photo taken by Şener, F., 2008)

A well-designed glass façade can provide a spiritual link between the manmade building's interior and outside environment. Such links have inspired the architects throughout the history. Glass is an innovative façade material and building element of the urban texture.

In many countries, the demands for heating, cooling and lighting in buildings compromise the largest sector of the total energy load. Reduction of energy consumption, the improvement of visual and thermal comfort conditions are important considerations in design and operation of buildings. In these respects, the windows play a critical role in determining building energy performance. For the characterization of the optical and thermal performance of a window, the three main areas of interest are the thermal transmittance, the solar gain and the visible light transmittance through the glazings. The quantitative properties of interest are the window overall heat loss coefficient, the total solar energy transmittance and the visible light transmittance. The total transmitted solar energy is the sum of the transmitted direct solar radiation and the incident solar radiation absorbed in the glazing which also effects the temperature of the space. (Santamouris M., 2003).

If the glass is used as a skin element in a museum building, it must have some features to reduce unwanted UV Radiation caused by sunlighting. This is most appropriate when daylight filters are used in the glazing. A filter can be defined as a device for changing, by transmission or reflection, the magnitude or spectral

composition of the flux incident upon it (IESNA RP 30, 1996). Windows are commonly described according to their number of panes of glass the type of tint or coating applied to the glass to increase its performance. Visible light transmittance is the percentage of visible light that passes through the window assembly. When visible light transmittance is higher, a greater fraction of incident natural light passes through the window (ASHRAE, 1997). In Figure 3.33, an illustration about the types of glazing and their properties is given.

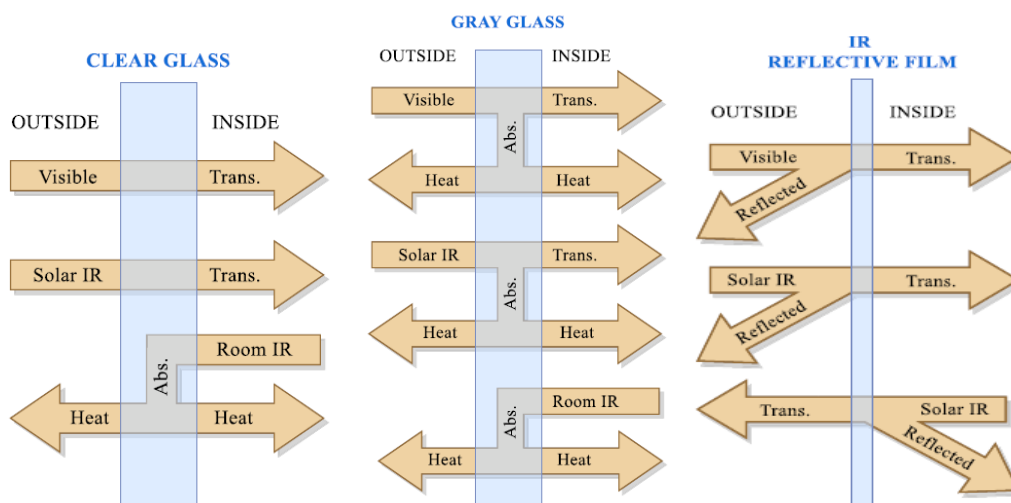


Figure 3.33 : Clear, low transmission and coated glazing and their properties about light and heat transmittance (Url-15)

Filters reducing UV, visible light or solar heat often filter some of the wavelengths in visible light. This effects the color rendition of the artworks. Colorless UV filters prevent the passage of all UV radiation below 400nm, allowing the transmittance of all visible radiation. Filters with a yellow tint absorb all UV radiation and short wavelength visible radiation which cause some natural dyes to fade, but they also change the color rendition (IESNA RP 30, 1996).

Ordinary window glass and the standard grades of clear or translucent plastics used for glazing roof-lights absorb only part of the UV radiation in daylight and additional filtering is necessary. Certain chemicals will absorb almost all UV radiation without affecting significantly the transmission or color of the daylight and can be incorporated in most transparent and translucent plastics and in varnishes to provide effective filtering (CIE 29.2, 1986).

Solar films are self-adhesive polyester sheets, usually acetate. They can reduce transmittance of UV radiation, visible light or solar heat or a combination of the

three. They are cut to size and are fitted either internally or externally. They do not require replacement of existing glazing, are relatively cheap and easy to apply. Varnishes containing UV absorbers can also be painted onto the inside of window glass. This option is useful for windows containing very small or large panes of glass, where it is impractical to apply films, or to uneven glass (IESNA RP 30, 1996).

Laminated glass in which a transparent UV absorbing vinyl is sandwiched between the glass sheets, is also available. Plastic sheets may be placed on the inside of windows and above daylights, or varnish applied carefully to the glass to give an even coating of sufficient thickness to provide full protection (CIE 29.2, 1986).

3.3 Artificial Lighting Design in Museum Buildings

The design of artificial lighting system is an important aspect for buildings. Design and analysis of artificial lighting system for interior has some fundamentals defined by the Illuminating Engineering Society listed below:

- Considering the function of spaces,
- Determining the quantity and quality of light needed,
- Selecting appropriate light sources,
- Designing the lighting system with respect to the interior,
- Designing the control mechanism for lighting,
- Coordinating the artificial lighting system to environmental parameters of the interior,
- Considering the energy efficiency and sustainability aspects (Kaufman J.E., Haynes H., 1981).

A visual display can be defined as an object based display. In museums, it is the exhibitions that the visitors experience. The age of the observer is critical because age provides predicting the lighting needs of the spaces. As there are many kinds of museums and some of them are visited by specific age groups only, this criterion must be taken into account. The reflectance of the task is another important aspect for determining the most appropriate lighting solutions for the interiors. Therefore

these four characteristics are used to establish the suitable lighting level for each specific lighting task:

- The visual display
- The age of observers
- The importance of speed and visual acuity for visual performance
- The reflectance of the observed task (IESNA, 2000).

The process of choosing design illuminance can be found in international lighting standards. Table 3.3 gives some illumination levels for museum spaces.

Table 3.2: Illumination levels for museum spaces (IESNA, 2000, IESNA RP 30, 1996)

Museum Spaces	Illuminance levels (lux)
Foyers, Circulation Areas	100
Reception, Shopping Area	300
Exhibition Halls (with irresponsible objects)	no limit
(objects with low responsivity)	200
(objects with medium responsivity)	50
(objects with high responsivity)	50
Storage	No light

Once the illumination level for a space is determined, the designer has to make several choices for artificial lighting. One of them is the artificial light source that can provide the ideal quality and quantity of light. A primary consideration of lamp design is that the lamps produce the desired output visible, infrared and ultraviolet radiation so the designer is suggested to obtain the overall solution. The general requirements expected from the artificial lighting system of a museum building can be listed as follows:

- The color temperature of the selected light source must be suitable for the illuminated artwork,
- The light source can be dimmed when needed,
- The lamp life must be long and the maintenance should not cause any accidents for the artworks,

- The lamp must not cause unwanted UV radiation,
- The integration of the lighting system with the museum space must be supplied (Önsoy B., 2002).

3.3.1 Selection of light source for museum interiors

The choice of lamp for a given task must always be chosen carefully while designing the artificial lighting system of a space. This is influenced by the ambiance that the architect or lighting designer wishes to create within the environment. Each lamp type can have a number of variations in construction, operation, minimum starting temperatures and color properties.

The efficacy of a light source can be defined as light output per unit of power input with the ratio of lm/W excluding gear losses. It can be formulated as follows:

$$\text{Lamp Efficacy} = \Phi / P$$

Φ = luminous flux (lm), P = lamp power (W)

Efficacy factors of some light sources can be seen in Table 3.3.

Table 3.3: Efficacy factors of some light sources (CIBSE, 1994)

Light source	Efficacy factors (lm/ W)
Tungsten incandescent	10-15
Florescent lamps	60-80
Metal halide	70-90
Tricolour florescent lamps	65-75
High pressure mercury vapour lamps	50-60

Different lamp types have different color properties. The color properties can also change by using special coatings for some lamp types. The color properties of lamps are classified by their color rendering group (CRG) and their correlated color temperature (CCT). The ability of a light source to render colors of surfaces accurately can be quantified by their CRI (CIBSE, 1994). In Table 3.5, the color

rendering groups, CIE general color rendering index values and typical application areas are given. For museum spaces, the accurate colour judgements are important for visual tasks so using lamps sources in color rendering groups 1A and 1B is recommended. The recommended value of CRI index for lamps must not be smaller than 80.

Table 3.4: The color rendering groups, CIE general color rendering index values and typical application areas (CIBSE, 1994).

Color Rendering Groups	CIE General Color Rendering Index (R_a)	Typical Application
1A	$R_a \geq 90$	Where accurate color matching is required.
1B	$90 \geq R_a \geq 80$	Where accurate color judgements are necessary or good rendering is required for reasons of appearance.
2	$80 \leq R_a \leq 60$	Where moderate color rendering is required.
3	$60 \leq R_a \leq 40$	Where color rendering is of little significance but marked distortion of color is unacceptable.
4	$40 \leq R_a \leq 20$	Where color rendering is of no importance at all and marked distortion of color is acceptable

Modern electric light sources for a museum building can be mainly categorized in three groups as incandescent, florescent and high intensity discharge lamps, whereas recently developing technologies in lighting area such as LED or fiber optic lighting are also preferred for lighting museums due to their energy efficiency aspects.

Incandescent lamps are the one of the oldest kinds of light sources in the lighting history. They are produced by an incandescent filament, sealed in glass bulb which contains an inert gas filling (CIBSE, 1994). The physical properties of incandescent lamps can be seen in Table 3.5.

Table 3.5: Physical properties of incandescent lamps (CIBSE, 1994).

Operation Position	Any
Control Gear	No
Starting	Prompt
Restarting	Prompt
Dimmable	Yes
Color Temperature (K)	2700K
CRG	1A

The color temperature of these lamps is approximately 2700 K as can be seen from Table 3.5. The light has a yellow- red component and is therefore highly flattering to the skin. The spectral content of the light produced by an incandescent source depends on its temperature, highly wattage lamps are bluer and low- wattage lamps are yellower. Dimmed lamps give yellow-red light (Stain B., Reynolds J. S., 2000).

Operating incandescent lamps at lower voltages reduces the colour temperature, increases the lamps life, decreases light output and efficacy, and increases the relative infrared output, which is not a desirable feature for museums. Incandescent lamps cause rise in the temperature of the spaces that they are used, as a result of this fact, they can not be recommended for museum lighting where the environmental parameters are of great importance. These sources can be dimmed easily (IESNA RP 30, 1996).

Fluorescent lamps have a tubular glass envelope. The light output comes from phosphors, which convert energy from a low-pressure mercury discharge. The spectral light distribution is tailored by the mix of phosphors. A wide range of white triphosphor, multi-band and halo phosphate phosphors plus special colors are available. White lamps are differentiated by color appearance or correlated color temperatures and color rendering group (CIBSE, 1994). Physical properties of fluorescent lamps are given in Table 3.6.

Table 3.6: Physical properties of fluorescent lamps (CIBSE, 1994).

Operation Position	Any
Control Gear	Yes
Starting	Prompt
Restarting	Prompt
Dimmable	Yes
Color Temperature (K)	2700-6500
CRG	1A, 1B

As fluorescent lamps do not cause rise in the temperature, they are more preferable in museum environment. Linear fluorescent lamps with a high color rendering index are ideal for continuous lighting effects in museums while illuminating large surfaces and they are suitable for wall washing effects and back lighting. They have low UV content, which can easily be filtered out. Because of their effectiveness, they can be supported for any museum's quest in terms of energy conservation (IESNA RP 30, 1996).

Tubular fluorescent lamps are longer than the compact fluorescent lamps but the technical properties of these light sources are similar to each other. The lamp life of fluorescent lamps can be 10.000 hour. They can be dimmed by using proper ballasts. They have different color temperatures suitable for different lighting effects. As an example, selection of 2700 K is suitable when a similar color temperature of incandescent light sources is needed to be obtained (Önsoy B., 2002). Fluorescent lamps do not rise the temperature but the control equipments of these light sources may lead extra heating which should be avoided in the exhibition cases. The lamp unit may be separated from the lamp and can be placed in a proper place where the rise in the temperature is not important (Thomson G., 1986).

High intensity discharge lamp kinds are high-pressure mercury, high-pressure metal halide and high-pressure sodium lamps. These lamps have higher efficacy and with appropriate color corrections can be utilized in most applications. HID lamps offer high efficacy but at the same time moderate color rendering. These sources must be used with great care in a museum environment because they produce ultraviolet radiation that must be filtered. They also can cause high illumination levels which

can cause severe damage on light sensitive objects. Physical properties of HID lamps are given in Table 3.7.

Table 3.7: Physical properties of HID Lamps (CIBSE, 1994).

Technical Properties	High-pressure mercury	High-pressure sodium lamps	High-pressure metal halide
Operation Position	Any	Any	Horizontal for double ended, Any for single ended
Control Gear	Yes	Yes	Yes
Starting	2-5 min	1.5-6 min	1-2 min
Restarting	4-7 min	>1 min	5-15 min
Color Temperature (K)	3300-4000	2000-3000	3000-6000
CRG	3	1B-4	1A-2

Museum lighting requires alternative light sources that can be used without damaging the objects. Minimizing light damage is possible by minimizing the energy absorbed by objects. A good solution for this case is using fiber optic systems for exhibition lighting. The operation of an optical fibre is based on the principle of total internal reflections. Light reflects or refracts while penetrating a different medium, depending on the angle at which it strikes a surface. In Figure 3.34, a section of a fiber optic cable is given.

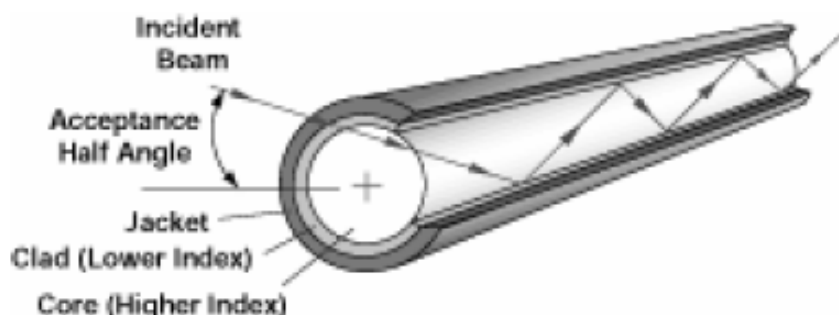


Figure 3.34 : Section of a fiber optic system (Url-16)

Absence of heat and elimination of electric wiring are the further benefits of using fiber optic cable. Outside layer of the fiber is made of a material with lower refractive index and interior core is made of a transparent material. Light waves within the acceptance cone angle $2\theta^\circ$ are reflected at the interface of two materials and therefore proceed almost without hindrance down the core by a series of 100%

reflections because of the fact about reflective indices. The core material demonstrates optical impedance that varies with the type of material, although in theory there is no loss at the reflection. The development of large, efficient plastic optical fibers has produced a lighting system. Optical fibers are applicable where a single remote source can supply a large number of relatively small point-source lights (Stain B., Reynolds J. S., 2000). The color rendering properties of the fiber optic systems must also be taken into consideration.

In Figure 3.35, comparison of different light sources is given from the light spectral output point of view. In each of the graphics, the spectral output caused by the sun is also given so that the comparison of the light sources can be made with respect to daylight. It can be said that the fiber optics can match with sunlight from as the curves of both of these light sources are alike.

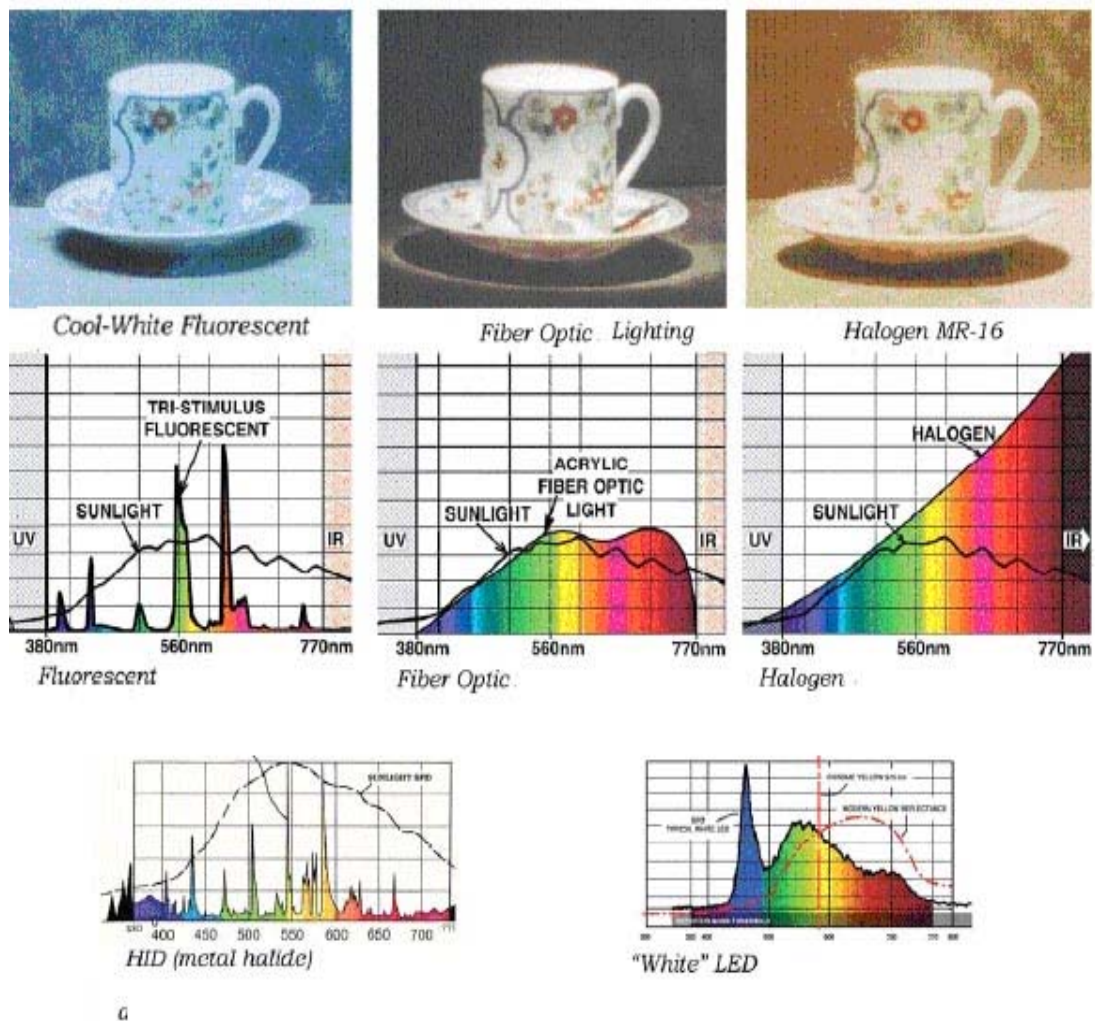


Figure 3.35 : Comparison of different light sources with fiber optics (Url-17)

Light emitting diodes can be defined as electronic components that let electricity pass in only one direction so that they emit visible light when electricity is applied. Selection of solid-state lighting is a significant method in order to reduce the amount of energy needed for general lighting of spaces in buildings. This has become the reason that developing LED technology is preferred in museum lighting due to the facts that they are energy efficient and they do not cause UV deterioration. As they also do not increase the temperature of the interior, it is suitable to illuminate light sensitive objects exhibited in galleries or in vitrines by LED light sources. In Figure 3.36, an interior view from Hunterian Museum at the University of Glasgow, Scotland is given as an example to LED application in a museum environment (Url-18).



Figure 3.36 : Illumination of a museum environment by using LED light sources, University of Glasgow, Scotland (Url-18).

3.3.2 Selection of luminaires and accessories for lighting museum interiors

There are four ways to illuminate a space using electric light sources. These are named as general lighting, localized general lighting, local lighting and task lighting. In any of these lighting systems, six different luminaires can be used:

- Direct
- Semi- direct
- General diffuse
- Direct- indirect
- Semiindirect
- Indirect

When a luminaire directs 90 percent or more of its light output downward, it is called a direct luminaire. The distribution of the luminaire may vary from one type to another. Direct luminaires are efficient in use but they can cause excessive glare in the form of veiling reflections. Semi indirect luminaires distribute 60-90 percent of the light downward and 10-30 percent upward. The light distributed upward is used to increase the luminance of the ceiling and upper walls. When the downward and upward components of a luminaire are equal or shared between 40-60 percent, the luminaire is called general diffuse. A direct- indirect is a special kind in which the light is evenly upward or downward distributed. An indirect luminaire gives 90 percent or more of its light upward so the direct and reflected glare can be reduced (CIBSE, 1994). The drawings in Figure 3.37 represent the direct, semi- direct, general diffuse, direct- indirect, semi indirect and indirect kinds of luminaries.

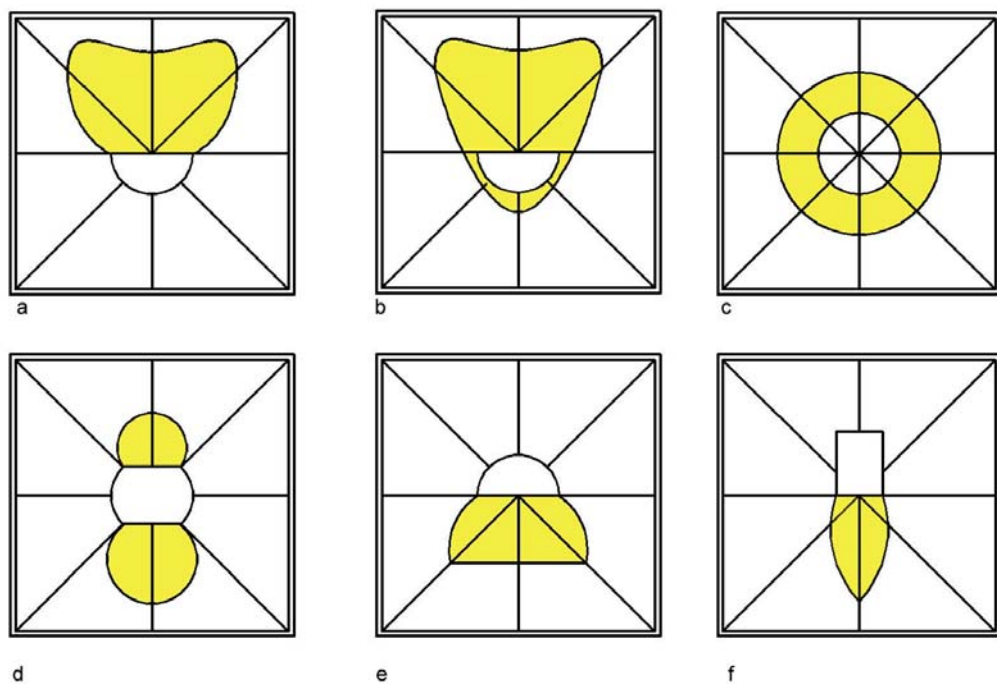


Figure 3.37 : The illustrations for different kinds of luminaires, a)direct, b)semi-direct, c)general diffuse, d)direct- indirect, e)semiindirect f) indirect (Graph drawn by Şener F., 2008)

Luminaries vary in their construction, mounting position, distribution of light, maintenance, the efficiency they provide on the task areas and their extend to effect visual comfort conditions. In museum interiors, luminaries for display lighting are suitable in use.

The distinguishing feature for this range of luminaries is that they are adjustable. Reflector lamps or separate optical systems are used to provide an extensive range of distributions from very narrow to wide spots as well as asymmetrical floodlighting distributions. They can be suspended, surface mounted or recessed into ceilings, wall or floor mounted, free standing or designed to use with track systems. Display lighting is intended to provide local emphasis or accent lighting to general lighting but these luminaries can also be used to localize a general lighting area (CIBSE, 1994). In Figure 3.38, polar curve and image of a display lighting luminaire is given as an example.

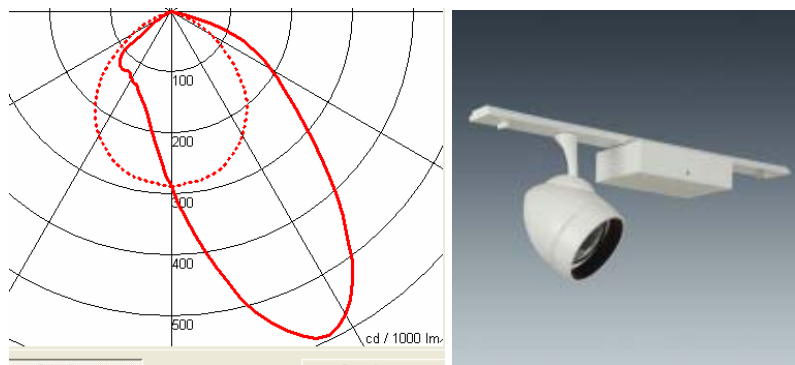


Figure 3.38 : Polar curve and image of a display lighting luminaire (Url-19)

Track lighting lets a comprehensive range of preferences allowing to connect the lighting design in a linear sequence, or for right angle shapes to be constructed. The introduction of the track resulted in a new flexibility in architectural lighting, especially in museum buildings. For changing exhibitions, the luminaires can be easily rearranged and realigned. If a different light distribution is required, another type of luminaire can simply be replaced by the spotlight.

The design of each range of luminaries consists of common features to allow the combination of spotlights, floodlights and wallwashers without disturbing the overall appearance of the ceiling. For adjustable focus on exhibits, many spotlights, floodlights and wallwashers can be rotated through 360° and tilted by up to 180° . For accurate alignment, many luminaires are also provided with an imprinted scale. This gives the lighting designer a flexibility where the exhibition layout can change from time to time.

4. PROTECTION OF MUSEUM OBJECTS

The preservation of museum objects is considered to be an important parameter for museum design so it is essential to develop a lighting conservation strategy based on overall exposure values of artifacts. This is possible by following the recommended lighting standards and carrying out the calculations for annual lighting exposure. Light is necessary in museums and galleries for viewing exhibitions, visual tasks such as reading and writing and for curatorial or collection management work. All common light sources, such as the sun, incandescent sources and fluorescent tubes, give out other forms of radiation, to varying degrees. The most significant of these are UV and infrared radiation. As museum objects are effected from these kinds of radiations, there are many kinds of standards and on going studies to prevent the deterioration of the museum objects.

4.1 Classification of Museum Objects According to Materials

Many museum objects may be progressively damaged and eventually destroyed if illuminated continuously. Sometimes partial destruction of materials and colours may result in aesthetic distortion. The extent to which materials deteriorate under given lighting conditions depends largely on their chemical constitution (CIE 29.2, 1986). The materials taking place in a museum collection can be classified mainly in two conservation categories due to their origin, if they are organic or inorganic. The term organic material includes the objects, which originated in animals or plants. Paper, cotton, linen, wood, parchment, leather, silk, wool, feathers, hair, dyes, oils, glues, gums and resins can be examples to the organic objects. Inorganic materials are materials such as metal, stone, glass where the materials are inorganic based.

The recommended classification for the museum objects in international standards divides the objects into four categories with respect to their responsivities to light. These are called irresponsible, low responsivity, medium responsivity and high responsivity museum objects. The recommended classification of the museum objects can be seen in Table 4.1.

Table 4.1 : The categorization of museum objects (CIE 157, 2004).

Category	Description
1. Irresponsible	The objects composed entirely of materials that are permanent, they have no light responsivity. Examples: most metals, stone, most glass, genuine ceramic, enamel, most minerals.
2.Low responsivity	The object includes durable materials that are lightly light responsive. Examples: oil, and tempera painting, fresco, undyed leather and wood, horn, bone, ivory, lacquer, some plastics.
3. Medium responsivity	The object includes fugitive materials that are moderately light responsive. Examples are costumes, watercolors, pastels, tapestries, prints and drawings, manuscripts, miniatures, paintings in distemper media, wallpaper, gouache, dyed leather and most natural history objects, including botanical specimens, fur and feathers.
4. High responsivity	The object includes highly light responsive materials. Examples are silk, colorants known to be highly fugitive, newspaper.

The annual light exposure at a point in a building corresponds to the cumulative illuminance exposure at that point over the course of the calendar year. The annual light exposure is measured in lux hours per year. The recommendations of museums and archives in terms of the lighting of sensitive objects most often follow precise and strict guidelines (CIE 157, 2004). The limiting illuminance levels for the classified objects and the limiting exposure values per year, is given in Table 4.2.

Table 4.2 : Recommended limiting illuminance and exposure values (CIE157,2004).

Material Classification	Limiting illuminance (lux)	Limiting exposure (lux h/ y)
1. Irresponsible	no limit	No limit
2. Low responsivity	200	600000
3. Medium responsivity	50	150000
4. High responsivity	50	15000

The deterioration of museum objects can also be investigated due to the sorts of exhibition objects such as pigments and dyestuffs, textile fibres, paper, wood, varnishes and lacquers. In CIE 29.2, Guide on Interior Lighting, each of these categorisations are investigated one by one. As an example to fading which is a potential risk for colored artworks, the painting category can be given. With some paintings, such as water colours, fading is very noticeable; the paint layer is thin and the exposure to radiation is greater than in the case of an oil painting. Moreover, some of the colours can disappear while others remain unchanged and this results in loss of the colour relationship for the painting. In oil paintings, the thickness of the paint, this case is similar but watercolor paintings have more risk to fade. For textile fibres, when the fibres are associated with dyes, mordants, sizes, pigments and dirt, complex reactions occur under the influence of light. One of these may cause the fibres to weaken and this can cause deterioration for the textiles exhibited (CIE 29.2, 1986).

4.2 Light and its Effects on Museum Objects

It is generally known that the deterioration process of materials requires energy. Light is the most powerful source of energy in museums. All organic materials are at risk under light. Inorganic materials like stone, metal, glass and ceramics are not affected by light in a great percentage but change may occur in a slow way. Light can only damage what it reaches and since most objects are opaque to light, its major effect is surface deterioration. Light can also lead to changes in color and strength of the materials. In Figure 4.1, an interior from the British Museum is given. As inorganic based materials are not effected from daylight, the illumination of the stone reliefs exhibited on the walls are supplied by using both daylight and artificial light. Therefore, natural and artificial illumination in museums can:

- accelerate the deterioration and corruption of several materials, because it acts as a catalyst to their oxidization;
- subsidize and raise the fragility level of cellulose fibres such as wood or paper;
- discolor, fade or blacken the paper or works of art;
- corrode significantly every natural fabric;
- increase the surface temperature of exhibits (Pavlogeorgatos G., 2003).



Figure 4.1 : The illumination of reliefs in British Museum by using daylight and artificial light (Photo taken by Yener, A., K., 2008)

Although damage to museum materials cannot be completely avoided, it can be controlled by taking certain precautions. Of these, eliminating the UV, limiting the illuminance and reducing the time of exposure are the most important ones in museums. The choice of the light sources from protection of objects point of view is therefore an important factor. In Table 4.3, relative damage ratios of some light sources are given.

Table 4.3 : Content of relative damage ratios for some light sources in museum buildings (CIE 157, 2004)

Light source	Relative Damage Ratio (%)
Clear sky (behind window)	1,6 – 1,7
Overcast sky (behind window)	0,7
Fluorescent lamps (cold)	0,45 – 0,55
Fluorescent lamps (warm)	0,40 – 0,55
Incandescent lamps	0,14 – 1,15

There are two processes by which exposure to light may cause damage, which can be defined as photochemical action and radiant heating effect. Photochemical action is

the process by which a molecule undergoes a chemical change, with the activation energy for the change being derived from the absorption of a photon.

The photochemical action can change the museum objects in different ways. It can cause fading, some colorant to darken, and in some cases loss of strength for the materials which may last with fraying of fibres on fabrics or surface cracking of the artifacts. Four factors determine the level of photochemical action:

- Irradiance
- Duration of exposure
- Spectral power distribution of incident radiation
- Action spectrum of receiving material (CIE 157, 2004).

Radiant heating can be defined as rising of the surface temperature above ambient temperature due to absorption of incident radiant flux. It is a less serious source of damage when compared with the photochemical action. It has the effect of raising the temperature of an illuminated surface and this causes a chemical activity. When there is a change in the temperature of the environment, it is possible to observe dimensional changes and deteriorations for the materials (CIE 157, 2004). Eliminating UV radiation is another important aspect in museum environments. The proportion of UV is higher in daylight than in artificial light sources and as the exhibits are usually more exposed to the former, priority should therefore be given to the installation of UV absorbing filters over windows and skylights (CIE 29.2, 1986). In Table 4.4, the UV content of some light sources is given.

Table 4.4 : UV content of the light sources (CIE 157, 2004)

Light source	UV content [$\mu\text{W}/\text{lm}$]
Daylight	400-1500
Tungsten incandescent	70-80
Tungsten halogen	40-170
Florescent lamps	30-100
Metal halide	160-700
Light emitting diode (LED)	<5

4.3 Research about Measurement of Damage on Museum Objects

There are several researches and on going studies about typical museum objects and the controlled levels of radiation that they are exposed to. The relationships between light exposure and damage caused by photochemical action are defined in these research areas. There are many kinds of standards and ongoing researches which are developed in order to study the damage on museum objects.

The Blue Wool Standards is one of the worldwide used standards for protection of museum materials. For many materials, the most obvious effect of exposure is fading, which is characterized by loss of color saturation and especially for darker colors lightening of appearance. In this system, a material is classified by exposing it to a broad- spectrum light source in a controlled environment cabinet alongside a standard card with eight dyed wool samples. Both the material and the samples are covered and visual comparisons are made to match the rate of fading of the material to one of the wool samples (CIE 157, 2004). By using the Blue Wool Standards, it is possible to estimate the light fastness of a dyed fabric or painting. These standards have been adapted to ISO Recommendation R 105 and the British Standard BS1006 so that sample cards are available. Each of the cards contain eight specially prepared blue dyeing on wool. They are chosen so that standard number 2 takes roughly twice as long to be perceptibly faded as standard 1, standard 3 roughly twice as long as standard 2, and so on through to standard 8 (Thomson G., 1986).

CIELAB is another most widely used system for exposure research. It is known that all materials do not demonstrate an on- line adding under exposure. Some of the materials can show yellowing while some of them change hue. This system is based on supplying the researchers the ability to record changes of surface color over time (CIE, 1986). This system enables the researchers to gather the data on the progressive nature of color change due to light exposure for many materials. A proposed scientific model for the visible effects of exposure is carried out by a group of researchers in Berlin, Germany.

Measuring light levels can be complicated, as the light often comes from mixed sources, and thus is subject to daily and seasonal changes. Lux meters and UV meters may not be adequate, as they provide single measurements of physical entities from which an extrapolation to the cumulative exposure is often uncertain. Accurate

evaluations can be achieved using data loggers like electronic monitoring cells, which yield visible LD and UV-LD, as well as humidity and temperature measurements in the museum environments (CIE 157, 2004).

5. INVESTIGATION OF KUNST MUSEUM STUTTGART FROM LIGHTING CONDITIONS POINT OF VIEW

Stuttgart Kunst Museum is an important triggering point for the citizens of Stuttgart taking place in the most central point of the city. This building was chosen as a case study for this thesis with regard to its modern architecture and its important placement in the city. The glass cube, deliberately designed to be unique in the city, has a positive impact on the city's urban topography, and significantly enhanced the identity of the surrounding built-up area.

5.1 General Information About Kunst Museum Stuttgart

The Kunstmuseum Stuttgart Building designed in 1999, by the Berlin architectural office Hascher and Jehle emerged as the winner of an international competition. The building consists of a glass cube enclosing a stone cube. The early design sketches of the building are given in Figure 5.1. The building is situated in Stuttgart Königstrasse at the central square and has a contact with the citizens of Stuttgart. The aerial view shows the placement of the museum building in Figure 5.2.

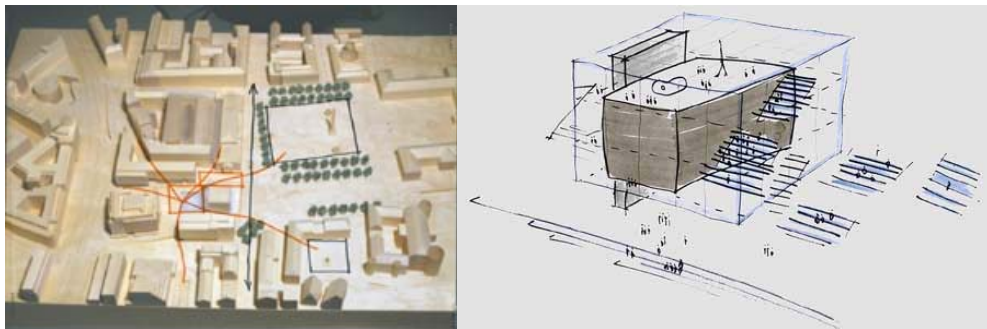


Figure 5.1 : Design sketches of Stuttgart Kunst Museum (Url-20)

The design approach of this museum is to create calm and elegant environment which is anchored in the modern times and as an architectural value, the glass cube is formed with an ensemble with the surroundings. The majority of the exhibition areas, which takes approximately 5,000 square meters, is below the ground level of the Kleinen Schlossplatz (Small Castle Square) continuing underground and using large

sections of the old motorway tunnel. An exterior view of the building is given in Figure 5.3. The floor plans and a section of the museum building is given in Figure 5.4.



Figure 5.2 : Aerial view of the Stuttgart Kunst Museum (Url-21)

Whereas parts of the museum's own collection are permanently displayed on the two basement levels, the cube is mainly used for special exhibitions. The building also contains a museum shopping area, an entrance foyer bar, a roof restaurant with view of the city as well as special meeting rooms for special events. The selection of glass as a material in the facade is to obtain a modern look between the old city architecture and have transparency for the view of the city and the surrounding slopes. The operating hours of the museum building is defined between 9:00-21:00.

The museum building contains paintings and sculptures in a great percentage. The basic inventory was donated by Count Silvio della Valle di Casanova in 1924 through the gift of his private collection of paintings to his adopted home town of Stuttgart. After 1945, Eugen Keuerleber took over the direction of the city art collection and defined four points of emphasis: The Swabian Impressionists, Adolf Hölzel and his followers, Otto Dix as well as the contemporary art of the region. The world's most important Otto Dix collection has formed the core of the city art collection. In 1986, Johann Karl Schmidt came to the collection as the new director and set new, inter-regional focusses. At the center of the exhibition and collection work were now above all the contemporary artists who are connected with the German south west through their origin or work and who enjoy world-wide recognition like Joseph Kosuth, Dieter Krieg, Wolfgang Laib, Markus Lüpertz,

Dieter Roth and K.R.H. Sonderborg. In addition, important art collections could be won on loan. In 1992 there was the collection of Rudolf and Bertha Frank, in 1994 the Konrad Knöpfel Foundation Fritz Winter, 2001 the collection of Etta and Otto Stangl. In 1998 also the archive Baumeister, the inheritance of Willi Baumeister, which is at home in Stuttgart, was promised for the planned new construction of the museum. Finally the inventory, which is already under the new director Marion Ackermann, has been expanded by the collection Teufel with works of the concrete art. The highlights of the city art collection, which today includes around 15,000 pieces, were presented at the opening of the art museum under the exhibition title "arrived - The collection in the own house" (Url-22)



Figure 5.3 : Exterior image of Stuttgart Kunst Museum (Photo taken by Şener, F., 2008)

5.2 Natural Lighting and Solar Control Systems of the Museum Building

Effective exhibit lighting must balance exhibition and conservation needs and enrich the museum experience (IESNA RP30, 1996). The Art Museum Building of Stuttgart uses daylighting in a small percentage as part of lighting design. Daylight is obtained by toplighting and sidelighting methods as part of natural lighting system to increase the ambient lighting level in Stuttgart Kunst Museum. The main toplighting takes place in the axis of the main corridor allowing daylight to penetrate into the almost 100m-long access circulation area which follows the course of the former motorway tunnel. An interior and exterior image showing the toplighting in the museum can be

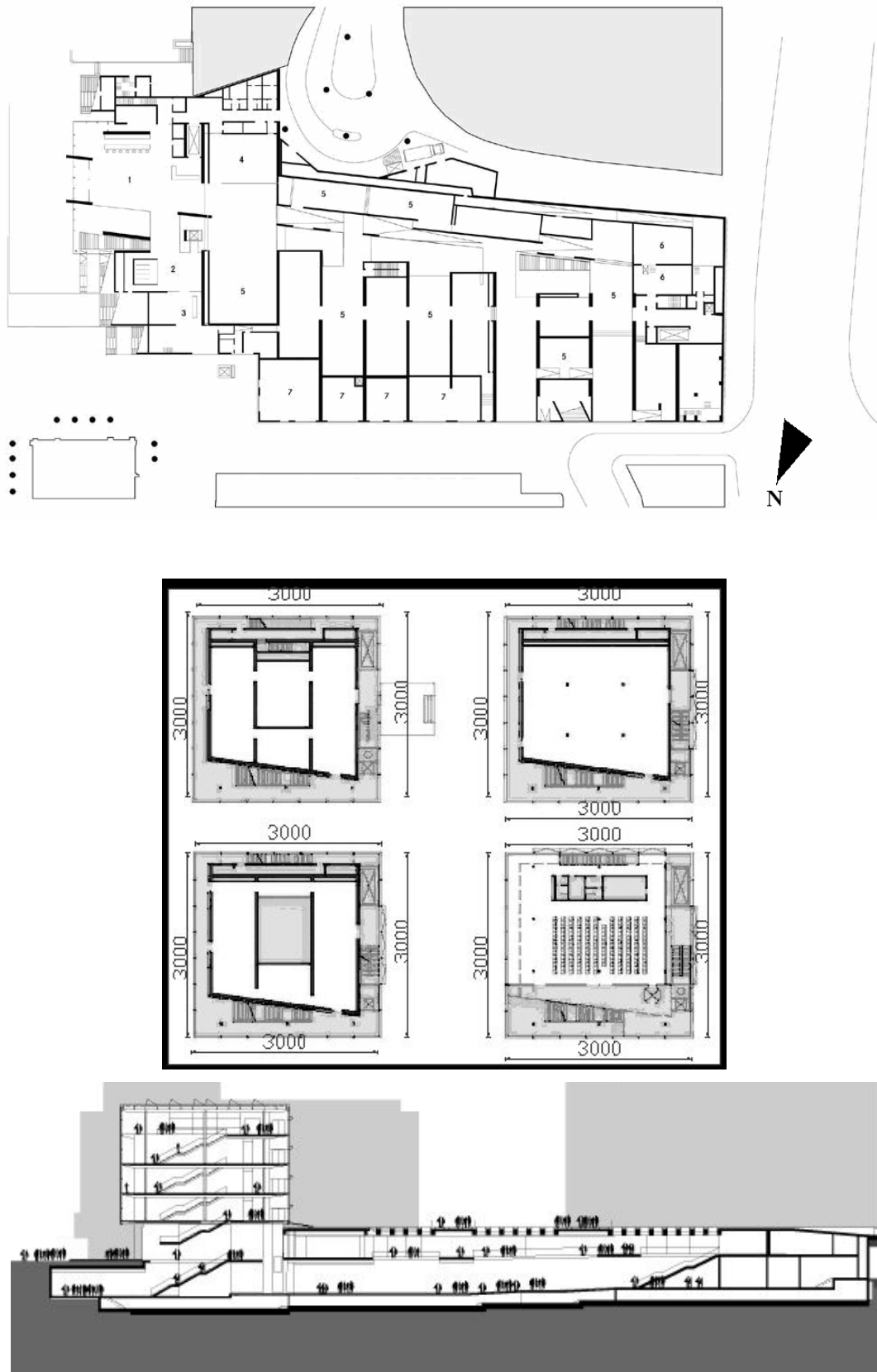


Figure 5.4 : Floor plans and section of the Kunstmuseum Stuttgart (Url-20).

examined in Figure 5.5. Sunlight entrance is controlled by using shading devices in the top openings.



Figure 5.5 : Toplighting in Stuttgart Kunst Museum from exterior and interior (Photos taken by Şener, F., 2008)

Some galleries of the museum building also uses side lighting methods. To block the sunlight in the exhibition spaces, cotton curtains are generally used in front of the windows. Homogenous distribution of daylight is ensured in the interior spaces to avoid glare problems caused by direct sunlight in the exhibition areas. In Figure 5.6, sidelighting of the museum building can be seen.



Figure 5.6 : Sidelighting in the museum façade (Photo taken by Şener, F., 2008)

The 2,800m² glass façade of the glass cube, comprises an outer layer of laminated safety glass, composed of 10 mm, extra-white toughened glass, a 1.52 mm PVB plastic film and 8 mm toughened clear glass. The 16 mm air space between the

glazings is filled with argon gas in order to afford heat and soundproofing properties (Url-23). The glass has blue-tinted silver color with light transmittance value of %56 and light reflectance value of %37. The glass is temperable in case of vandalism or exterior climatic conditions.

Shading films were installed on the facade to block the direct sunlight entering through the side openings. The glass façade is covered with stripped shading films that are given in Figure 5.7.

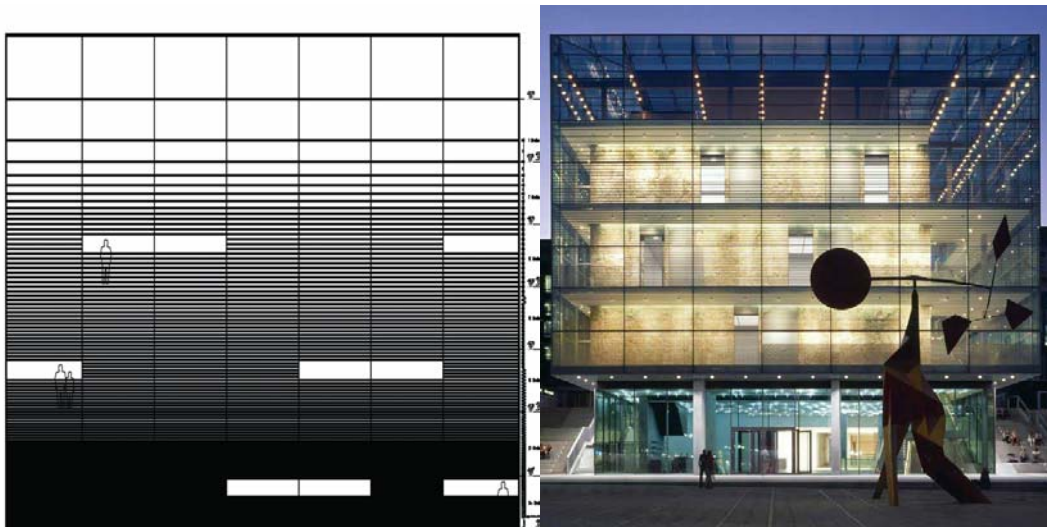


Figure 5.7 : Drawing of solar control films for the frontal façade and its integration to the building (Url-20)

5.3 Artificial Lighting System of the Museum Building

The museum building contains different spaces designed for different activities so the lighting requirements vary from one space to another. In order to perform the visual tasks in an accurate way and to have an evenly lit atmosphere in the interior, the selection of lighting systems differ due to the activity performed and the types of the collections that the museum involves.

The lighting design of the Kunstmuseum Stuttgart was created by Andreas Schmid. It is possible to examine the artificial lighting system of the museum in the division of the following spaces: entrance foyer, circulation areas, museum shopping area, top restaurant of the museum and the exhibition halls.

The lighting of entrance foyer, which is supplied by 334 fluorescent tubes, can be defined as a conspicuous element of the light and building control network. It also

offers the visitors a different visual environment with the placement of the lamps in an irregular way. Due to the selection of the designer, no luminaries were used with the white tubular fluorescent lamps that are mounted to the ceiling with the height of eight meters. In Figure 5.8, an interior image of the entrance foyer is given.



Figure 5.8 : Image showing the artificial lighting design in the entrance foyer (Url-24)

Lighting control modules are networked together in a LON-based system. The system is operated via control panels manually. The system is based on occupancy and it is designed as a daylight responsive system. Illumination is provided by luminous ceiling elements combined with low-voltage halogen downlights. This automation is also performed by the lighting control system. The system consists of 720 circuits in total (Url-24). The flowchart of the designed LON automation system is given in Figure 5.9.

With the help of the automation system, different lighting levels can be supplied in the same space. This flexibility is essential in galleries where the exhibitions are not stable. When lower illuminance levels are required in a museum space according to the content of the exhibition, the automation system helps to arrange the proper conditions. In Figure 5.10, different lighting solutions using this automation system for the gallery can be examined. Other systems under groups of heating, ventilation, air conditioning, shading and daylight control can be connected to the automation system used in Stuttgart Kunstmuseum via standardized interfaces and controlled by operating elements.

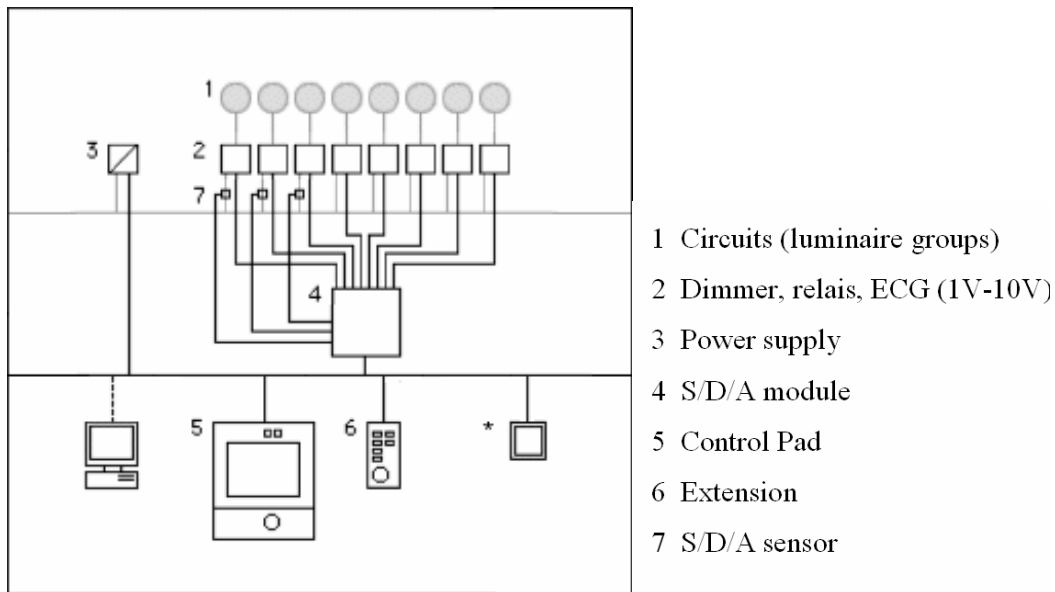


Figure 5.9 : Flowchart of the automation system for artificial lighting (Url-24).



Figure 5.10 : Different lighting opportunities for a gallery in Kunstmuseum Stuttgart (Url-24)

The lighting for circulation areas of the museum is supplied by daylighting and artificial lighting. The corridors and staircases are generally illuminated by downlights mounted on the tracks on the ceiling. Some examples to natural and artificial lighting systems for circulation areas are given in Figure 5.11. Downlights ensure general lighting on the public areas, while track systems enable additional spotlights and wallwashers to be positioned for special requirements.

The downlights used in the galleries have a cut off angle of 30 degrees. The diffuser layer on the luminaires optimise visual comfort conditions. The diffuser effectively increases the size of the light source thereby reducing the luminance in the light aperture. The small hole in the centre of the diffuser simplifies lamp replacement. In Figure 5.12, the diagrams for the selected downlights are given.



Figure 5.11 : Examples to natural and artificial lighting for corridors and staircases in Kunstmuseum Stuttgart (Url-20)

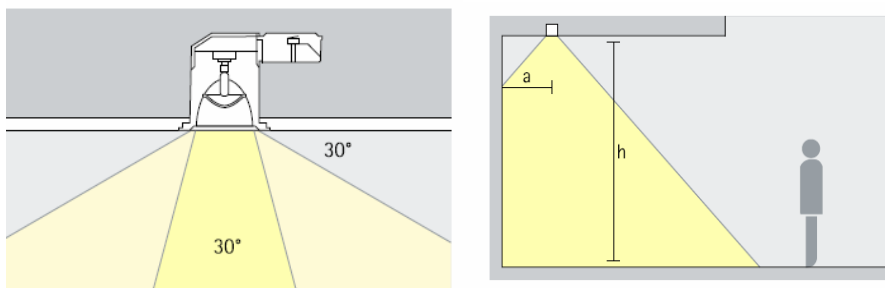


Figure 5.12 : Illustration of the the downlights light distribution (Url-24)

5.4 Investigations of the Museum Galleries from Daylighting and Artificial Lighting Conditions points of view

The museum building contains several galleries and the selected seven galleries were investigated from lighting conditions points of view. All the investigated galleries were examined in terms of the collections that they have. Seven of the galleries contain paintings in the group of low responsive material, which must be illuminated with the maximum illuminance limit of 200 lux (CIE157,2004). The homogenous distribution of light on the exhibition area is essential for better display of the two dimensional exhibitions. In one of the galleries, the exhibition involves metal sculptures. According to the international lighting standards, a limitation for inorganic based art works do not exist as these materials are under the categorization of non-sensitive objects to light.

When daylight is used as a light source, it might cause some disadvantages for the display. As it leads deterioration for artworks and also illumination level differences on the display areas, the control of sunlight is essential in museums. In four of the

investigated galleries, daylight is used as a light source. On account of the fact that all the galleries contain two dimensional artifacts exhibited on the walls, vertical measurements were held in order to determine the illumination levels for the artifacts exhibited in the museum spaces. For the drawings on the walls, the mid points of the artifacts were measured. The results of the investigations made per each gallery are described in Appendix A, in Tables between A.1 and Table A.7. Each table summarizes the descriptions of the galleries, floor plans, the exhibition contents, results of the illumination levels and the used lighting strategies.

In order to make a quantitative analysis of lighting conditions, illuminance measurements both horizontal – at eye level plane, and vertical – over the artworks were carried out with the luxmeter PRC Krochmann RadioLux 111. These measurements were only collected in the summer period between the hours of 12:00-15:00 under clear sky conditions. Nine points were determined to measure the horizontal illumination level of the entire space. The height of the reference plane was considered as the same height of the average eye level which is 150 cm above the floor. The values measured for the spaces are the results of the combinations of both the daylighting-if used and the artificial lighting. The results of the measurements for general lighting of each gallery is illustrated in diagrams in Appendix B.

5.5 Daylight Modelling of Kunstmuseum Stuttgart

The possibility to visualize internal spaces before their construction is an important technological development for the architects and the designers. Therefore, computational visualization with synthetic images is a powerful development, which effectively helps the architect's design in many ways. Among them, the possibility of understanding and optimizing the architectural proposal from the daylighting point of view can be mentioned. Daylight simulation in buildings can also help to predict the conditions for environmental comfort and energy efficiency optimization in architecture. Some daylight simulation software tools use innovative algorithms and they emphasize the precision required by the simulation of the architectural space, under various lighting conditions.

5.5.1 RADIANCE as a daylight modelling tool

The daylighting performance of a building depends on complex interactions of a large number of design features and elements like functional, behavioral, structural and economical requirements. Therefore, computer simulations have been developed to save time and try different design options to accelerate optimization of daylighting and lighting design while providing scientifically realistic measurements. One of the most commonly used lighting simulation tools is RADIANCE, which was developed at the Lawrence Berkeley Laboratory in California and the Ecole Polytechnique Federale de Lausanne in Switzerland. The basic concept behind RADIANCE is to produce renderings by performing an accurate physics simulation of the bouncing of light around a scene and into the observer's eye.

5.5.1.1 General information on RADIANCE descriptions and the flowchart of the tool

The idea for the original goals on developing RADIANCE Software was to produce an accurate tool for lighting simulation and visualization based on ray-tracing. The main consideration of the RADIANCE system design goals which are given below, reflect many years of experience in architectural lighting simulation that can be physically-motivated, or user-motivated. The main goals can be given as:

- Ensure accurate calculation of luminance
- Model both electric light and daylight
- Support a variety of reflectance models
- Support complicated geometry
- Take unmodified input from CAD systems (Ward, G., 1994)

The diagram in Figure 5.13 shows the flow between programs that are defined as boxes, and data defined by ovals. The central program is `rpict`, which produces a picture from a scene description. `Rview` is a variation of `rpict` that computes and displays images interactively, and `rtrace` computes single ray values. Other programs can connect many of these elements together, such as the executive programs `rad` and `ranimate`, the interactive rendering program `rhoio`, and the animation program `ranimove`. The program `obj2mesh` acts as both a converter and scene compiler, converting a Wavefront `.OBJ` file into a compiled mesh octree for efficient rendering. (Ward, G., 2003)

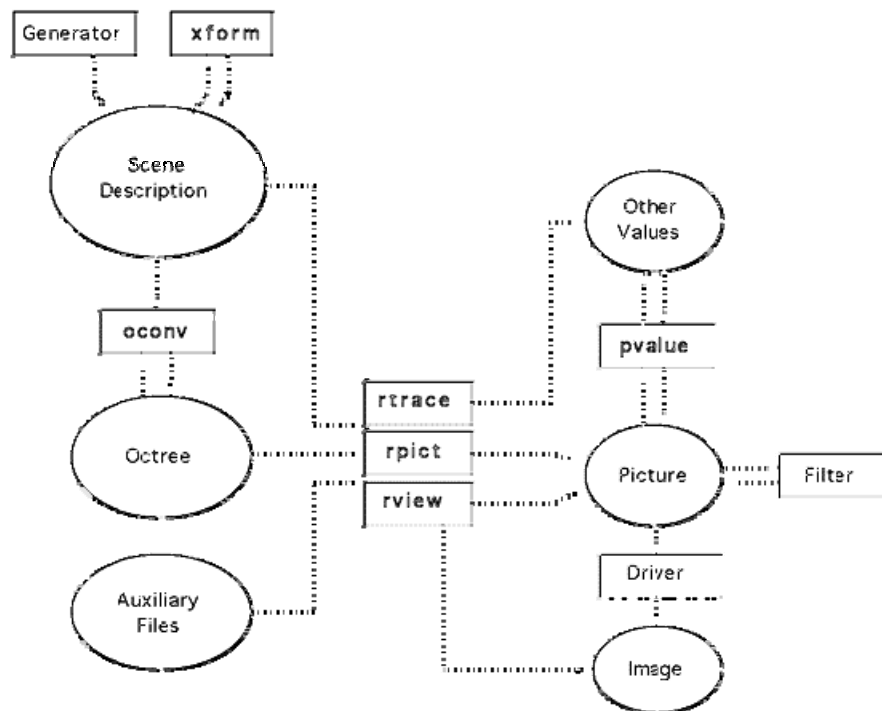


Figure 5.13 : Flowchart of the RADIANCE software (Ward, G., 2003)

A scene description file represents a three-dimensional physical environment in Cartesian world coordinates. In RADIANCE, materials of the objects are classified into types such as plastic, glass, mirror, ect. Every material has some physical values. As an example, in order to define the plastic material type in RADIANCE, the material's reflectance, the fraction of specularity and roughness value must be given. The material definition of 'glass' is shown below (Ward, G., 2003.):

```
mod glass id
```

```
0
```

```
0
```

```
3 rtn gtn btn
```

Glass material in RADIANCE is optimized for thin glass surfaces. One transmitted ray and one reflected ray is produced. By using a single surface in place of two, internal reflections are avoided. The surface orientation is irrelevant, as it is for plastic, metal, translucent materials. The only specification required is the transmissivity at normal incidence. Transmissivity is the amount of light not absorbed in one traversal of the material. Transmittance is the total light transmitted

through the pane including multiple reflections. To compute transmissivity (tn) from transmittance (Tn) the below given formula (5.1) is used.

$$tn = [\text{sqrt}(.8402528435+.0072522239 \times T_n \times T_n) - .9166530661] / (.0036261119 / T_n) \quad (5.1)$$

Standard 88% transmittance glass has a transmissivity of 0.96. A pattern modifying glass will affect the transmissivity. (Ward, G., 2003).

5.5.1.2 Description of RADIANCE simulation engine

There are two approaches, which can be used for detail estimation of a luminous environment in the interior of a building; which can be defined as radiosity and ray-tracing. Radiosity can be described as a method that the space is divided into a mesh of patches. Each patch is considered as a Lambertian reflector, which means that it has a constant luminance, independent of the viewing direction. The flux that leaves each patch is given by Lambert's cosine law. Therefore, each patch receives and reflects light back to into space. The whole process is iterative and proceeds until all reflected flux has finally been absorbed. The calculation of view factors between different patches is one of the most difficult parts of this method. A render made by using radiosity can be seen in Figure 5.14 (A.Tsangrassoulis ,V. Bourdakis, 2003).



Figure 5.14 : An interior render with radiosity method (Url-24)

The advantage of the radiosity method is that calculations can be done by diffuse interreflections between surfaces. As disadvantages for this method is that, 3D mesh requires memory and it does not account for specular reflections or transparency effects (Doulos L., Tsangrassoulis A., Topalis F.,2005). This method is good at simulating specular reflections and transparency, since the rays that are traced through the scenes can be easily bounced at mirrors and refracted by transparent objects.

RADIANCE uses a light backward ray tracing method that is capable of solving the rendering equations under any kind of reflection or transmission, in geometrically complicated environments. For the estimation of lighting levels, deterministic and stochastic ray-tracing techniques are used to achieve the best balance between speed and accuracy (A.Tsangrassoulis ,V. Bourdakis, 2003).

In the ray-tracing technique, either forward or backward, rays are traced from the source or back to the source. Each ray carries a weight proportional to the intensity of the corresponding ray. On striking a surface, new rays are generated and their weight depends on the surface's reflectance. When the weight of one ray falls below an arbitrary value, it is taken to be absorbed and the process is repeated with a new emission. Backward tracing is considered as a much more efficient approach than forward tracing, since only a low percentage of light rays, similar to the interaction with the view will be considered in the calculation. In contrast, in following the light rays from the source, most of the calculation would be useless, as the majority do not contribute to the required image (Reinhart C.F., Herkel S., 2000).

The ray-tracing algorithm has the following advantages that it has accurate estimation of direct illumination, shadows, specular reflections and transparency effects. This method is also memory efficient. The disadvantages can be counted as this method is computationally expensive and if the point of calculation changes, the whole process should be repeated (A.Tsangrassoulis ,V. Bourdakis, 2003). A render made by using radiosity can be seen in Figure 5.15.



Figure 5.15 : An interior render with raytracing method (Url-24)

5.5.1.3 Sky models used in RADIANCE simulation

The main source of light in the sky is obviously the sun itself. However, as a result of atmospheric scattering and reflection off clouds, the entire sky dome also emits light. The overall distribution of light over the sky dome therefore depends on current environmental conditions. Figure 5.16 illustrates a range of different sky conditions showing just how variant this lighting distribution can be.

The RADIANCE standard release includes the sky model generator program gensky. This utility program will produce RADIANCE format sky luminance distributions for four sky model types, with the option to create a sun description for the non-overcast sky models. Another sky model generator program is gendaylit. This program is not part of the standard release, and so it is not updated with each release of RADIANCE. However, like RADIANCE, it is freely available and it gives the user access to the Perez All-weather model which is not supported by gensky (Mardaljevic J., 2000).

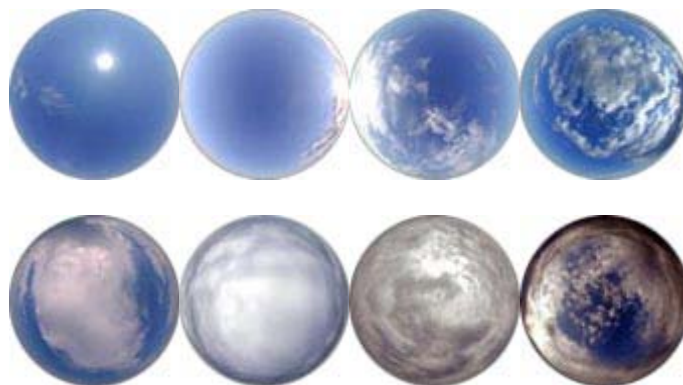


Figure 5.16 : Examples of different sky distributions (Url-14).

The gensky program can produce sky luminance distributions based on:

- the CIE uniform luminance model;
- the CIE overcast sky model;
- the CIE clear sky model;
- the Matsuura intermediate sky model.

The absolute luminance of any of these sky luminance patterns is controlled by supplying the program with either the zenith luminance or the diffuse horizontal illuminance. The clear and intermediate sky models allow the option to automatically create a description of the sun in the case that solar luminance is either directly supplied to the program or calculated from horizontal direct illuminance. The sun position can either be defined by altitude and azimuth or calculated by gensky from the time and geographical coordinates (Mardaljevic J., 2000).

The CIE uniform luminance model represents a sky with a constant value of luminance, where the overcast sky distribution model is based on a completely clouded sky and the sun's position are not apparent.

The passage of radiation through the clouds usually produces close to white light by mixing as moisture droplets are quite large and affect all frequencies of light. However, if the atmosphere is heavily polluted the overcast sky color appearance can be slightly yellow. The distribution of luminance in such a sky is symmetrical about the zenith and is lower at the horizon than overhead. Given a zenith luminance (L_z) and its altitude (a), the luminance at any point (L) in the sky is given by the equation:

$$L = L_z \frac{1 - 2 \sin(a)}{3} \quad (5.2)$$

Looking at this formula, it is clear that the luminance at the zenith ($a=90$) is three times brighter than at the horizon ($a=0$). This is significant as it means that skylights can be much more effective for daylighting per unit area than side windows as they allow more light in (Url-14). In Figure 5.17, illustrative image and sky luminance distribution for CIE Overcast Sky Model is given.

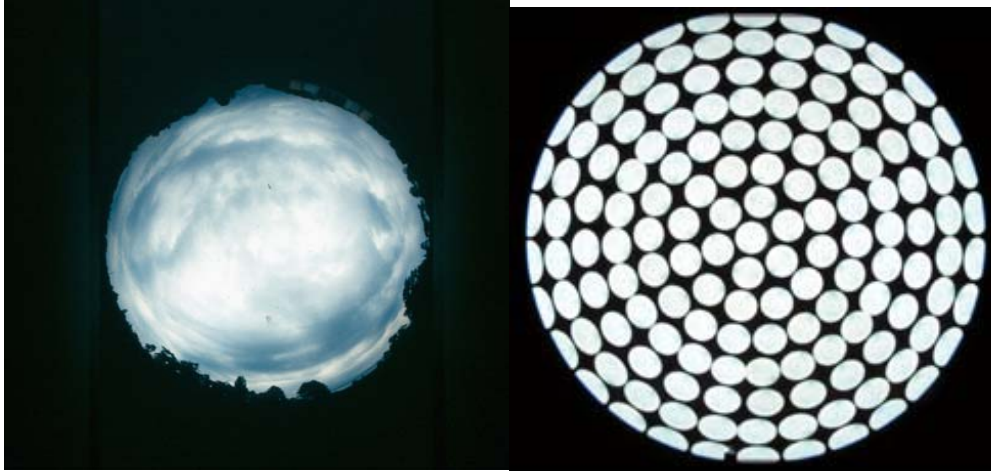


Figure 5.17 : Illustrative image and sky luminance distribution for CIE Overcast Sky Model (Scartezzini J., 2002)

A clear sky assumes that the sun is visible, resulting in a very non-uniform luminance distribution where the area around the sun is much brighter than any other area. The CIE Clear Sky model relates the luminance (L) at any point in the sky vault with the zenith luminance (L_z):

$$\frac{L}{L_z} = \frac{(a+b e^{-3k}+c \cos^2(k))(1-e^{-d \sec(z)})}{(a+b e^{-3z}+c \cos^2(z s))(1-e^{-d})} \quad (5.3)$$

Where:

a, b, c, d are adjustable coefficients,

k is the angle (in radians) between the point with luminance L and the Sun,

z is the zenith angle of the point and z_s is the zenith angle of the Sun.

According to CIE Publication 22, Standardization of Luminance Distribution on Clear Skies, Paris, 1973, the CIE clear sky model uses:

$$a = 0.91 \quad b = 10.0$$

$$c = 0.45 \quad d = 0.32$$

Additionally CIE has also standardized a clear sky for polluted atmospheres, using the following coefficients:

$$a = 0.856 \quad b = 16.0$$

$$c = 0.30 \quad d = 0.32$$

The blue colour of the clear sky is strongly dependant on the height of the location above sea level and the amount of the atmospheric pollution. Nitrogen dioxide makes the colour of the atmosphere slightly brown and this can be seen when looking towards an urban area from the surrounding countryside. High water vapour levels, in the absence of pollution, tend to give the sky a whiter appearance (Url-14). In Figure 5.18, illustrative image and sky luminance distribution for CIE Clear Sky Model is given.

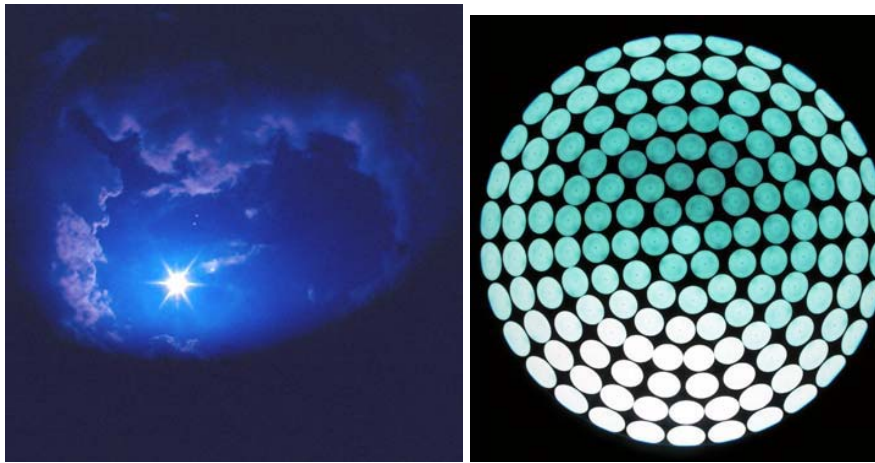


Figure 5.18 : Illustrative image and sky luminance distribution for CIE Clear Sky Model (Scartezzini J., 2002).

The Matsuura Intermediate Sky Model is a formulation based on a model that was proposed by Matsuura to describe sky conditions that have a higher turbidity than the CIE clear sky model. At the time that the Matsuura model was implemented into the Gensky program, it was recognized from CIE. Hereafter, it is referred to as the intermediate sky model. This model takes the form:

$$L(\gamma, \theta) = \frac{L_z \cdot a \cdot b}{2.326} \quad (5.4)$$

$$a = [1.35 \sin(5.631 - 3.59\xi) + 3.12] \sin(4.396 - 2.6\xi s) + 6.37 - \xi$$

$$b = \text{EXP}\{-0.5630[(2.629 - \xi)(1.562 - \xi s) + 0.812]\}$$

L_z = zenith luminance

$$\xi = \pi/2 - \gamma$$

$$\xi_s = \pi/2 - \gamma_s$$

θ = angle from sun to sky point

γ = sky point altitude

γ_s = sun altitude

The zenith luminance is normalised to the diffuse horizontal irradiance (Mardaljevic J., 2000).

In comparison to the CIE clear sky model, the intermediate formulation generally predicts lower luminance for the circumsolar region and slightly higher zenith luminances. Additionally, horizon brightening which can be a prominent feature of the clear sky model, is generally absent. Figure 5.19 shows plots of the sky luminance versus altitude together with false colour luminance maps for the clear, intermediate and overcast models. The sky point luminance along an arc from $\gamma = 0^\circ$ (due North), across the zenith to $\gamma = 0^\circ$ (due South) is plotted on the graph (dashed line on the false-colour maps). Each sky model was normalised to the same diffuse horizontal illuminance (30,000 lux). The sun altitude and azimuth were 45° and 180° respectively, though the sun itself was not modeled (Mardaljevic J., 2000).

5.5.2 ECOTECT as a daylight modeling tool

ECOTECT is software package for the conceptual building design that was written as a demonstration of the ideas presented in PhD thesis by Dr. Andrew Marsh at the School of Architecture and Fine Arts at The University of Western Australia. It comprises several unique features such as shadows and shading, solar analysis, lighting design, thermal performance, ventilation, and acoustic analysis. Of these features, shadows and shading analysis will be used to test the sun penetration through the daylight openings.

As shadows and reflections are an important aspects of building design, ECOTECT provides a variety of options for controlling their display. Sun-path diagrams are a convenient way of representing the annual changes in the path of the sun through the

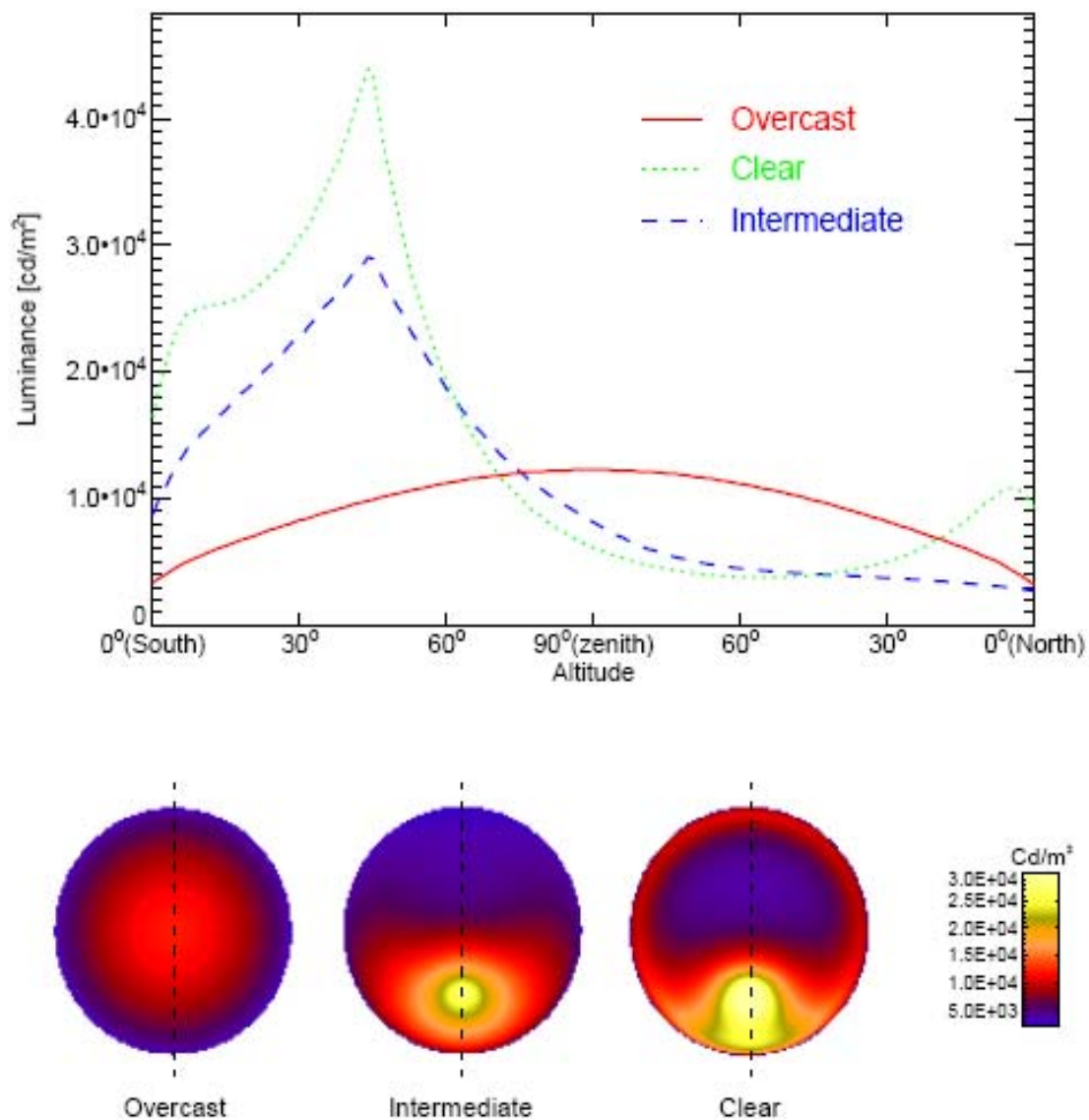


Figure 5.19 : Comparison of overcast, intermediate and clear sky models in false colour luminance maps (Mardaljevic J., 2000).

sky on a single 2D diagram. They provide a unique summary of solar position that the designer can refer to when considering shading requirements and design options. In Figure 5.20, displaying daily and annual paths of the sun in ECOTECT is represented.

A sun path diagram displays an interactive resizable projection of the entire sky dome onto a flat image. The position of the sun for a particular date and time can be displayed as a dotted line running across the model and daily or annual paths of the sun can be determined for each specific situation. There are two categories of the mentioned diagrams, polar and cylindrical diagrams.

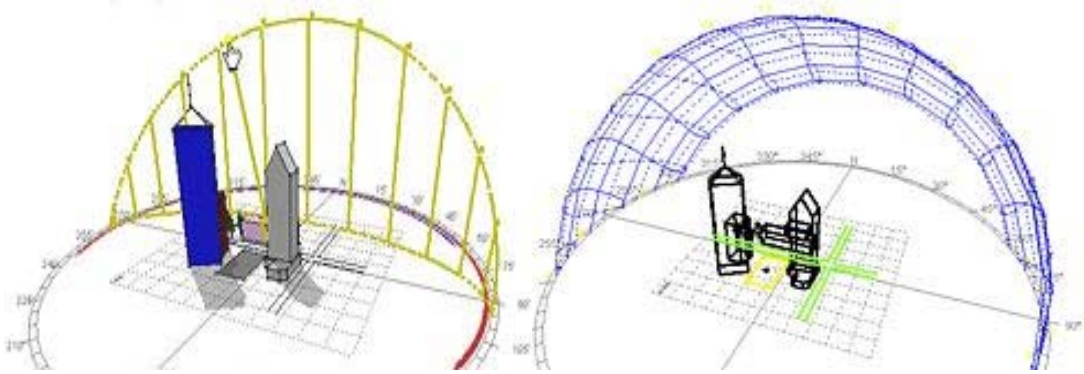


Figure 5.20 : Displaying daily and annual paths of the sun in ECOTECT (Url-14)

Polar sun-path diagrams can be likened to a photograph of the sky with a 180° fish eye lens, taken looking straight up towards the zenith. The paths of the sun at different times of the year can then be projected onto this flattened hemisphere for the current location. In Figure 5.21, an example to polar sun-path diagram used in ECOTECT is given.

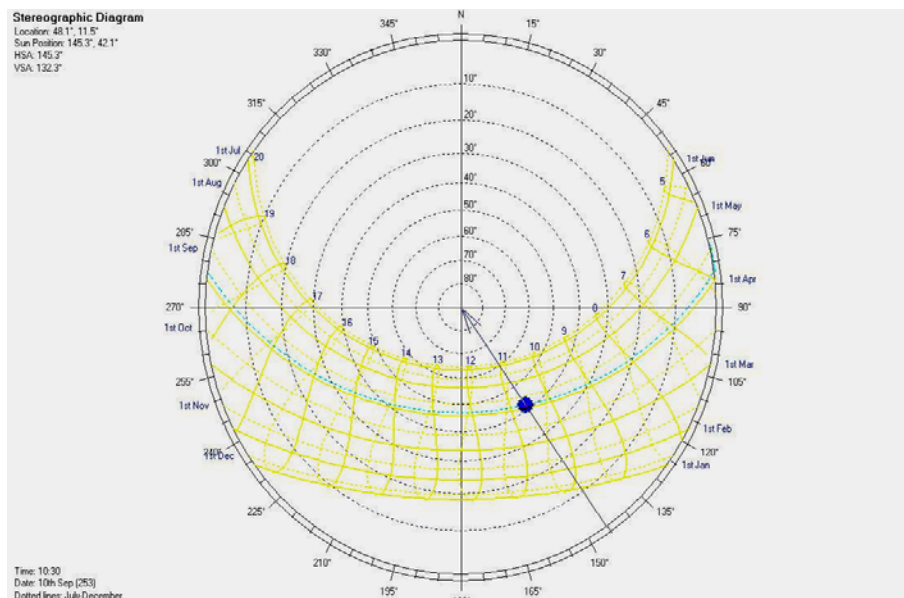


Figure 5.21 : An example image for polar sun-path diagrams in ECOTECT (Url-14)

Cylindrical sun-path diagrams are simply 2D graphs of the sun position in cartesian coordinates. The azimuth is plotted along the horizontal axis whilst the altitude is plotted vertically. Reading off positions is simply a matter of reading off the two axis. In Figure 5.22, an example to cylindrical sun-path diagrams is given.

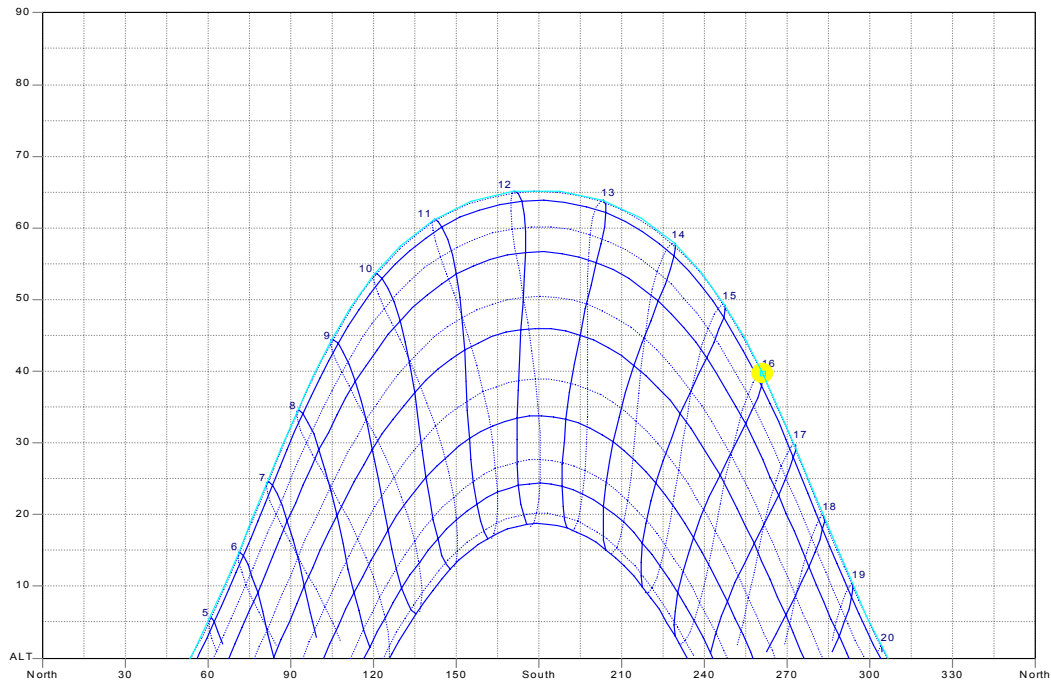


Figure 5.22 : An example image for cylindrical sun-path diagrams in ECOTECT (Url-14)

When light strikes the surface of an object, some portion of it may be transmitted, some absorbed and the rest is reflected. Thus, the transparency of a material can affect the amount of light reflected. A completely transparent object will not cast a reflection even if it is tagged. The Figure 5.23 shows the effect of varying transparency on the reflected sun-patch while using the ECOTECT simulation tool. The refractive effects of glass are also taken into account when determining shadow color through window objects.

When attempting to shade a window, the ECOTECT simulation tool uses the horizontal and vertical shadow angles relative to the window plane. These are calculated for any time due to the azimuth and altitude of the sun.

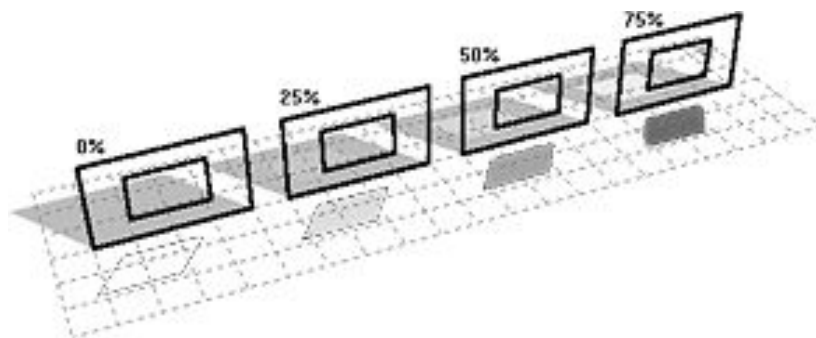


Figure 5.23 : Range of shadow colors due to the transparency in ECOTECT (Url-14)

Horizontal Shadow Angle (HSA) is the angle between the normal of the window or the wall surface and the current sun azimuth. Vertical Shadow Angle (VSA) is obtained with the Equation 5.5. Figure 5.24 illustrates the Horizontal Shadow Angle (HSA) and Vertical Shadow Angle (VSA) that the ECOTECT tool takes into consideration (Url-14).

$$VSA = \arctan (\tan(\text{Altitude})/\cos(\text{HSA})) \quad (5.5)$$

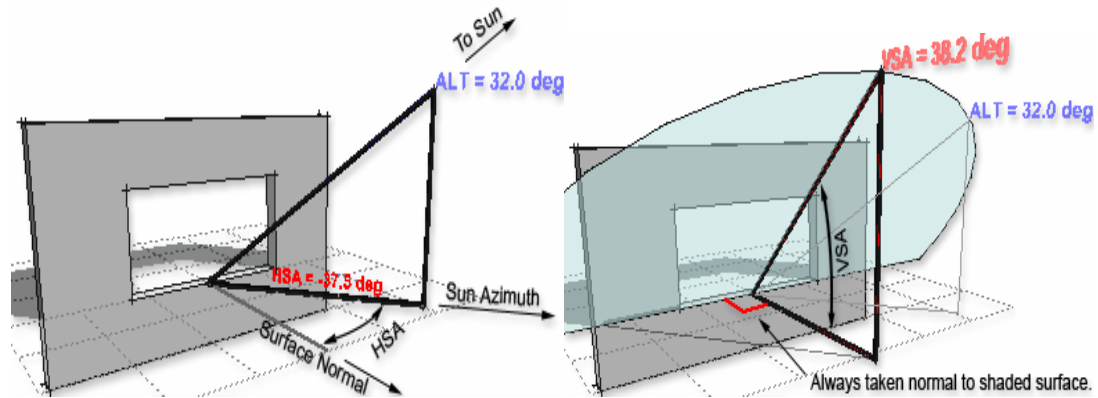


Figure 5.24 : The derivations of horizontal and vertical shadow angles (Url-14)

5.5.3 Daylight modelling of the investigated gallery

The daylight modelling for the investigated museum was carried out in one gallery, taking place at the third floor by considering the results of the investigations performed in the seven galleries of Kunstmuseum Stuttgart. The gallery has white walls and a white ceiling, which is a similar tendency for many of the modern art exhibition halls. The ground floor is grey in color. The plan shape is trapezoid, with the dimensions a:14.30m, b:17.80m, c:15.70m, d:17.90m. In Figure 5.25 and 5.26, the plan and the placement of the simulated gallery in section are given.

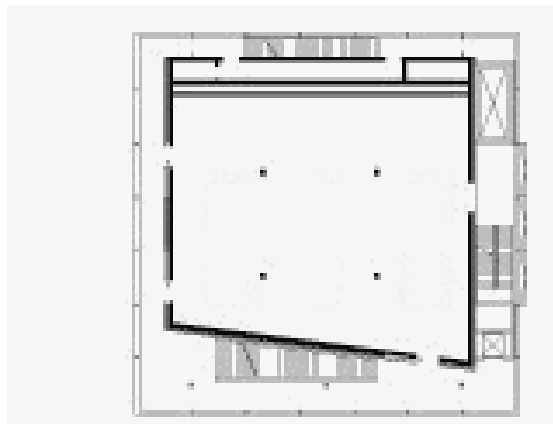


Figure 5.25 : The plan of the simulated gallery (Url-19)

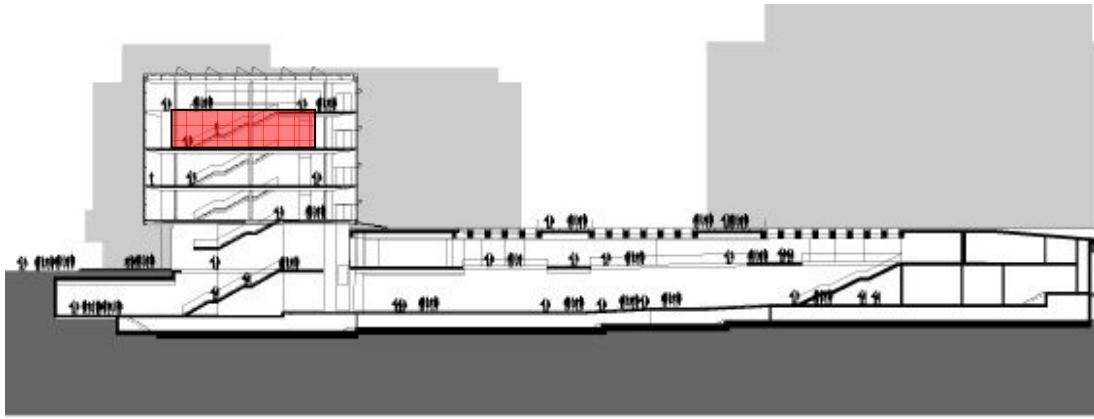


Figure 5.26 : The placement of the simulated gallery in the museum's section (Url-19)

The walls of the investigated gallery are beige painted with reflectance of 80%. The ceiling is a white PVC membrane covered system to have even distribution of lighting in the gallery. The floor finishing material is grey colored linoleum floor covering. An image showing the interior is given in Figure 5.27.

The daylighting analyses were carried out by the help of ECOTECH and RADIANCE Simulation Tools. In this study, the ECOTECH tool was used to study sunlight penetration within the galleries of the museum and to determine the critical points where direct sunlight strikes the exhibition areas and to decide the required time periods when the solar control must be supplied. The exhibited paintings were also modelled to illustrate the shaded portion of light falling on the artifacts.



Figure 5.27 : Image from the investigated gallery, Gallery 1 (Url-19)

Firstly, general 3D modelling of the illustrated gallery was build up in ECOTECT simulation tool. The geographical conditions for the location of the case study building was introduced to the program as latitude 48.76 and longitude 9.18. The orientation of the building is also loaded to the model. In Figure 5.28, the gallery zone and the yearly solar path can be examined in the output file of ECOTECT simulation tool.

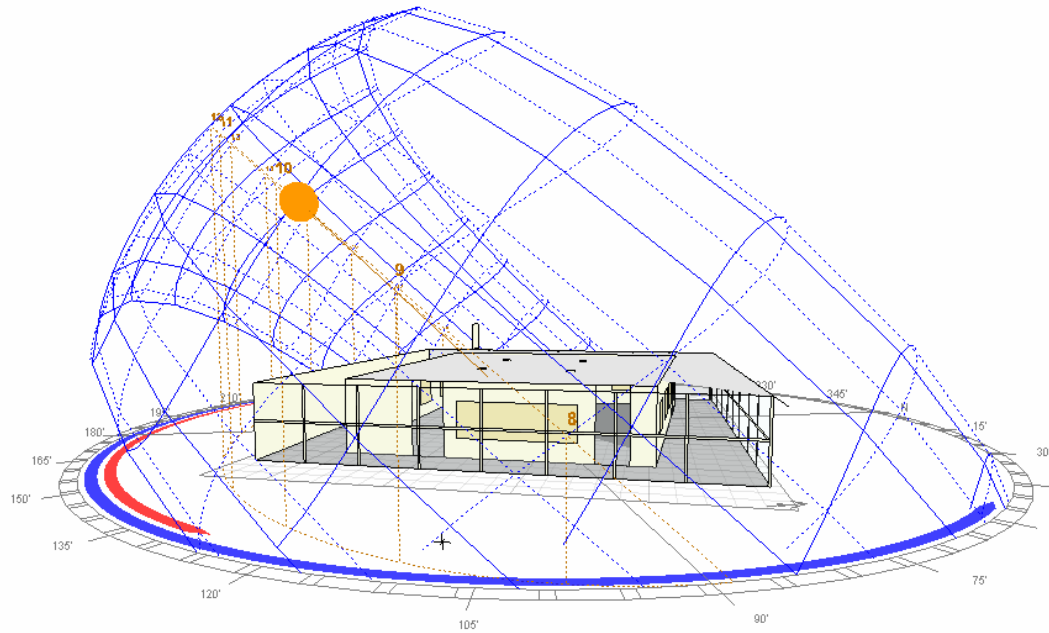


Figure 5.28 : Schematic description of the investigated gallery zone modelling in ECOTECT with the daily and annual sunpath (Url-14)

To have accurate simulation results, necessary material attachments is to be done. In ECOTECT, there are several types of materials in the divisions of building components. In Figure 5.29, the glazing attachments can be seen. The glass cube contains double-glazing with Low-E coating. The attached glazing can be seen in material library of ECOTECT.

The investigated space consists of four walls and each of the walls were named as wall A, B, C and D which are shown in Figure 5.30. After setting up the physical model, the simulations were carried out for the 15th of each month in a year, which is the representative day for the months. The simulations were made for the hours between 05:00- 19:00 to test the direct sunlight penetration onto the exhibitions.

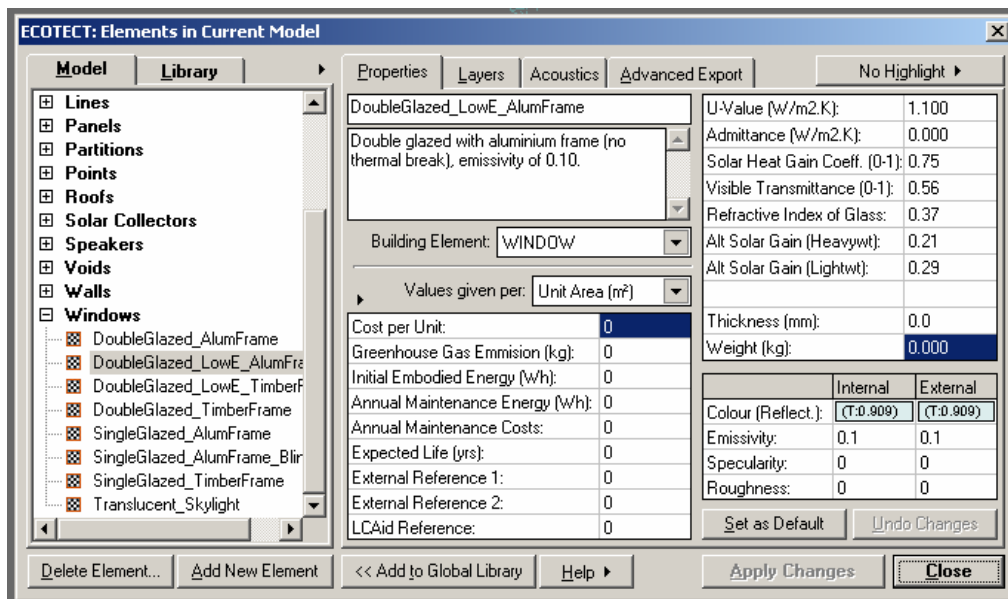


Figure 5.29 : A screenshot from the simulation tool showing the material library (Url-14)

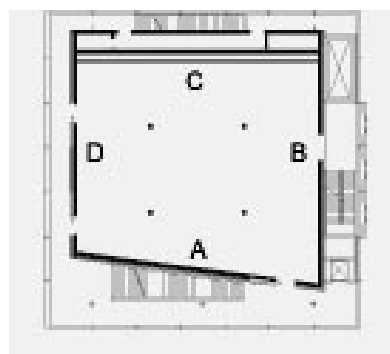


Figure 5.30 : The names of the walls in Gallery 1 (Url-19)

The outputs where direct sunlight strikes the museum objects for the particular hours in the sample day for each month can be seen in the Appendix C as ECOTECT images. As an example to the analyses, the daylighting results of the ECOTECT image for 15 January is given in Figure 5.31, where sunlight penetration from the south east oriented windows strike the paintings on the wall A for the hour of 09:00. The ECOTECT outputs obtained from the simulated gallery for the particular times when direct sunlight strikes the walls are given in Appendix C. Direct sunlight is represented by the yellowish color. The results of the ECOTECT simulations are listed in tables for hourly outputs in Appendix D. The situation that direct sunlight is seen on the wall surface is given in the tables as ‘affected’. Opposite situation is represented as ‘Not Affected’.



Figure 5.31 : A sample ECOTECT image for 15 January at 9:00

By taking the results of the simulation into consideration, the annual results for direct sunlighting is formed in tables months and hours. The yellow shaded sun figure illustrates the times when direct sunlight strikes the walls and the tick illustrates that there is no risk of direct solar exposure. The Tables 5.1, 5.2 and 5.3 give the annual results of the ECOTECT simulations for affected walls A, B and C.

By running ECOTECT software with Radiance Control Manager, the hourly illumination levels can be calculated by RADIANCE Simulation Engine. In order to perform the lighting calculations, an analysis grid must be specified and a virtual camera must be inserted in the model. ECOTECT contains three kinds of cameras for a model named as normal, parallel and wide angle, changing to the type of image which is needed to be obtained. In the visualization menu of the ECOTECT program, the camera views can be seen. The final image to be generated can be chosen as Luminance Image (cd/ m^2), illuminance image (lux), daylight factors (%DF), or sky components (%SC).

A luminance image is based on the amount of the light reflected off each surface in the scene, exactly the same as a camera sees. An illuminance image shows the amount of light falling on each surface. This is an analytical image showing lux levels. Daylight factors image is a worst case percentage of available daylight on surfaces. For sky components image, all materials are output as matte black to ensure only direct light from the sky (Url-14). Of these features, illuminance image in lux is selected in order to calculate the amount of light falling on the walls of the gallery and the paintings on the walls. CIE Intermediate Sky Model is chosen as sky conditions for the calculations.

Four cameras are inserted to the ECOTECT model in order to evaluate the illumination levels and the shadows on four walls of the gallery under the same conditions of date and time. Each of the camera views are oriented to one wall of the gallery. The camera for walls A, B, C and D are named as Camera 1, 2, 3 and 4 respectively.

Table 5.1 : Annual Simulation Results per Hours for Wall A

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
05:00	√	√	√	√	√	√	√	√	√	√	√	√
06:00	√	√	√	√	√	√	√	√	√	√	√	√
07:00	√	√	√	√	√	√	√	√	√	√	√	√
08:00	√	√	√	√	√	√	√	√	√	☀	☀	√
09:00	☀	☀	√	√	√	√	√	√	√	☀	☀	☀
10:00	☀	☀	☀	√	√	√	√	√	√	☀	☀	☀
11:00	☀	☀	√	√	√	√	√	√	√	√	☀	☀
12:00	☀	☀	√	√	√	√	√	√	√	√	☀	☀
13:00	√	√	√	√	√	√	√	√	√	√	√	√
14:00	√	√	√	√	√	√	√	√	√	√	√	√
15:00	√	√	√	√	√	√	√	√	√	√	√	√
16:00	√	√	√	√	√	√	√	√	√	√	√	√
17:00	√	√	√	√	√	√	√	√	√	√	√	√
18:00	√	√	√	√	√	√	√	√	√	√	√	√
19:00	√	√	√	√	√	√	√	√	√	√	√	√

Table 5.2 : Annual Simulation Results per hours for Wall B

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
05:00	√	√	√	√	√	√	√	√	√	√	√	√
06:00	√	√	√	√	√	√	√	√	√	√	√	√
07:00	√	√	√	√	☀	☀	☀	√	√	√	√	√
08:00	√	√	√	☀	☀	☀	☀	☀	☀	☀	☀	√
09:00	☀	☀	☀	√	√	√	√	√	☀	√	√	☀
10:00	√	√	√	√	√	√	√	√	√	√	√	√
11:00	√	√	√	√	√	√	√	√	√	√	√	√
12:00	√	√	√	√	√	√	√	√	√	√	√	√
13:00	√	√	√	√	√	√	√	√	√	√	√	√
14:00	√	√	√	√	√	√	√	√	√	√	√	√
15:00	√	√	√	√	√	√	√	√	√	√	√	√
16:00	√	√	√	√	√	√	√	√	√	√	√	√
17:00	√	√	√	√	√	√	√	√	√	√	√	√
18:00	√	√	√	√	√	√	√	√	√	√	√	√
19:00	√	√	√	√	√	√	√	√	√	√	√	√

Table 5.3 : Annual Simulation Results per hours for Wall C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
05:00	√	√	√	√	√	√	√	√	√	√	√	√
06:00	√	√	√	√	√	√	√	√	√	√	√	√
07:00	√	√	√	☀	☀	☀	√	√	√	√	√	√
08:00	√	√	☀	☀	☀	☀	☀	☀	√	√	√	√
09:00	√	☀	☀	√	√	√	√	☀	√	√	√	√
10:00	√	√	√	√	√	√	√	√	√	√	√	√
11:00	√	√	√	√	√	√	√	√	√	√	√	√
12:00	√	√	√	√	√	√	√	√	√	√	√	√
13:00	√	√	√	√	√	√	√	√	√	√	√	√
14:00	√	√	√	√	√	√	√	√	√	√	√	√
15:00	√	√	√	√	√	√	√	√	√	√	√	√
16:00	√	√	√	√	√	√	√	√	√	√	√	√
17:00	√	√	√	√	√	√	√	√	√	√	√	√
18:00	√	√	√	√	√	√	√	√	√	√	√	√
19:00	√	√	√	√	√	√	√	√	√	√	√	√

The Radiance Image Viewer gives the calculated outputs in different formats, which are contour lines, contour bands, false color images, daylight factors, human sensitivity, set exposure and custom scale. In this study, maps with contour lines and false color images are used in order to see the results of illuminance calculations. In Figure 5.32 and Figure 5.33, false color renderings of the four camera views showing the illuminance levels on a colored method is given as an example to RADIANCE image outputs. Blue color represents illuminance levels of 50 lux and under, while red color represents the values of 950 lux and more. The illuminance scales can be changed to upper limits when a more specific result for a particular point is needed to be evaluated.

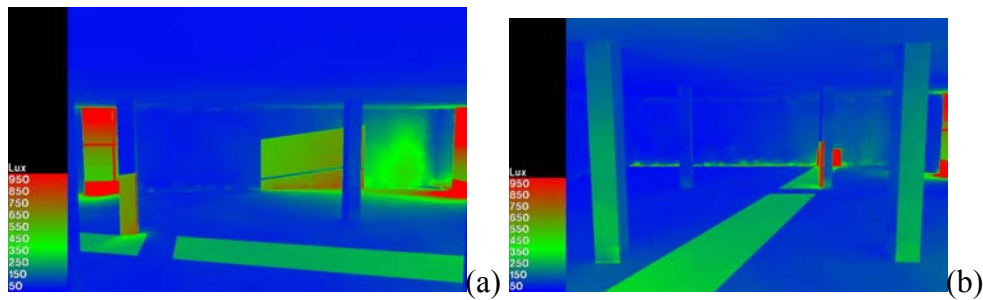


Figure 5.32 : The false color renderings of the camera views for Wall A (a) and Wall B (b), generated by RADIANCE calculations for 15 January at 09:00.

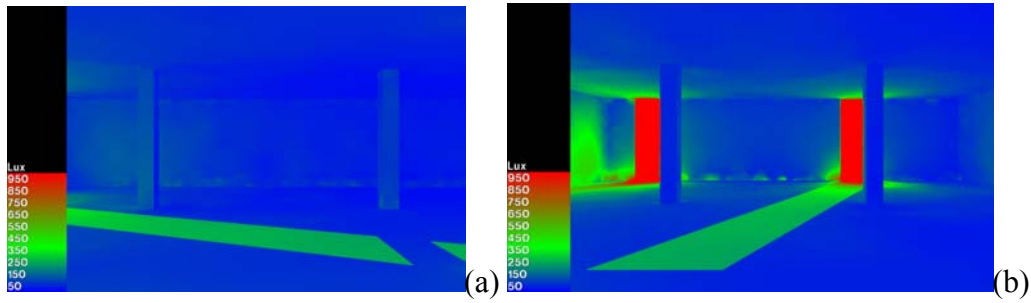


Figure 5.33 : The false color renderings of the camera views for Wall C (a) and Wall D (b) generated by RADIANCE calculations for 15 January at 09:00.

In order to predict the illuminance levels on the walls when daylight directly or indirectly penetrates into the gallery space, RADIANCE simulation engine was used. The calculations were performed for winter and summer conditions with the representative days of 15 January and 15 July. The contour lines feature of the software is chosen in order to see the possible daylighting levels on the walls so that the current daylighting system can be compared for winter and summer conditions. In Figure 5.34, a sample RADIANCE simulation output is given for 15 January at 9:00. The four views represent the four gallery walls which are the viewpoints of the RADIANCE cameras attached for walls.

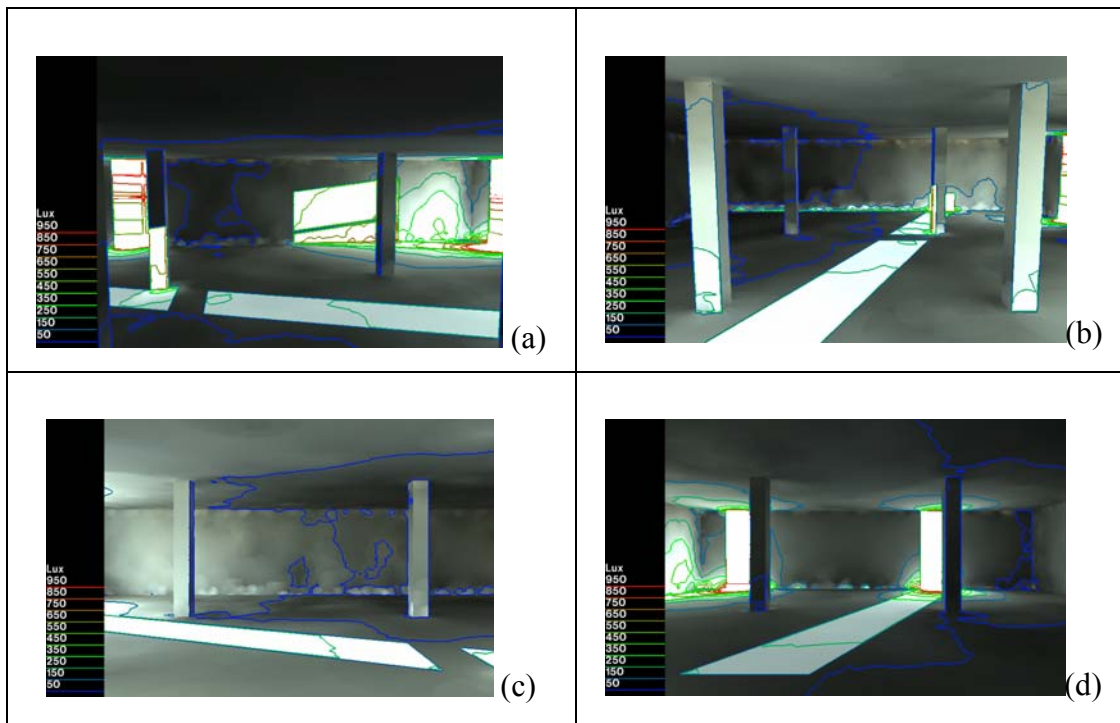


Figure 5.34 : Illuminance distributions on Wall A (a), Wall B (b), Wall C (c) and Wall D (d) generated by the contour lines feature of the RADIANCE calculation tool.

As can be seen from the RADIANCE views, daylight levels are represented in different colors which are given next to each figure. The same calculations are performed on 15 January and 15 July between the hours of 06:00 – 17:00 when daylight is available in the gallery. The calculated RADIANCE outputs for winter and summer conditions are given in Appendix E.

The daily paths of the sun for 15 January and 15 July are given in Figures 5.36 and 5.37. Both of the images show the path of the sun for the particular representative days and the position of the sun is given for 09:00 as an example to emphasize the differences in the simulation results. As can be seen from Figure 5.36, direct sunlight can penetrate into the investigated gallery in winter conditions causing differences of illuminance levels on walls. Penetration of direct sunlight in summer conditions is avoided due to the position of the sun that is also given in Figure 5.36.

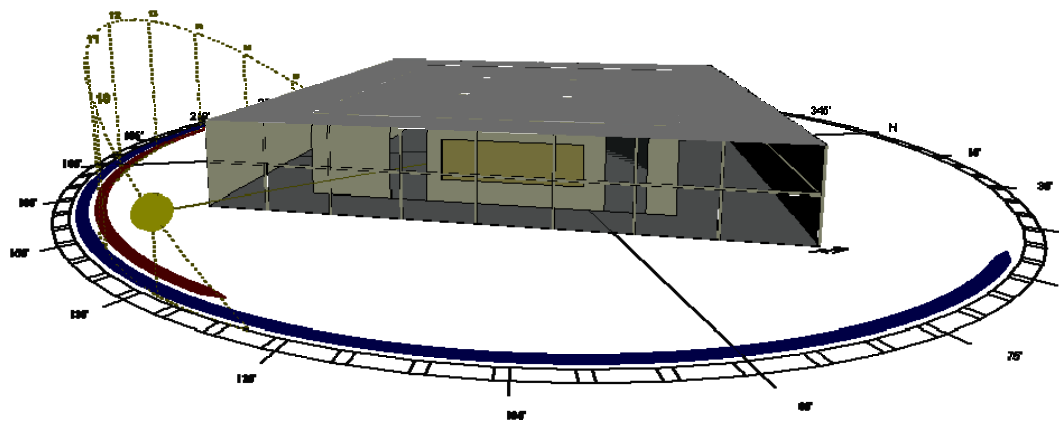


Figure 5.35 : Daily path of the sun for 15 January generated by ECOTECT

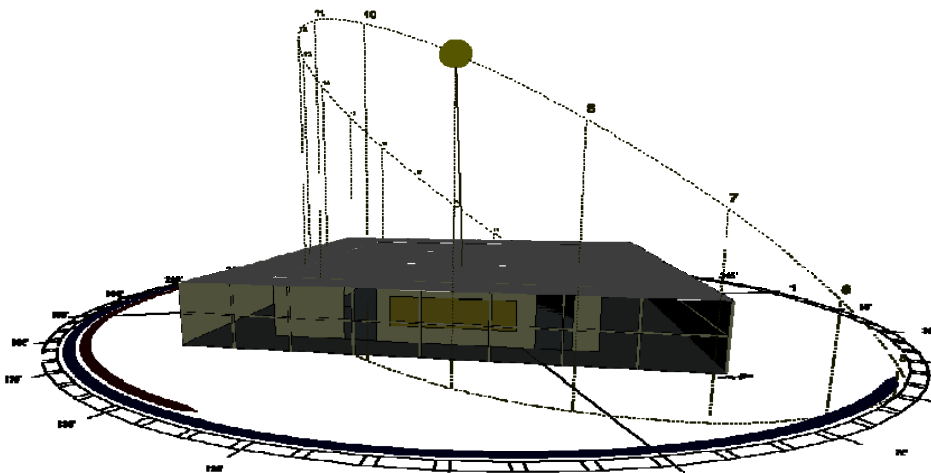


Figure 5.36 : Daily path of the sun for 15 July generated by ECOTECT

5.6 Discussion of Results

In Chapter 5, Kunstmuseum Stuttgart was investigated from lighting conditions point of view and lighting simulation techniques are introduced with two simulation programs. The investigations were made under the general headings of gallery investigations, lighting measurements and computer based lighting simulations.

Performed lighting measurements are divided into two which are general lighting measurements in nine points at the height of 1.5m and vertical lighting measurements where mid points of the artifacts are considered. In these galleries, oil paintings under the category of low- responsivity materials, are recommended to be illuminated with a maximum of 200 lux. According to the results of lighting measurements carried out for general lighting of the seven selected gallery spaces, four galleries exceed the limits of 200 lux while three of them are approximately illuminated with the recommended lighting value 200 lux. The maximum average level measured is 727 lux, which is in Gallery 5, and the minimum average level measured is 171 lux in Gallery 3 and 7. As for the vertical lighting level measurements performed on the mid point of the artifacts, the most critical gallery among the investigated galleries is Gallery 1 where the average value measured on the objects is 577 lux, which exceeds the recommended value 200lux.

In Figure 5.37 comparison of the measured general lighting levels with the recommended values are illustrated. On X axis, the galleries which are numbered are given, where illumination levels are represented on Y axis. Measured levels are represented by red color, where the recommended values for lighting are represented by blue color. Measured vertical lighting levels on artifacts and its comparison with the recommended values is given in a graphical exposition Figure 5.38.

In three of the naturally illuminated galleries, which are oriented to northern directions, textile curtains control daylight. One of the galleries numbered as Gallery 1 does not have any solar control devices in despite of its south - east orientation. The distribution of the hours that the walls of the gallery are affected from direct sunlight to the months is given as a graph in Figure 5.39. The X axis of the graph symbolises the months where in Y axis gives the total number of hours with exposure to direct sunlight. Each of the exhibition walls are identified with a different color.

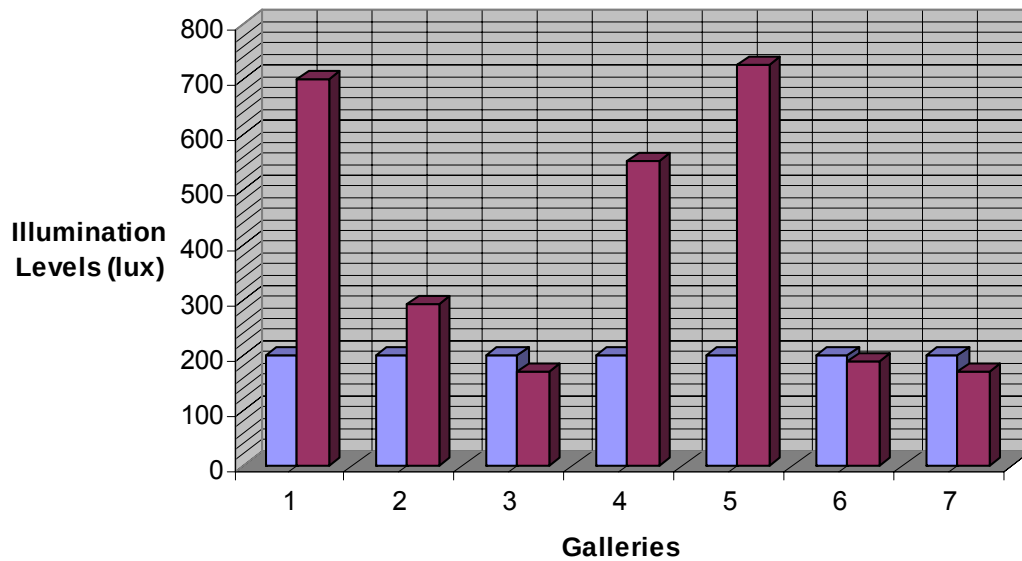


Figure 5.37 : Comparison of the measured general lighting levels with the international standards

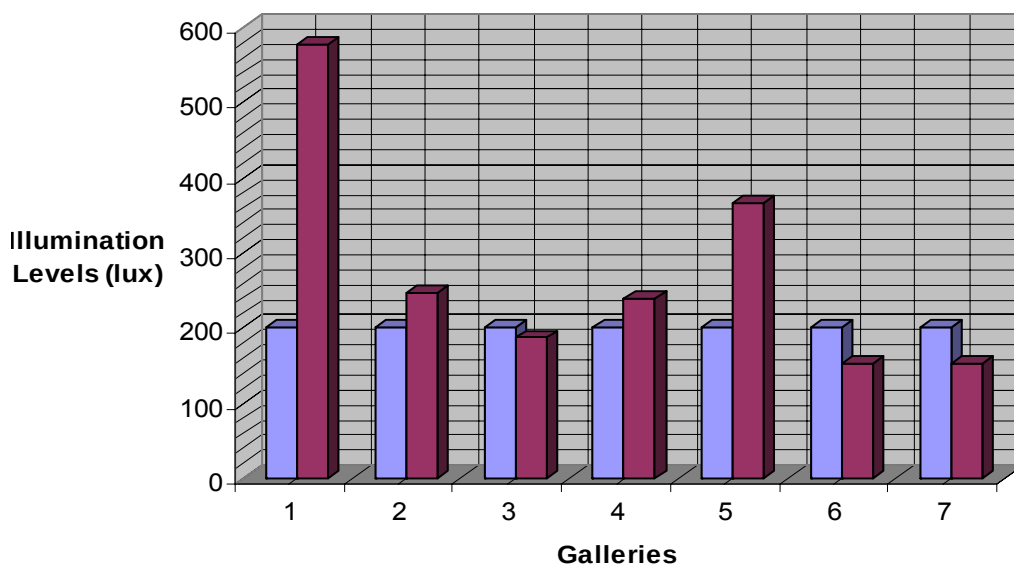


Figure 5.38 : Comparison of the average of measured vertical lighting levels on artifacts with the international standards

Due to Gallery 1's precarious design for daylight and results of measured illuminance levels that are higher than the international lighting standards, this gallery was selected as a case study gallery area for daylighting simulation. As the orientation of this gallery is to eastern directions, daylight can penetrate into the space in the morning hours. The prediction of the hours when daylight might affect the exhibition walls were made with the help of lighting simulation tools. ECOTECT simulation tool was used to predict the times of direct sunlight in a year on sample

days of the months. A model of the gallery was developed by attaching the building component materials to the sample model, taking the orientation of the gallery into consideration and loading the geographical data of Stuttgart.

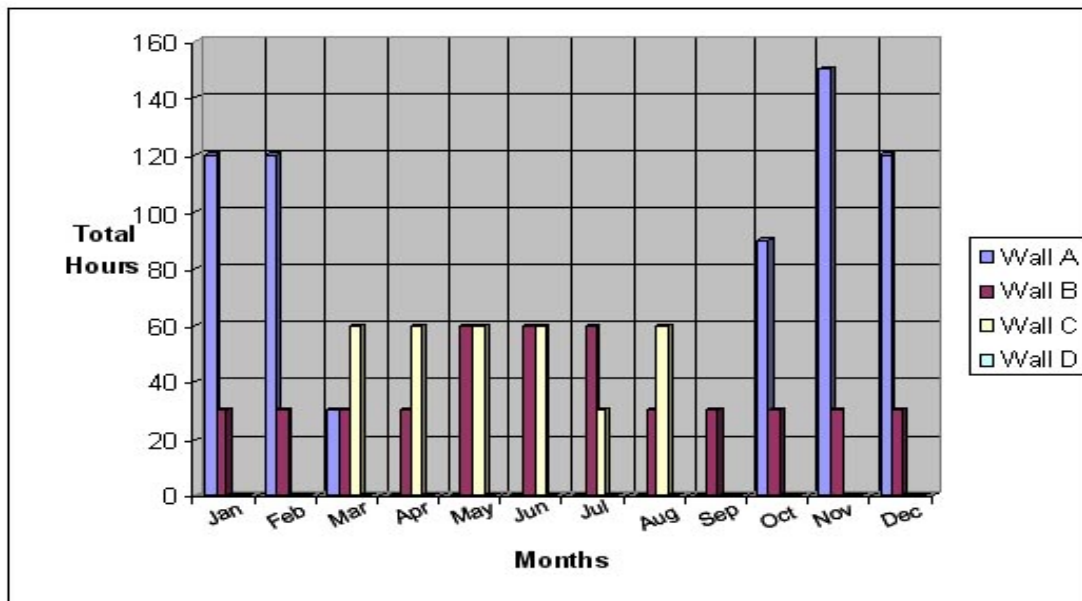


Figure 5.39 : Distribution graphic of the total annual hours with direct sunlight evaluated for gallery walls per months

The selected days that the simulations were performed can be defined as the days with representative conditions for each of the months. According to the results of the ECOTECT simulations, the total of annual hours that direct sunlight strikes the exhibition walls were calculated. In an approximate annual calculation for direct sunlight exposure, the result of total affected hours for Wall A is 630 hours, for Wall B 450 hours, for Wall C 330 hours in total while Wall D is not affected from direct sunlight. The results are given in Figure 5.40. where X axis represents the total hours of exposure and Y axis represents the four gallery walls named as Wall A, B, C and D each represented with a different color.

As can be seen from the ECOTECT evaluations made for direct sunlight exposure, Wall A is the most effected wall from direct sunlight if a shading system is not developed for this gallery. Wall D does not have the risk of direct sunlighting on paintings but as this wall has got two windows on the both edges, the middle area left for exhibition is not recommended as a suitable area for an exhibition because of the excessive luminance contrast causing glare for the viewers. Using Wall B and Wall

C might be a good solution for exhibitions of paintings if a shading system is designed for the gallery.

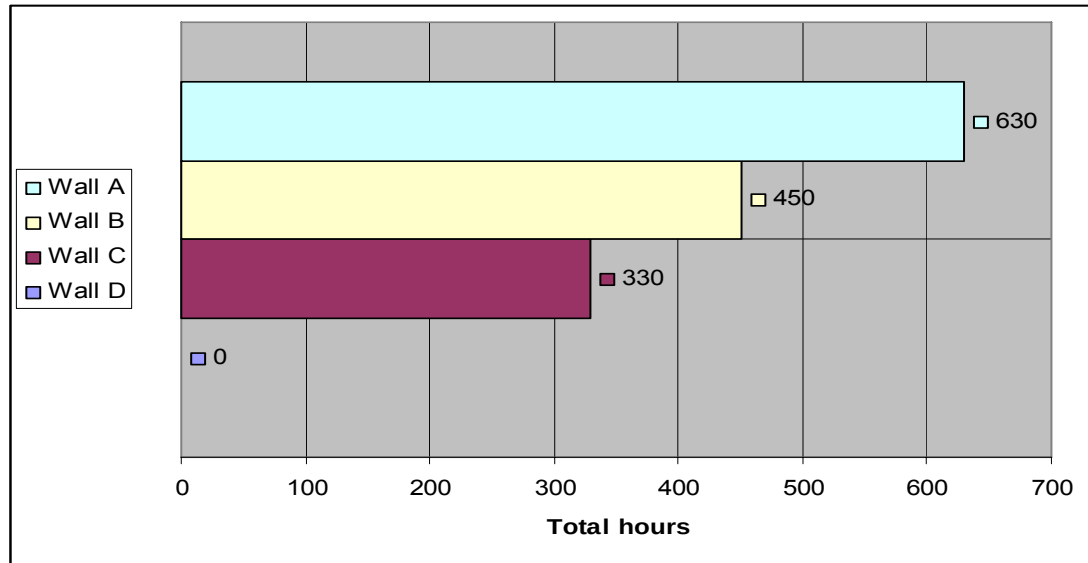


Figure 5.40 : Distribution graphic of the total hours with direct sunlight on gallery walls

In order to predict the daylight availability of the case gallery, RADIANCE simulation engine was used. By using the RADIANCE Control Manager Software, the maximum daylighting levels caused by sidelighting in winter and summer conditions were evaluated for each wall. Due to the results of the RADIANCE simulations for 15 January, the calculated highest illuminance levels on the walls are given in Table 5.4. The levels exceeding the recommended value of 200 lux are highlighted with a gray background color. According to the results of the calculations, highest illuminance levels are met on Wall A with 950 lux for winter conditions. Daylight strikes wall B only at 9:00 with the highest illuminance level of 350 lux. Wall C is the least effected exhibition area for winter conditions. Wall D has the highest illuminance level 350 lux at 10:00 caused by the windows that are on this wall. In Figure 5.41, a graphical illustration for hourly maximum illuminance levels calculated on walls is given for winter conditions.

Table 5.4 : Maximum illuminance levels on the walls per hours on 15 January (lux)

Hours	Wall A	Wall B	Wall C	Wall D
06:00	150 lux	50 lux	50 lux	50 lux
07:00	250 lux	50 lux	50 lux	50 lux
08:00	250 lux	150 lux	50 lux	150 lux
09:00	550 lux	350 lux	50 lux	250 lux
10:00	850 lux	150 lux	150 lux	350 lux
11:00	950 lux	50 lux	50 lux	350 lux
12:00	550 lux	50 lux	50 lux	250 lux
13:00	350 lux	50 lux	50 lux	250 lux
14:00	350 lux	50 lux	50 lux	250 lux
15:00	250 lux	50 lux	50 lux	250 lux
16:00	250 lux	50 lux	50 lux	250 lux
17:00	150 lux	50 lux	50 lux	150 lux

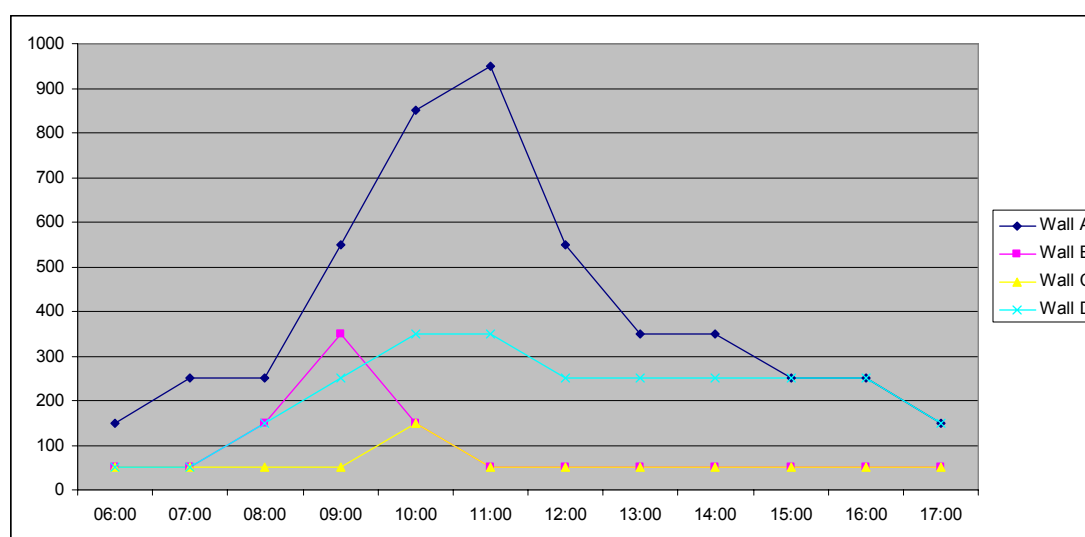


Figure 5.41 : Hourly maximum illuminance levels calculated on walls for 15 January per hour.

According to the results of evaluations for summer conditions, the artifacts exhibited on Wall A, Wall C and Wall D can be at risk with maximum illuminance levels exceeding the recommended levels which can cause hazardous effects for the artifacts. Daylight strikes Wall B at 07:00 with the highest illuminance level of 450 lux. In Table 5.5, calculated illuminance levels on the walls per hours for summer conditions are given. Figure 5.42 represents the hourly maximum illuminance levels calculated on walls for 15 July per hours.

As a result of the performed daylighting simulations, the time limits when solar control is needed for winter conditions change between 07:00 and 16:00 in order to reach the recommended lighting standards for exhibitions of paintings. As the maximum illumination level recommended for the exhibition of low responsivity

artworks is 200 lux, using a flexible daylight control system on the windows is recommended when the interior illumination exceeds this value.

Table 5.5 : Maximum illuminance levels on the walls per hours on 15 July (lux)

Hours	Wall A	Wall B	Wall C	Wall D
06:00	150 lux	150 lux	50 lux	150 lux
07:00	350 lux	450 lux	350 lux	250 lux
08:00	450 lux	350 lux	650 lux	350 lux
09:00	550 lux	150 lux	250 lux	350 lux
10:00	150 lux	150 lux	250 lux	350 lux
11:00	350 lux	50 lux	50 lux	250 lux
12:00	150 lux	50 lux	50 lux	150 lux
13:00	150 lux	50 lux	50 lux	150 lux
14:00	150 lux	50 lux	50 lux	150 lux
15:00	150 lux	50 lux	50 lux	150 lux
16:00	150 lux	50 lux	50 lux	50 lux
17:00	150 lux	50 lux	50 lux	50 lux

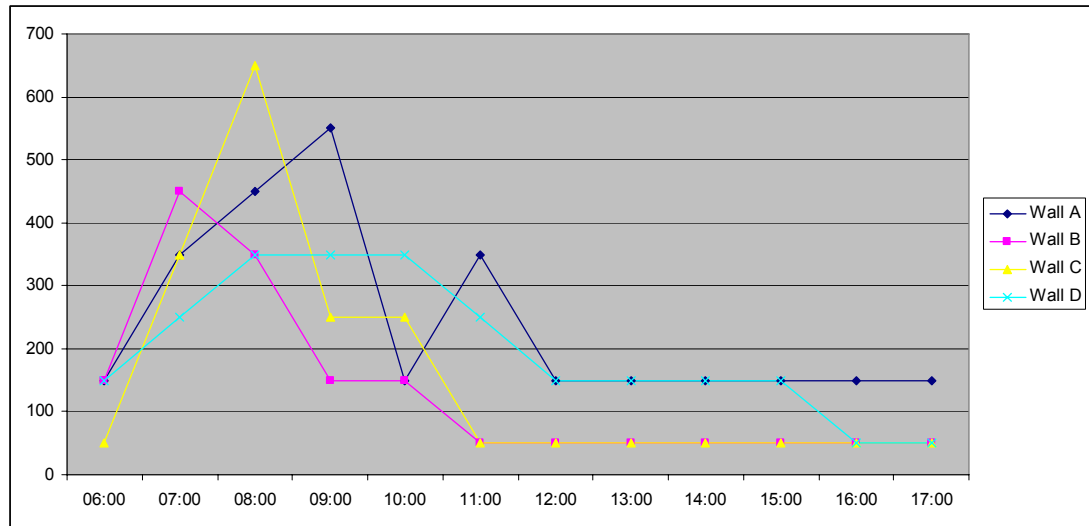


Figure 5.42 : Hourly maximum illuminance levels calculated on walls for 15 July per hour.

Wall A is not recommended to be used as an exhibition area for low responsivity artworks if the current system is preferred. For summer conditions, design of a shading system is proposed, a flexible shading system for this gallery can be useful in the morning hours between 06:00 and 11:00. Daylight can be used as part of natural lighting system after 11:00 where the evaluated highest illuminance levels are up to 150 lux, which is also suitable for the recommended standards. The design of a proper artificial lighting system must be performed with respect to the daylight simulation results.

6. CONCLUSION AND RECOMMENDATIONS

Energy efficiency in buildings and renewable energy sources became of significant importance in the last few decades. Lighting energy is a remarkable part of the overall energy consumption in buildings therefore daylighting is an important parameter in energy efficient building design. Introducing natural light into buildings also provides a visually and psychologically pleasing environment. When the building type is a museum, this situation is followed by a challenging process as daylight must carefully be introduced into the space because of the light responsive objects.

Daylight carries the harmful portion of light, which can cause deterioration on many light sensitive objects so the design of daylight openings and solar control strategies is essential when daylight is admitted in a museum environment. The appropriate method to design a museum building and its daylighting system can be performed by accomplishing the visual comfort conditions and conservation requirements in the early steps of the design. The grouping of similar categories of objects in a specific zone is of key importance in determining exhibition layout in order to provide visual comfort conditions and protect eye health of the visitors.

As far as it is concerned, museum galleries might use daylight if a proper daylight redirecting system or solar control system is integrated into the design. As a part of this study, an investigation was made at Kunstmuseum Stuttgart from lighting conditions point of view evaluating the visual comfort, conditions ensured by daylighting and artificial lighting systems and preservation of the artifacts. The selected museum is an existing building in Stuttgart, which was emerged as a winner of an international architecture competition. Seven galleries of this building, where generally two-dimensional artifacts are exhibited, were investigated. Among them, one gallery is chosen as a case gallery for daylight simulations due to the critical results of the investigations. The ECOTECT simulation tool was used to predict the time periods throughout the year when direct sunlight enters the space through the windows. RADIANCE simulation engine was also used in order to calculate the daylight illumination on the sample days. The calculations were performed for

winter and summer conditions. The calculated maximum illumination levels on the exhibition surfaces caused by daylight are given in Table 5.4 and 5.5. As can be seen from the results, the illumination levels exceed the recommended limit value of 200 lux for some defined hours. In Chapter 5 in Figure 5.41, the annual evaluation of the total hours when sunlight affects the artifacts is given. Due to the results of the performed evaluations, the wall named as Wall A is the most affected exhibition surface of the investigated gallery. According to the results of the ECOTECT and RADIANCE simulations, it is clear that development of a shading strategy is essential. For this gallery, using shading devices for the defined hours when daylight strikes the objects can be efficient. Wall A, B and C are suitable for display if the direct sunlight is controlled. As Wall D contains two daylight openings, it is not recommended to exhibit the paintings on this wall.

The appropriate method to design the lighting system of a museum environment is possible if with the correctly integrating daylighting and artificial lighting systems. Artificial lighting is used in museum buildings when daylight is not preferred or in times when daylight is not sufficient. In museum buildings, artificial lighting systems for the exhibition galleries must be designed with respect to daylighting for general lighting energy conservation and supplying the conservation needs of the artifacts in a museum environment. For the simulated gallery, the daylighting simulations were performed both to conserve the artifacts by testing the maximum lighting levels if the recommended lighting levels are provided and to decide the time limits when solar control is necessitated. The design of an appropriate artificial lighting system can be designed basing on the daylighting performance simulations that are carried out for specific times of the year. To reduce the lighting energy consumption, the outputs of the ECOTECT and RADIANCE programs can be used and necessary evaluations can be supplied in order to determine when daylighting can be used as part of the lighting system without damaging the artifacts. In this way, the lighting energy used for museum lighting can be reduced while protecting the museum objects.

Today the simulation technology in architecture supplies diverse computational tools for architects, lighting designers and building physicists. It is possible to predict the results of the feasible environments by using these simulation engines. It is possible to use lighting simulation tools for visual comfort and energy consumption assumption in the design phase of buildings. In order to investigate the daylight

performance of museums and exhibition areas and predict the time period when a shading system is required, the lighting simulation tools can be used in an efficient way.

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- Url-8.** <http://www.vam.ac.uk/res_cons/conservation/about/policies/index.html>, accessed at 29.06.2008.
- Url-9.** <<http://www.daniel-libeskind.com>>, accessed at 14.02.2008.
- Url-10.**<http://www.archaeologiemuseum.it/f01_uk.html>, accessed at 23.05.2008.
- Url-11.** <http://www.arkitera.com/v1/reklam/lamp83_6/3.jpg>, accessed at 31.07.2008.
- Url-12.** <<http://www.arch.hku.hk/teaching/SBT99/SBT99-02/sld021.htm>>, accessed at 31.09.2008.
- Url-13.**<http://www.sustainability.vic.gov.au/resources/documents/Window_protection.pdf>, accessed at 31.07.2008.
- Url-14.** <<http://squel.com/ecotect/ecotect.html>>, accessed at 07.10.2008.
- Url-15.**<<http://ocw.mit.edu/NR/rdonlyres/Architecture/4-430Fall-2006/A202B48D-B3F0-4E8C-AD21-F33CC16FFF81/0/lec4.pdf>> accessed at 20.11.2006
- Url-16.**<<http://www.elektrotekno.com/ptopic15447.html>>, accessed at 26.07.2008
- Url-17.** <<http://www.nouvir.com/pdfs/06MuseumLightingPDF.pdf>>, accessed at 26.07.2008
- Url-18.** <<http://lsgc.com/downloads/Hunterian%20Museum.pdf>>, accessed at 26.07.2008
- Url-19.**<<http://www.relux.biz>>, accessed at 29.06.2008.
- Url-20.**<<http://www.hascherjehle.de/kunstmuseum-stuttgart/content/plaene.htm>>, accessed at 20.11.2006.
- Url-21.** <<http://www.googleearth.com>>, accessed at 26.07.2008

Url-22. <<http://www.kunstmuseum-stuttgart.de>>, accessed at 16.01.2008.

Url-23. <<http://www.yourglass.com>>, accessed at 29.06.2008.

Url-24. <<http://www.erco.com/projects.htm>>, accessed at 31.08.2008.

Url-25. <<http://www.cg.tuwien.ac.at>>, accessed at 01.11.2008

APPENDICES

APPENDIX A : Investigation tables of the galleries in Kuntmuseum Stuttgart

APPENDIX B : Measured illuminance levels in the investigated museum galleries and comparison of the measurement results with recommended standards

APPENDIX C : Results of ECOTECT calculations as ECOTECT image outputs for Gallery 1 for the particular times when direct sunlight strikes the exhibition walls

APPENDIX D : Results table generated from ECOTECT daylighting evaluations for sample days of each month

APPENDIX E : RADIANCE simulation results for Wall A, Wall B, Wall C and Wall D on sample days of winter and summer conditions

APPENDIX A

Table A.1 : Investigations for Gallery 1

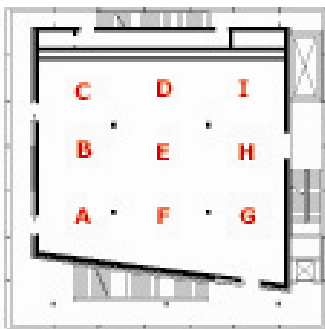
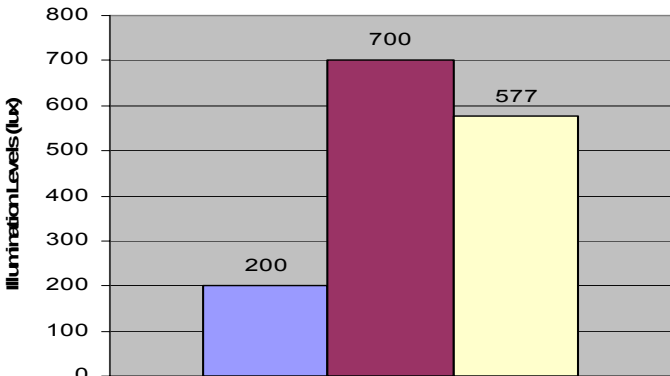
Name of the gallery: 1 Placement: Third floor Dimensions: a:14.30m, b:17.80m, c:15.70m, d:17.90m Number of artifacts exhibited: 14 paintings Surface Materials: White luminous ceiling, white walls, grey PVC floor covering.	Artificial Lighting: Luminous ceiling element with a PVC light distributing layer. Daylighting: 2 windows oriented to south east with dimensions of 1.5m x 3.5m, 1 window oriented to south east with dimensions of 1.5m x 3.5m. Solar Control: No	
Average of the horizontal illumination levels measured on the space: 700 lux Average of the vertical illumination levels measured on the paintings: 577 lux		
  Representative image and floor plan of Gallery 1		
Measurement results of the horizontal illumination levels in the gallery		
A: 483 lux	D: 721 lux	G: 580 lux
B: 762 lux	E: 1.290 lux	H: 836 lux
C: 422 lux	F: 781 lux	I: 416 lux
 Recommended Average Value of General Lighting Measurements Average Vertical Illuminance Value Measured on Artifacts Measured illuminance levels and comparison with recommended standards		

Table A.2 : Investigations for Gallery 2

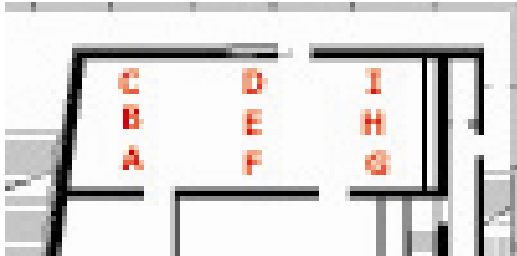
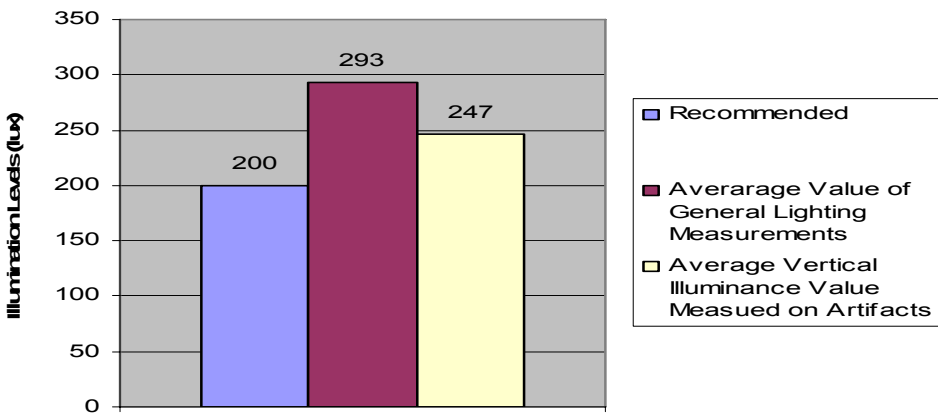
Name of the gallery: 2 Placement: Second floor Dimensions: a:14.30m, b:6.5m, c:14.9m, d:7.6m Number of artifacts exhibited: 19 paintings Surface Materials: White luminous ceiling, white walls, grey floor covering	Artificial Lighting: Luminous ceiling element with a PVC light distributing layer Daylighting: 1 window oriented to south east with dimensions of 1.5m x 3.5m Solar Control: No	
Average of the horizontal illumination levels measured on the space: 293 lux Average of the vertical illumination levels measured on the paintings: 247 lux		
  Representative image and floor plan of Gallery 2		
Measurement results of the horizontal illumination levels in the gallery		
A: 483 lux	D: 316 lux	G: 234 lux
B: 762 lux	E: 574 lux	H: 305 lux
C: 422 lux	F: 418 lux	I: 206 lux
 Measured illuminance levels and comparison with recommended standards		

Table A.3 : Investigations for Gallery 3

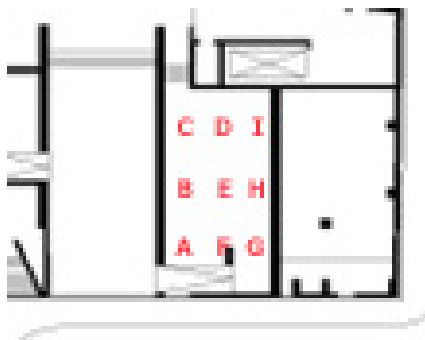
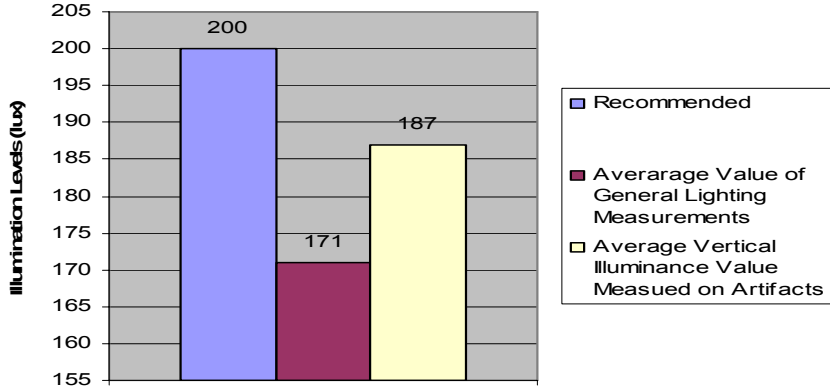
Name of the gallery: 3 Placement: Ground floor Dimensions: 6.5m x 13m Number of artifacts exhibited: 17 paintings Surface Materials: White luminous ceiling, white walls, wood floor covering	Artificial Lighting: Luminous ceiling element with a PVC light distributing layer, spotlights Daylighting: 1 window oriented to north-east with dimensions of 1.5m x 2m. Solar Control: Beige textile solar curtains	
Average of the horizontal illumination levels measured on the space: 171 lux Average of the vertical illumination levels measured on the paintings: 187 lux		
  Representative image and floor plan of Gallery 3		
Measurement results of the horizontal illumination levels in the gallery		
A: 145 lux	D: 198 lux	G: 72 lux
B: 173 lux	E: 322 lux	H: 219 lux
C: 127 lux	F: 129 lux	I: 150 lux
 Measured illuminance levels and comparison with recommended standards		

Table A.4 : Investigations for Gallery 4

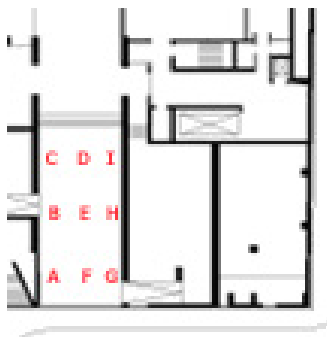
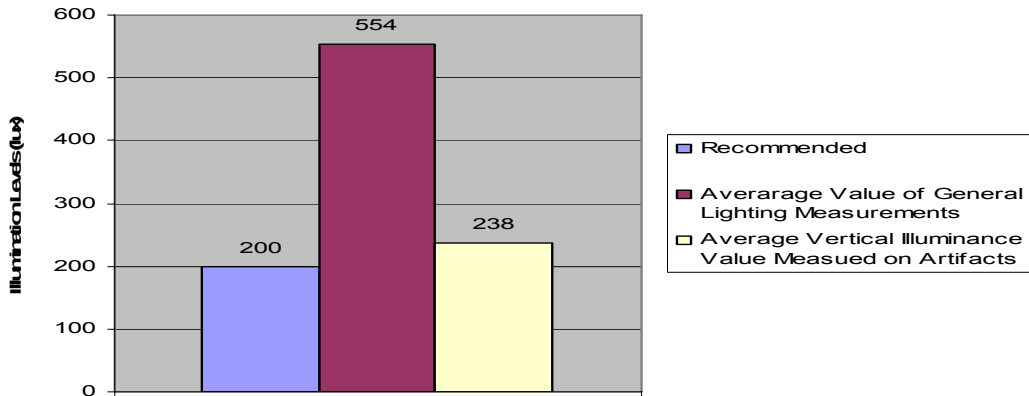
Name of the gallery: 4 Placement: Ground floor Dimensions: 6.5m x 14m Number of artifacts exhibited: 6 paintings Surface Materials: White luminous ceiling, white walls, wood floor covering		Artificial Lighting: Luminous ceiling element with a PVC light distributing layer, spotlights Daylighting: 1 window oriented to north east with dimensions of 6m x 2m. Solar Control: Beige textile solar curtains
Average of the horizontal illumination levels measured on the space: 554 lux Average of the vertical illumination levels measured on the paintings: 238 lux		
  Representative image and floor plan of Gallery 3		
Measurement results of the horizontal illumination levels in the gallery		
A: 1010 lux	D: 434 lux	G: 892 lux
B: 313 lux	E: 450 lux	H: 360 lux
C: 284 lux	F: 1027 lux	I: 220 lux
 Measured illuminance levels and comparison with recommended standards		

Table A.5 : Investigations for Gallery 5

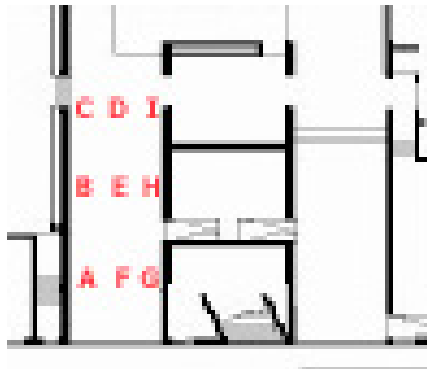
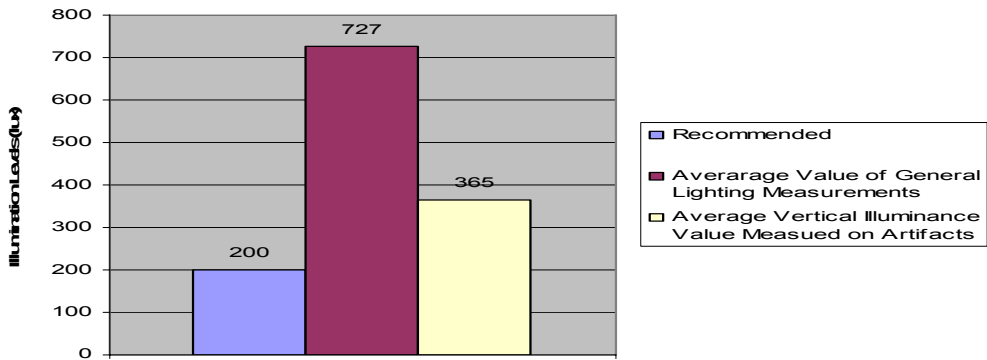
Name of the gallery: 5 Placement: Ground floor Dimensions: 21m x 6.5 m Number of artifacts exhibited: 12 paintings, 2 sculptures Surface Materials: White luminous ceiling, white walls, wood floor covering		Artificial Lighting: Luminous ceiling element with a PVC light distributing layer, spotlights Daylighting: 1 window oriented to north east with dimensions of 600m x 200m. Solar Control: Beige textile solar curtains
Average of the horizontal illumination levels measured on the space: 727 lux Average of the vertical illumination levels measured on the paintings: 365 lux		
  Representative image and floor plan of Gallery 5		
Measurement results of the horizontal illumination levels in the gallery		
A: 1048 lux	D: 248 lux	G:1031 lux
B: 413 lux	E: 610 lux	H: 437 lux
C: 208 lux	F: 1063 lux	I: 203 lux
 Measured illuminance levels and comparison with recommended standards		

Table A.6 : Investigations for Gallery 6

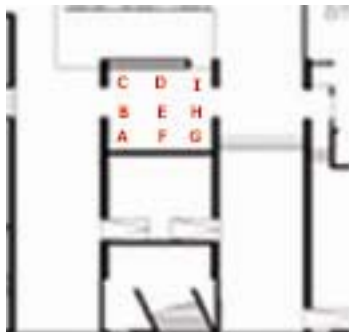
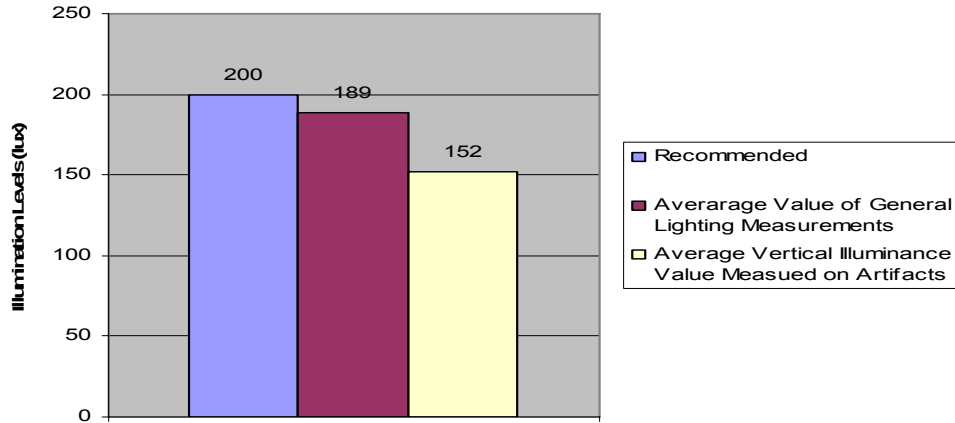
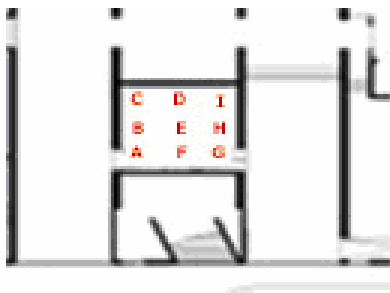
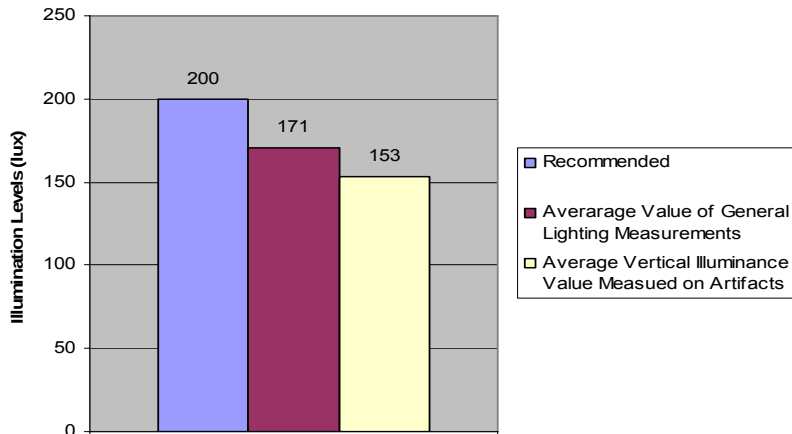
Name of the gallery: 6 Placement: Ground floor Dimensions: 8m x 7m Number of artifacts exhibited: 10 paintings Surface Materials: White luminous ceiling, white walls, wood floor covering	Artificial Lighting: Luminous ceiling element with a PVC light distributing layer, spotlights Daylighting: No. Solar Control: No	
Average of the horizontal illumination levels measured on the space: 727 lux Average of the vertical illumination levels measured on the paintings: 365 lux		
 Floor plan of Gallery 6		
Measurement results of the horizontal illumination levels in the gallery		
A: 164 lux	D: 159 lux	G: 167 lux
B: 153 lux	E: 221 lux	H: 144 lux
C: 120 lux	F: 238 lux	I: 177 lux
 Measured illuminance levels and comparison with recommended standards		

Table A.7 : Investigations for Gallery 7

Name of the gallery: 7 Placement: Ground floor Dimensions: 8m x 7m Number of artifacts exhibited: 9 paintings Surface Materials: White luminous ceiling, white walls, wood floor covering		Artificial Lighting: Luminous ceiling element with a PVC light distributing layer, spotlights Daylighting: No Solar Control: No
Average of the horizontal illumination levels measured on the space: 727 lux Average of the vertical illumination levels measured on the paintings: 365 lux		
 Floor plan of Gallery 7		
Measurement results of the horizontal illumination levels in the gallery		
A: 128 lux	D: 255 lux	G: 171 lux
B: 195 lux	E: 253 lux	H: 187 lux
C: 199 lux	F: 140 lux	I: 177 lux
 Measured illuminance levels and comparison with recommended standards		

APPENDIX B

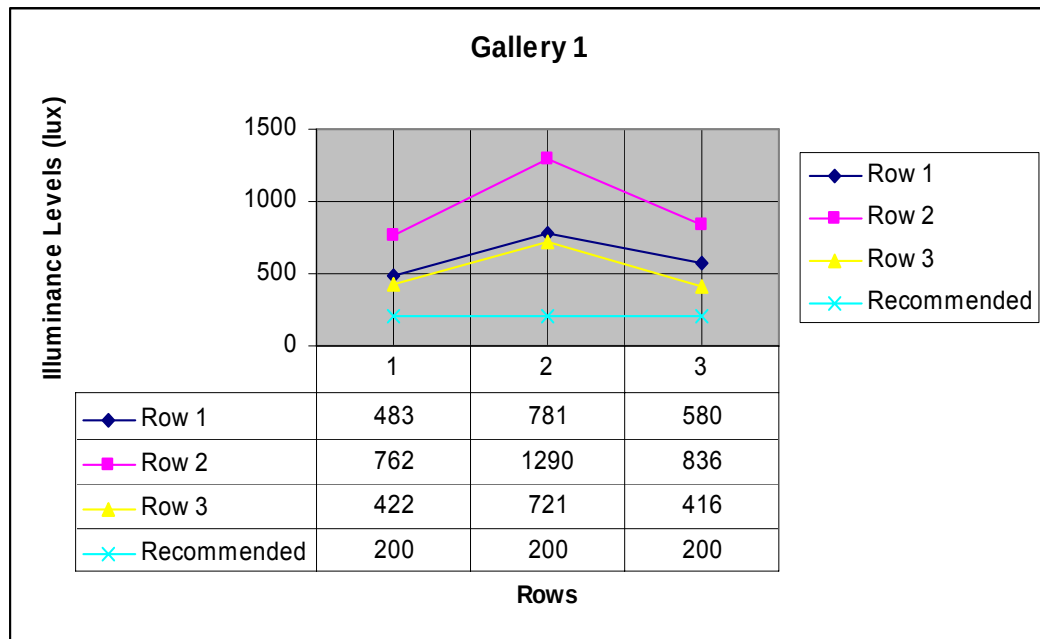


Figure B.1 : Measured illuminance levels and comparison with recommended standards for Gallery 1

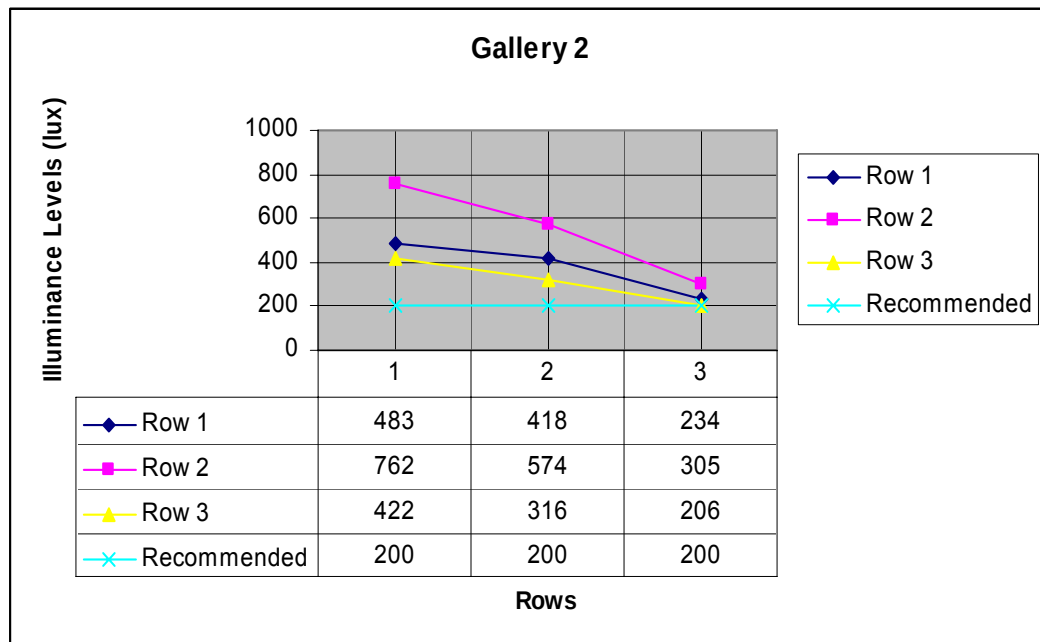


Figure B.2 : Measured illuminance levels and comparison with recommended standards for Gallery 2

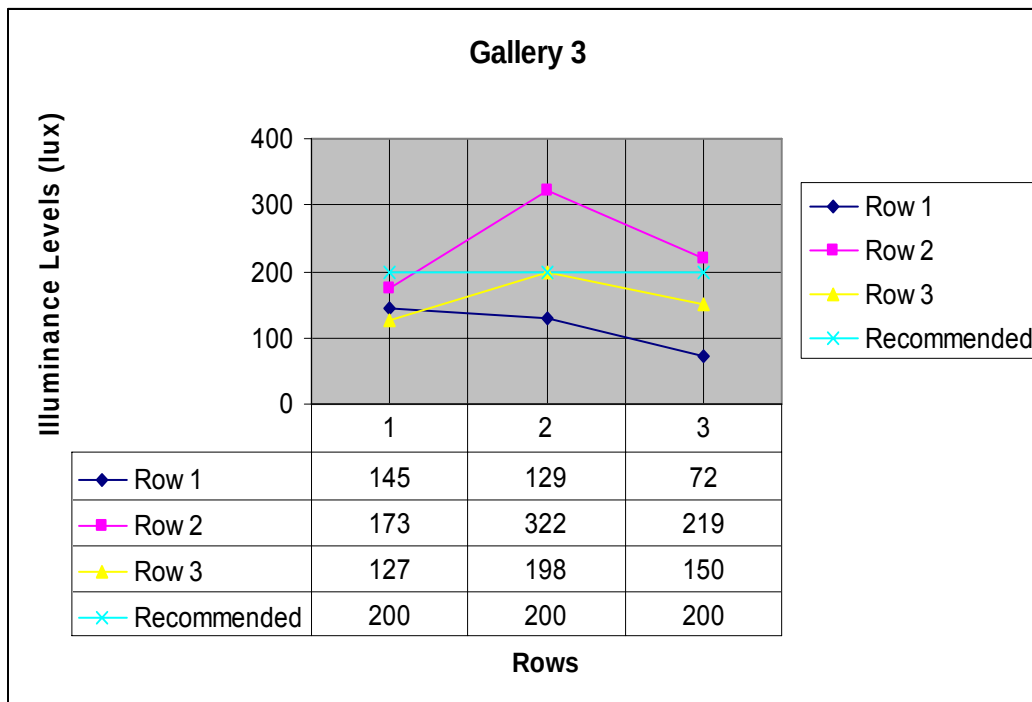


Figure B.3 : Measured illuminance levels and comparison with recommended standards for Gallery 3

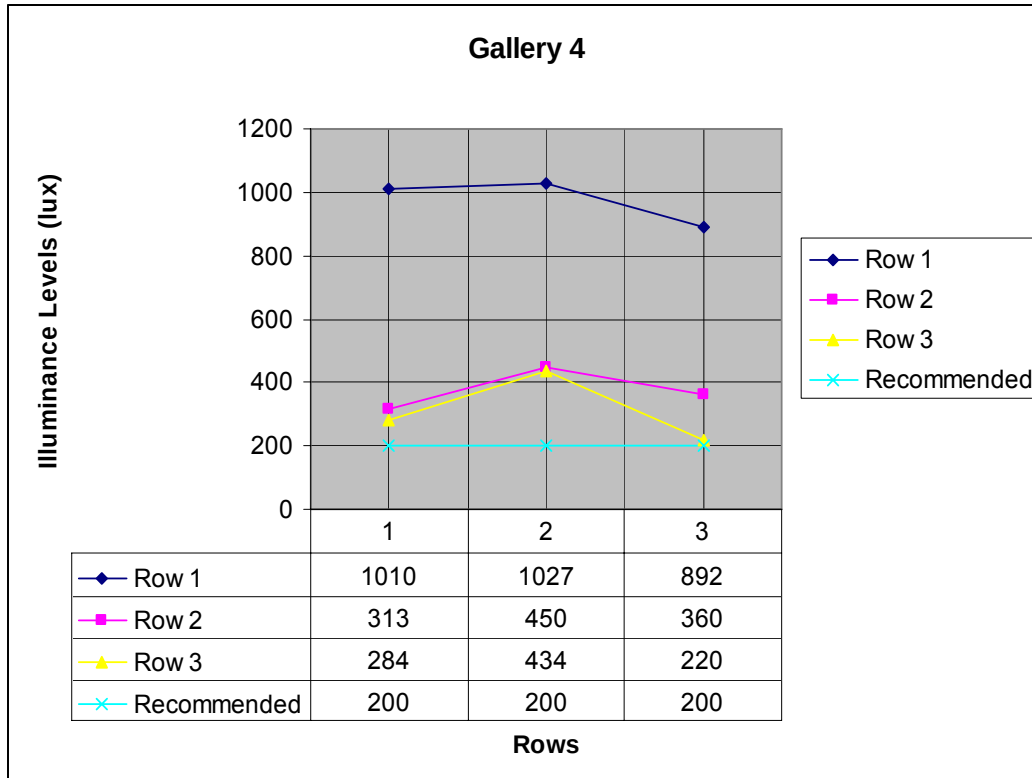


Figure B.4 : Measured illuminance levels and comparison with recommended standards for Gallery 4

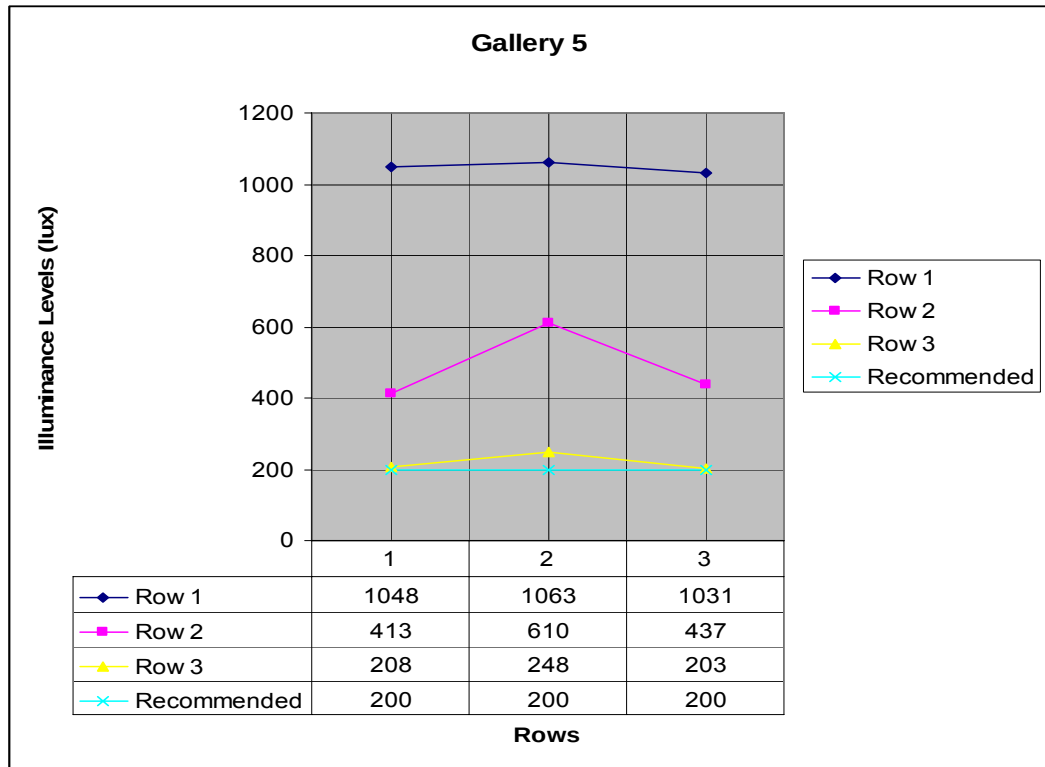


Figure B.5 : Measured illuminance levels and comparison with recommended standards for Gallery 5

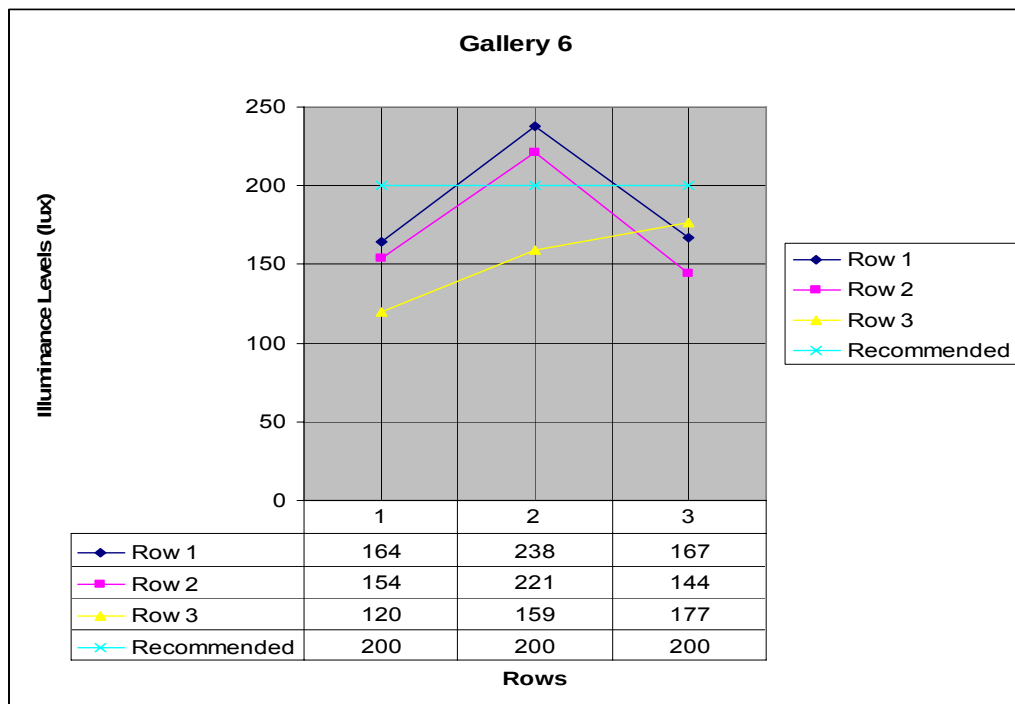


Figure B.6 : Measured illuminance levels and comparison with recommended standards for Gallery 6

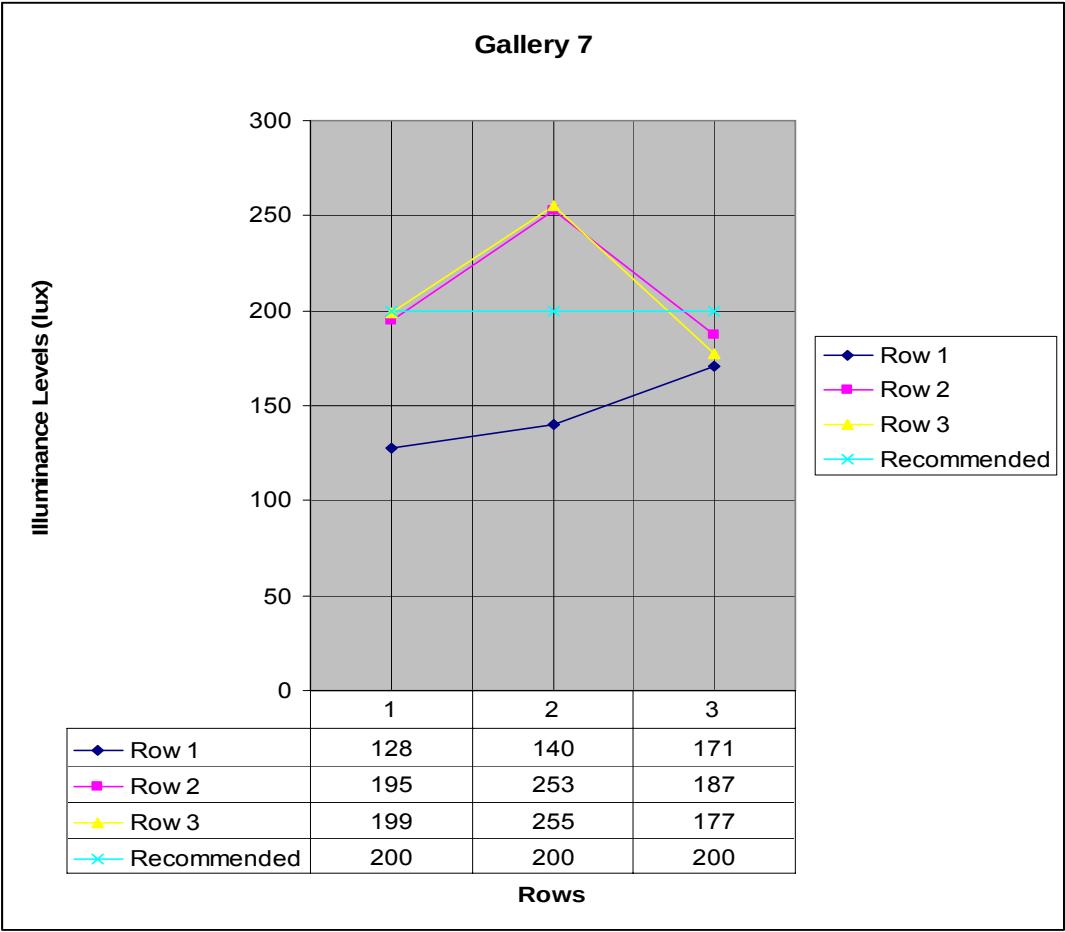


Figure B.7 : Measured illuminance levels and comparison with recommended standards for Gallery 7

APPENDIX C

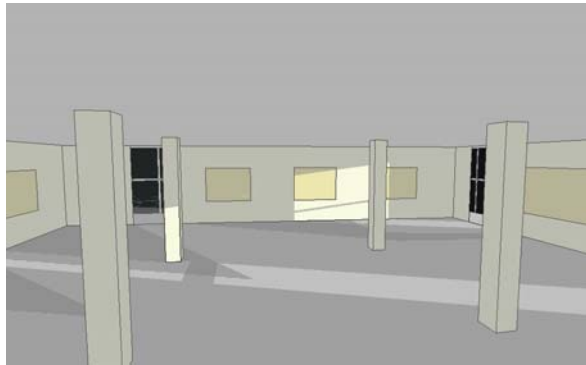


Figure C.1 : ECOTECT outputs for Gallery 1 for 15 January 09:00, Wall A



Figure C.2 : ECOTECT outputs for Gallery 1 for 15 January 10:00, Wall A



Figure C.3 : ECOTECT outputs for Gallery 1 for 15 January 11:00, Wall A

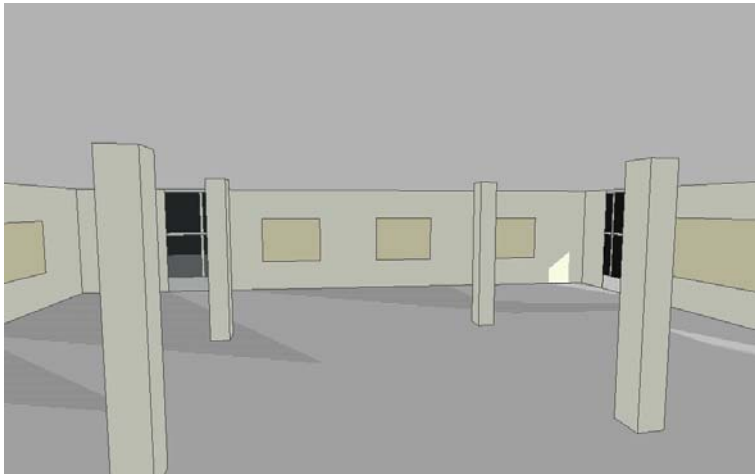


Figure C.4 : ECOTECT outputs for Gallery 1 for 15 January 12:00, Wall A

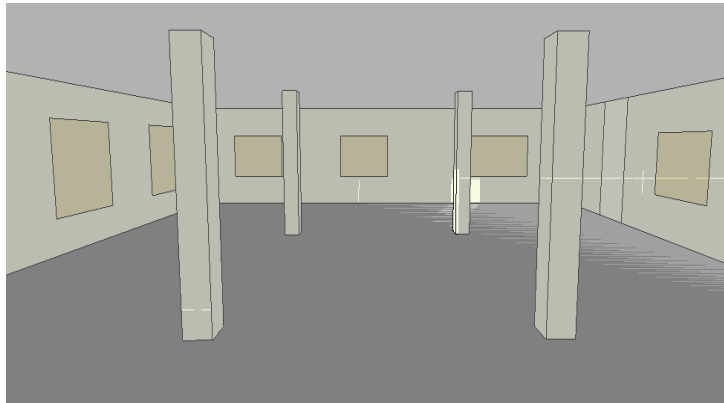


Figure C.5 : ECOTECT outputs for Gallery 1 for 15 January 10:00, Wall B



Figure C.6 : ECOTECT outputs for Gallery 1 for 15 February 09:00, Wall A



Figure C.7 : ECOTECT outputs for Gallery 1 for 15 February 10:00, Wall A

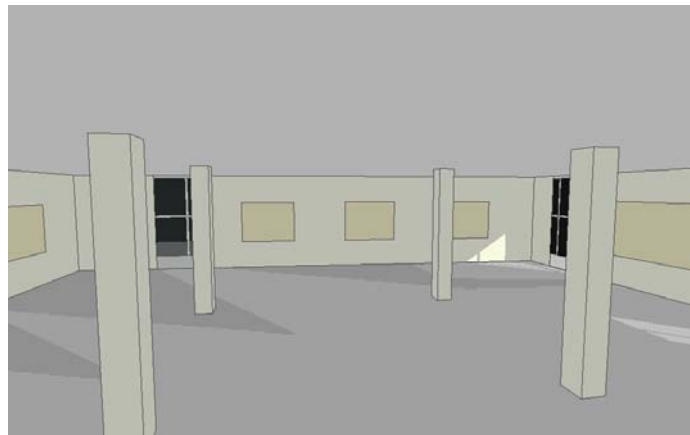


Figure C.8 : ECOTECT outputs for Gallery 1 for 15 February 11:00, Wall A

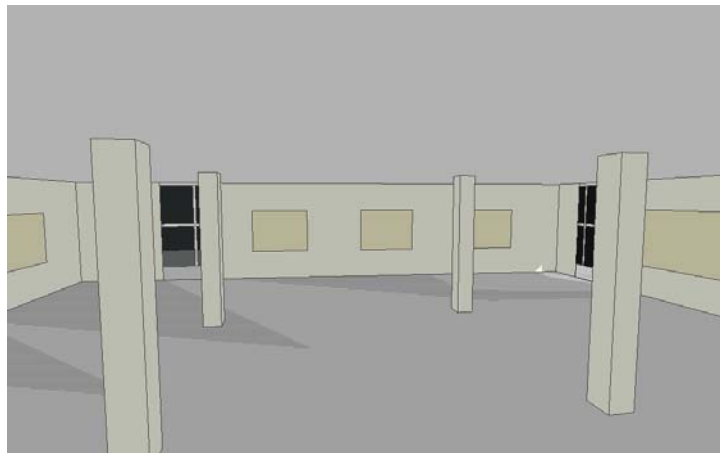


Figure C.9 : ECOTECT outputs for Gallery 1 for 15 February 12:00, Wall A

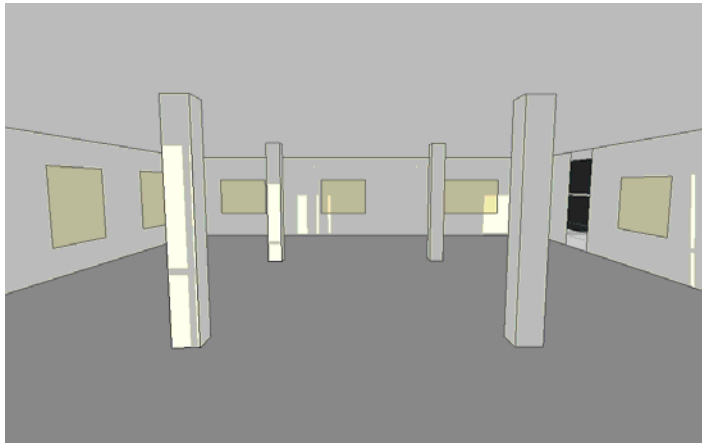


Figure C.10 : ECOTECT outputs for Gallery 1 for 15 March 09:00, Wall B

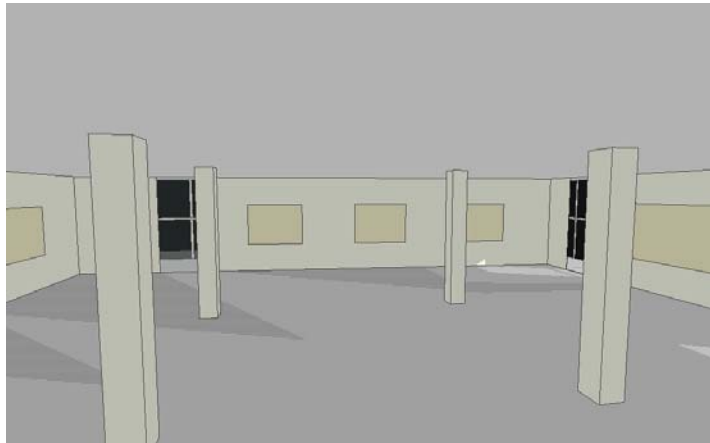


Figure C.11 : ECOTECT outputs for Gallery 1 for 5 March 11:00, Wall A

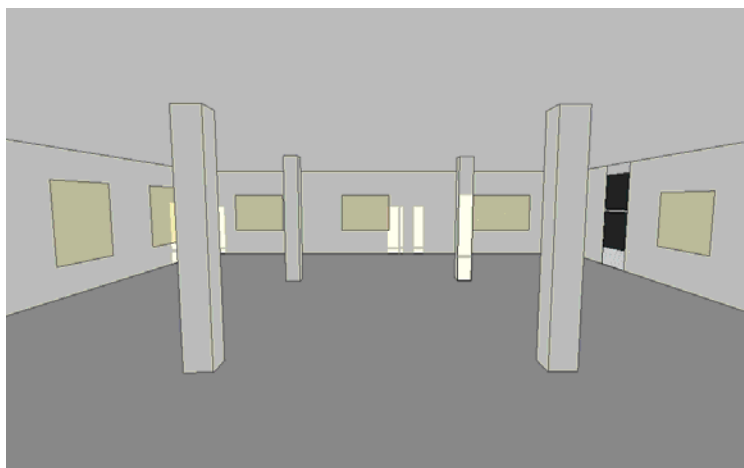


Figure C.12 : ECOTECT outputs for Gallery 1 for 15 March 08:00, Wall B

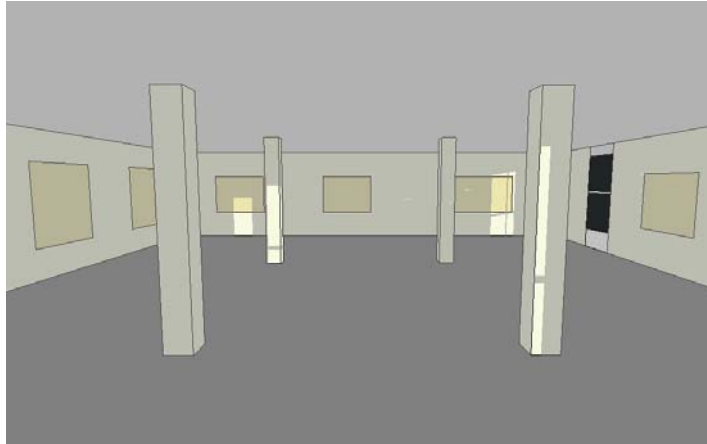


Figure C.13 : ECOTECT outputs for Gallery 1 for 15 April 07:00, Wall B

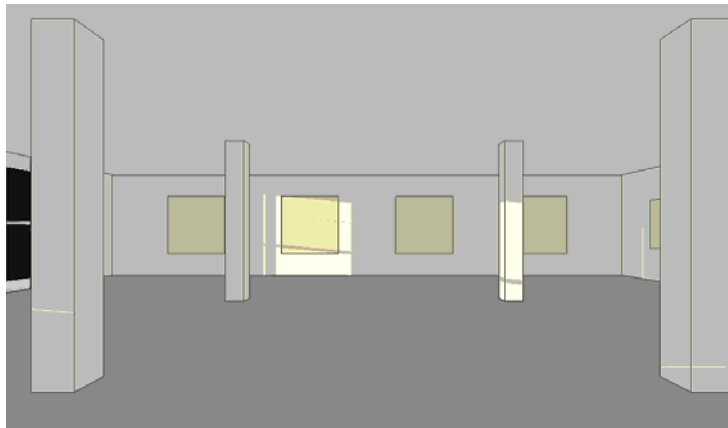


Figure C.14 : ECOTECT outputs for Gallery 1 for 15 April 07:00, Wall C

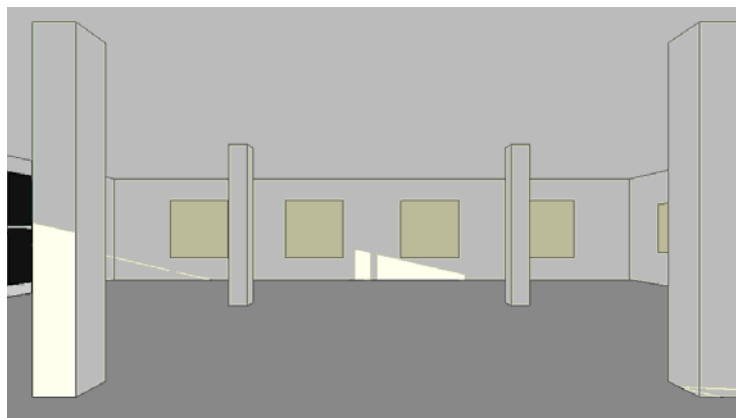


Figure C.15 : ECOTECT outputs for Gallery 1 for 15 April 08:00, Wall C

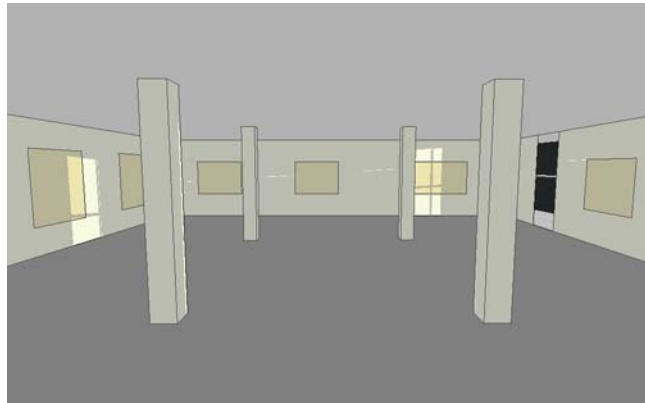


Figure C.16 : ECOTECT outputs for Gallery 1 for 15 May 06:00, Wall B

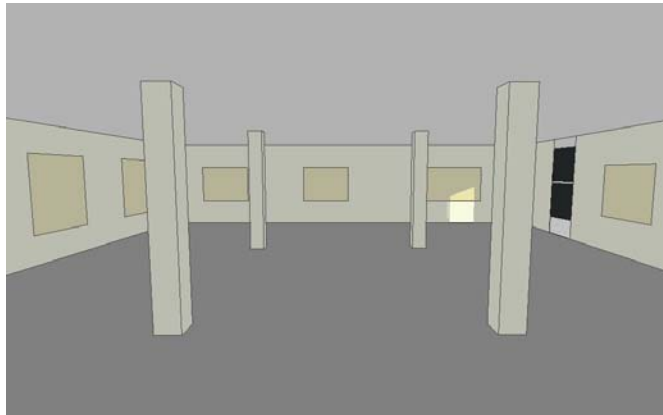


Figure C.17 : ECOTECT outputs for Gallery 1 for 15 May 07:00, Wall B

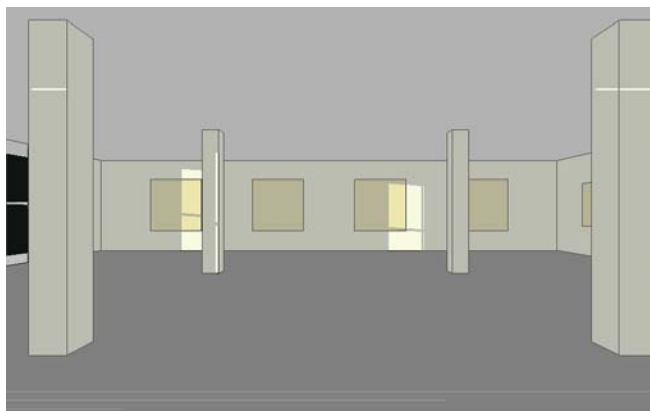


Figure C.18 : ECOTECT outputs for Gallery 1 for 15 May 06:00, Wall C

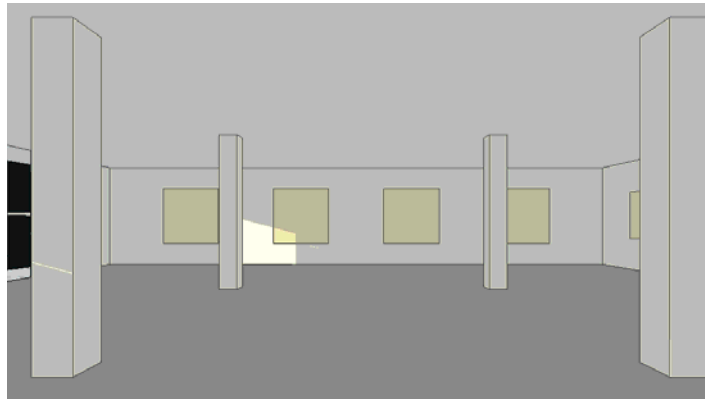


Figure C.19 : ECOTECT outputs for Gallery 1 for 15 May 07:00, Wall C

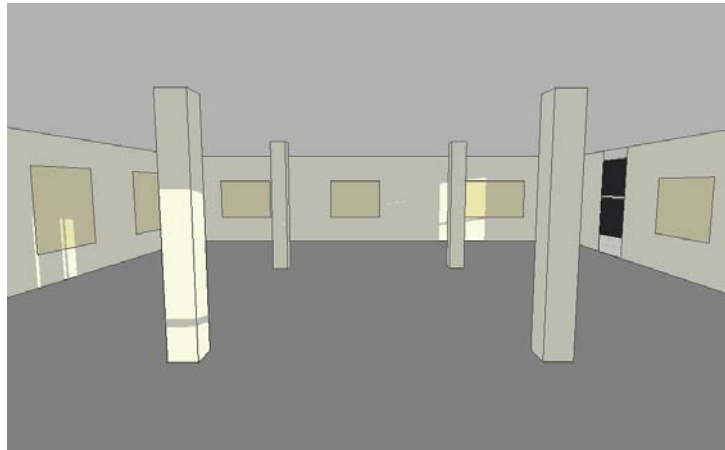


Figure C.20 : ECOTECT outputs for Gallery 1 for 15 June 06:00, Wall B

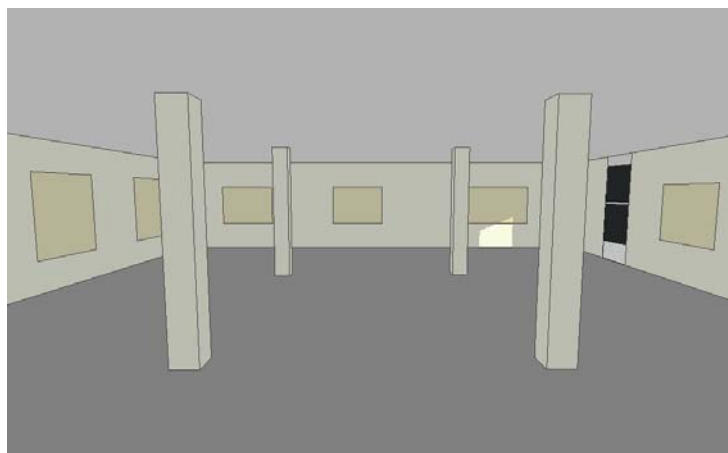


Figure C.21 : ECOTECT outputs for Gallery 1 for 15 June 07:00, Wall B

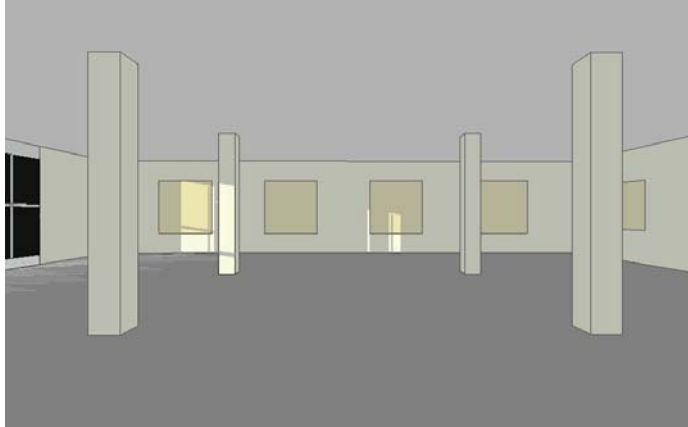


Figure C.22 : ECOTECT outputs for Gallery 1 for 15 June 06:00, Wall C

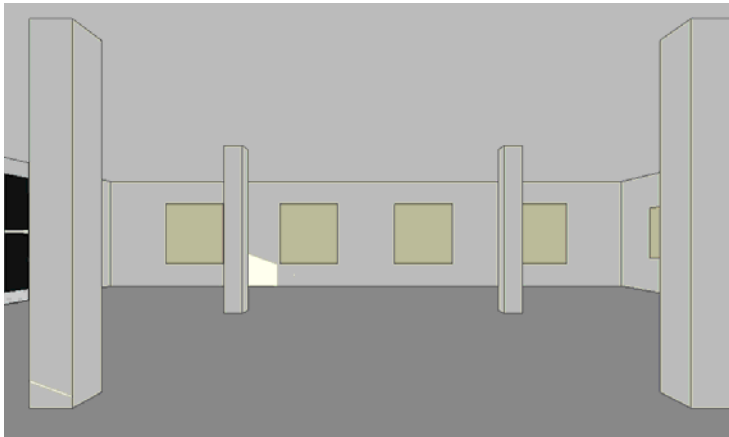


Figure C.23 : ECOTECT outputs for Gallery 1 for 15 June 07:00, Wall C

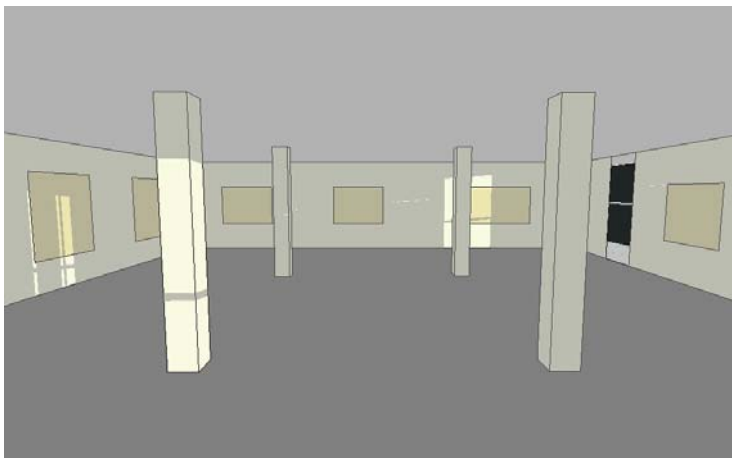


Figure C.24 : ECOTECT outputs for Gallery 1 for 15 July 06:00, Wall B

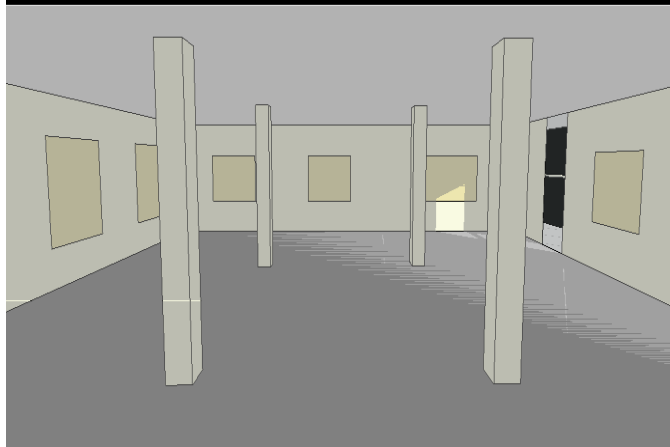


Figure C.25 : ECOTECT outputs for Gallery 1 for 15 July 07:00, Wall B

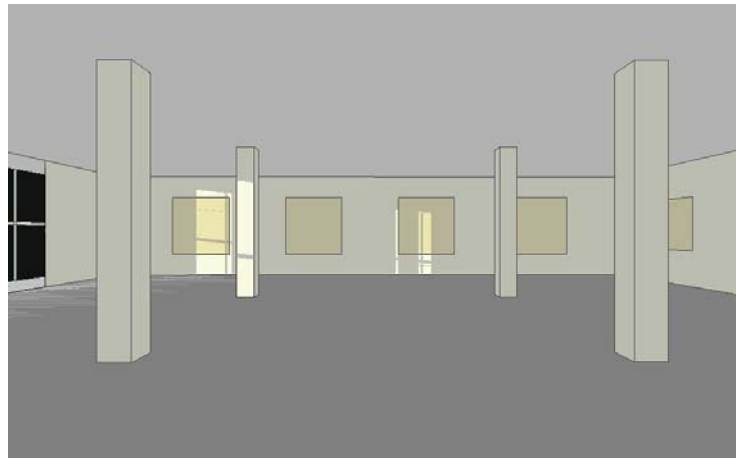


Figure C.26 : ECOTECT outputs for Gallery 1 for 15 July 06:00, Wall C

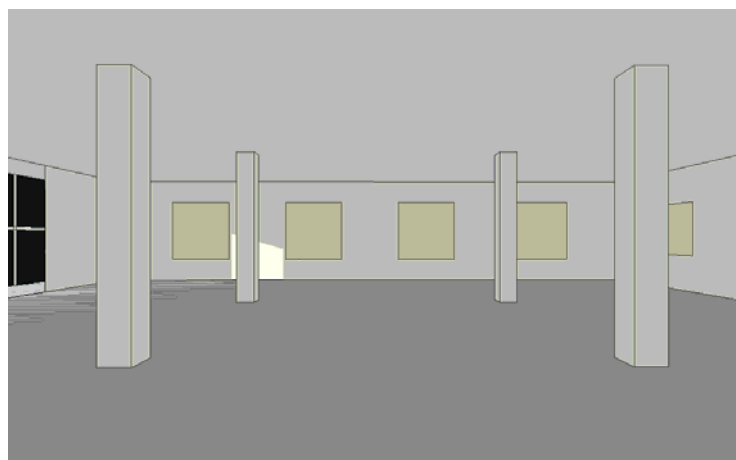


Figure C.27 : ECOTECT outputs for Gallery 1 for 15 July 07:00, Wall C

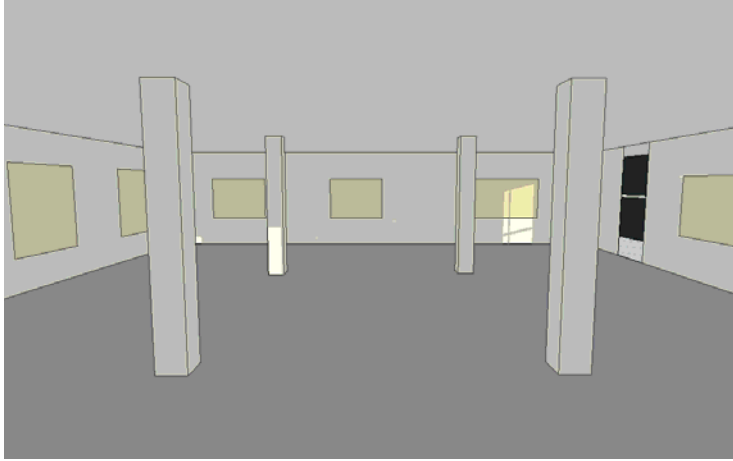


Figure C.28 : ECOTECH outputs for Gallery 1 for 15 August
07:00, Wall B

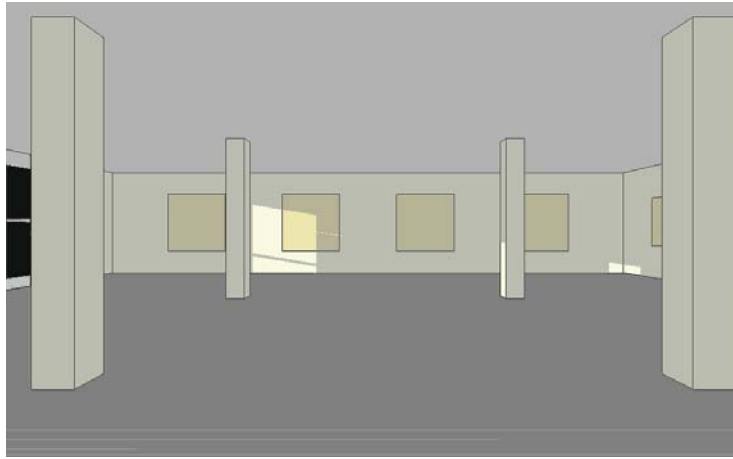


Figure C.29 : ECOTECH outputs for Gallery 1 for 15 August
07:00, Wall B

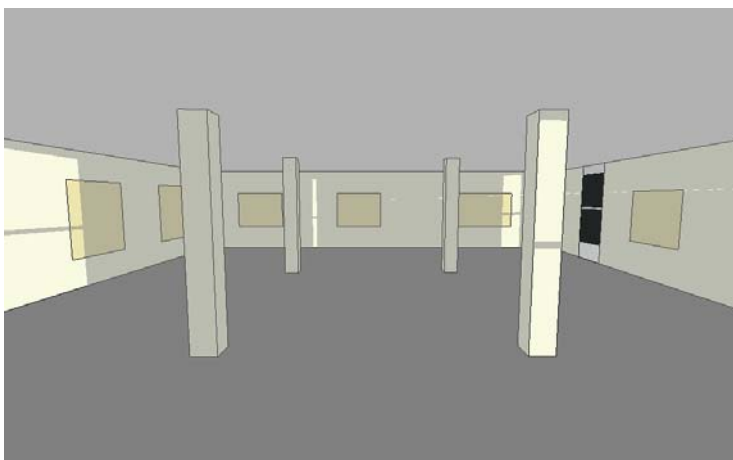


Figure C.30 : ECOTECH outputs for Gallery 1 for 15 September
07:00, Wall B

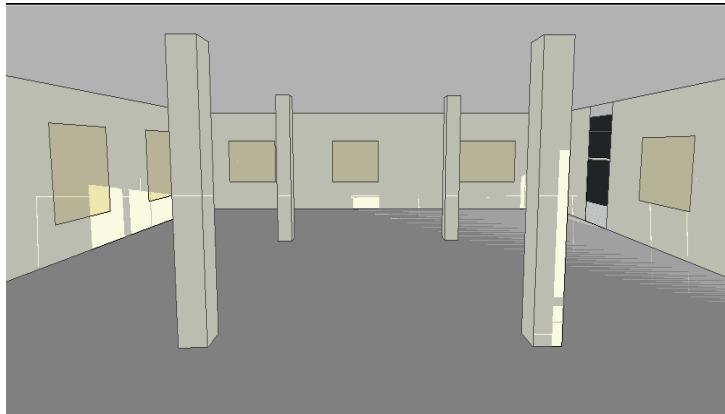


Figure C.31 : ECOTECT outputs for Gallery 1 for 15 September 08:00, Wall B

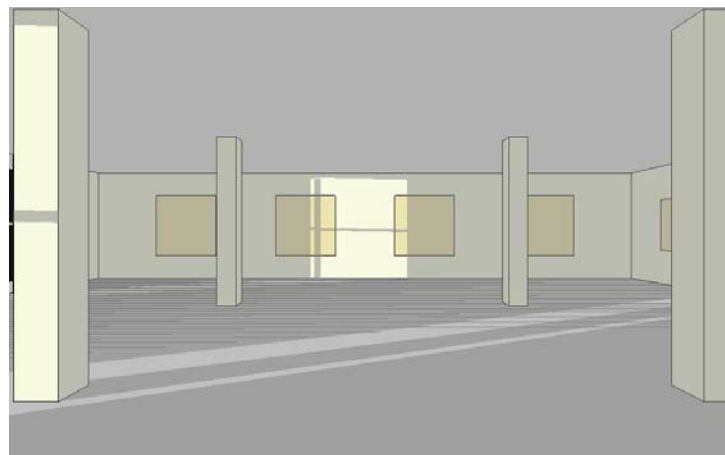


Figure C.32 : ECOTECT outputs for Gallery 1 for 15 September 07:00, Wall C

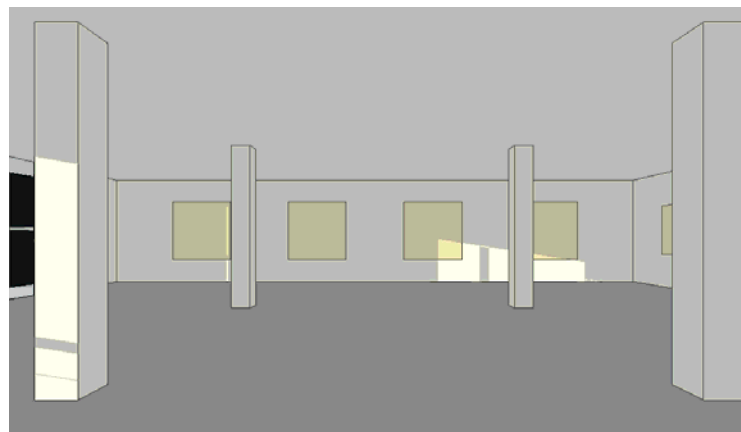


Figure C.33 : ECOTECT outputs for Gallery 1 for 15 September 08:00, Wall C

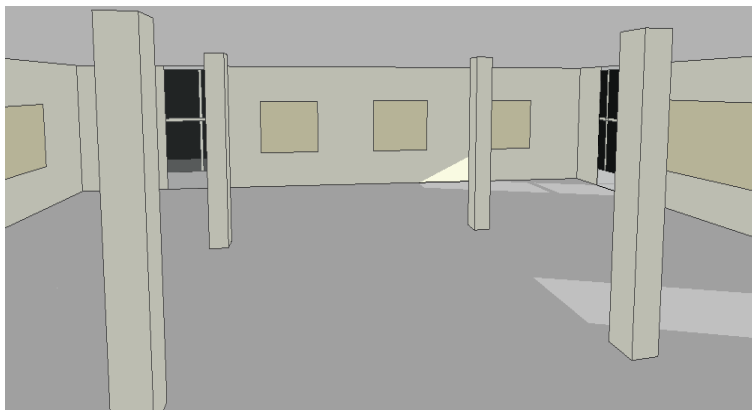


Figure C.34 : ECOTECT outputs for Gallery 1 for 15 October 09:00, Wall A

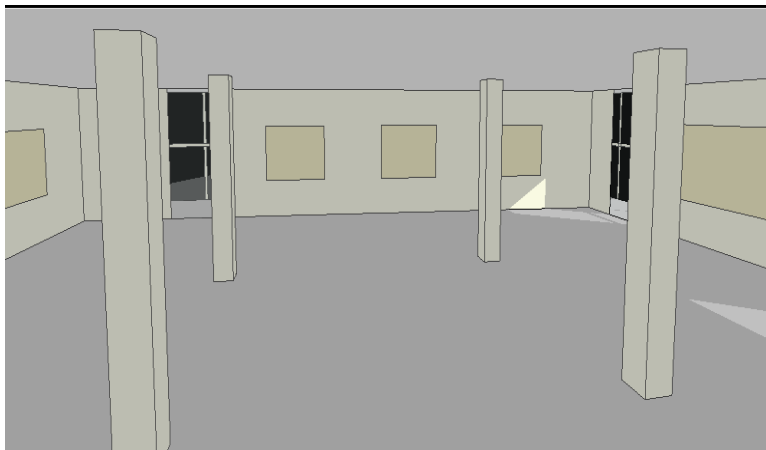


Figure C.35 : ECOTECT outputs for Gallery 1 for 15 October 10:00, Wall A

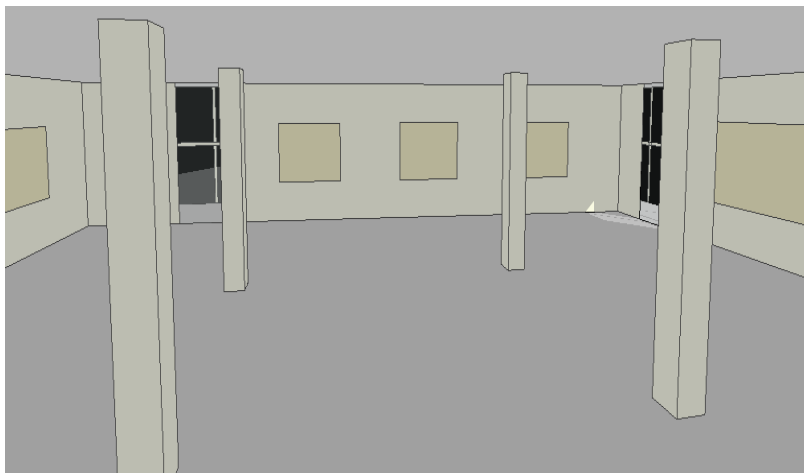


Figure C.36 : ECOTECT outputs for Gallery 1 for 15 October 11:00, Wall A

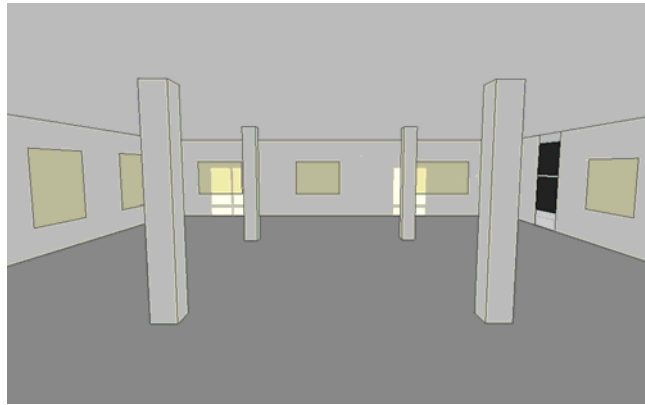


Figure C.37 : ECOTECT outputs for Gallery 1 for 15 October 07:00, Wall B

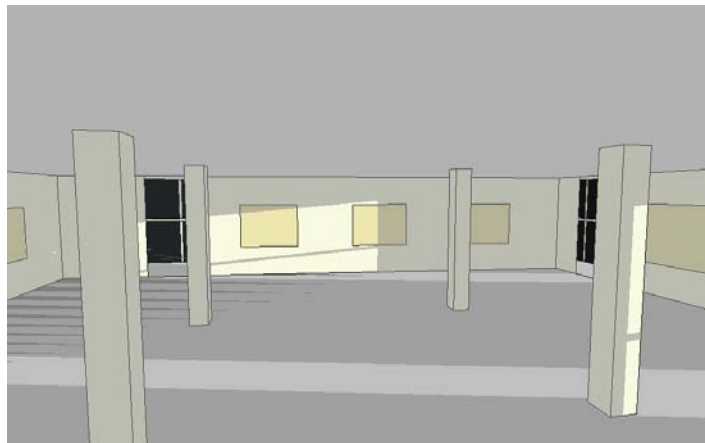


Figure C.38 : ECOTECT outputs for Gallery 1 for 15 November 08:00, Wall A



Figure C.39 : ECOTECT outputs for Gallery 1 for 15 November 09:00, Wall A



Figure C.40 : ECOTECT outputs for Gallery 1 for 15 November 10:00, Wall A

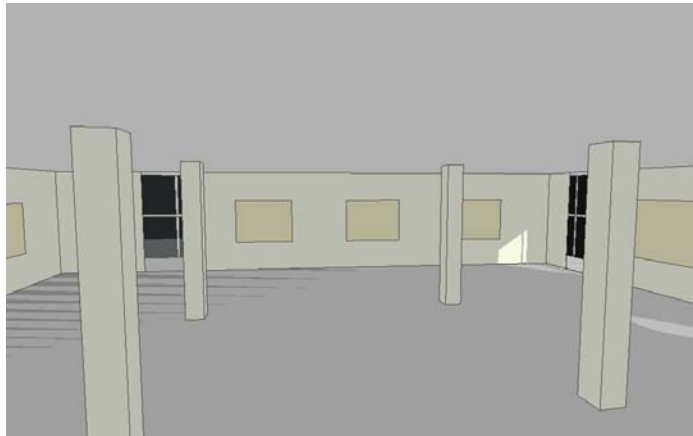


Figure C.41 : ECOTECT outputs for Gallery 1 for 15 November 11:00, Wall A

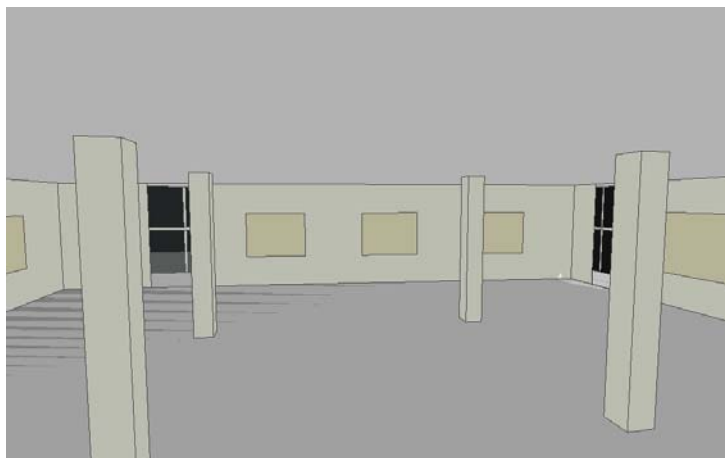


Figure C.42 : ECOTECT outputs for Gallery 1 for 15 November 11:00, Wall A

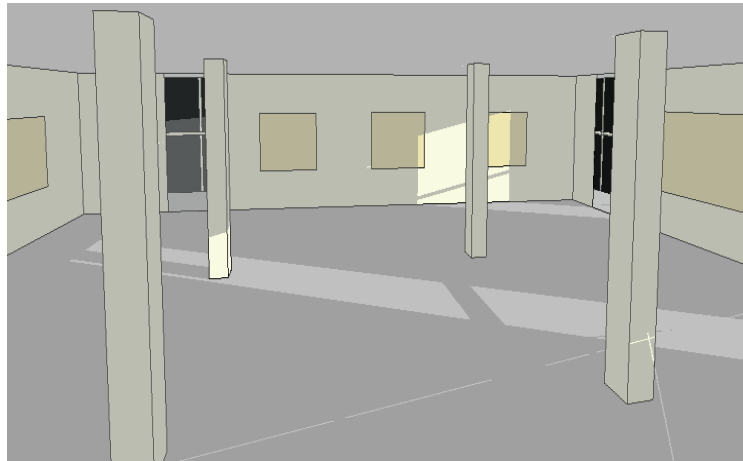


Figure C.43 : ECOTECT outputs for Gallery 1 for 15 November 12:00, Wall A

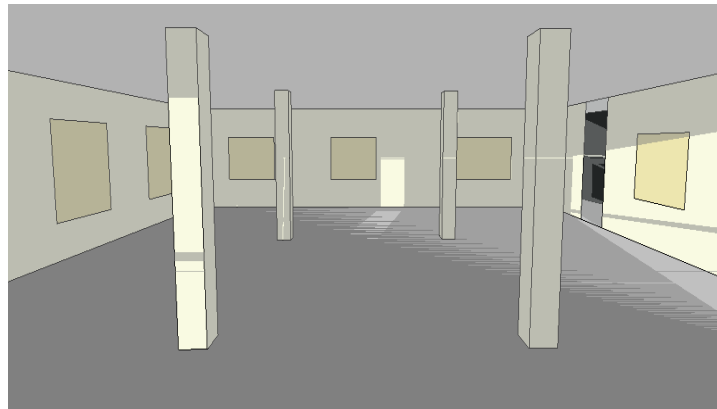


Figure C.44 : ECOTECT outputs for Gallery 1 for 15 November 08:00, Wall B

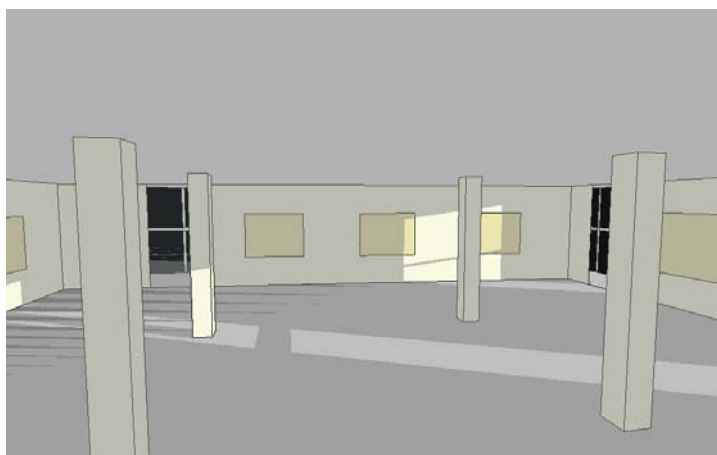


Figure C.45 : ECOTECT outputs for Gallery 1 for 15 December 09:00, Wall A



Figure C.46 : ECOTECT outputs for Gallery 1 for 15 December 10:00, Wall A

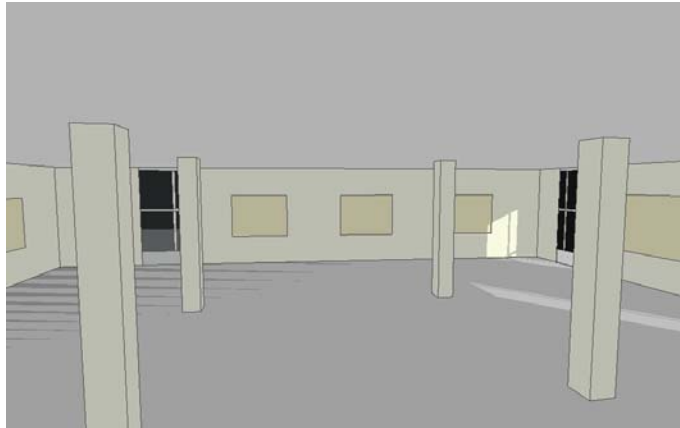


Figure C.47 : ECOTECT outputs for Gallery 1 for 15 December 11:00, Wall A

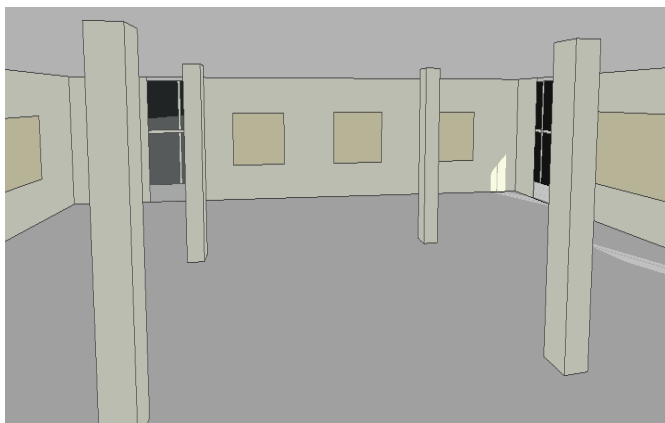


Figure C.48 : ECOTECT outputs for Gallery 1 for 15 December 12:00, Wall A

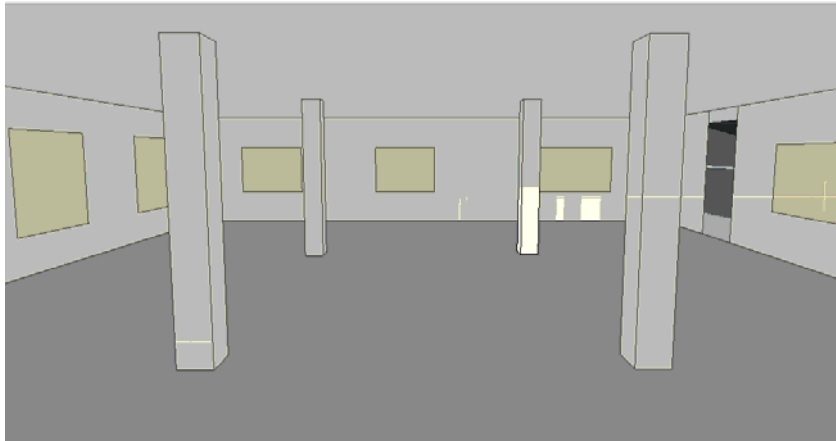


Figure C.49 : ECOTECT outputs for Gallery 1 for 15 December 09:00, Wall B

APPENDIX D

Table D.1 : Results Table for 15 January

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Not affected	Not affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Affected	Affected	Not affected	Not affected
10:00	Affected	Not affected	Not affected	Not affected
11:00	Affected	Not affected	Not affected	Not affected
12:00	Affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.1 : Results Table for 15 February

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Not affected	Not affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Affected	Affected	Not affected	Not affected
10:00	Affected	Not affected	Not affected	Not affected
11:00	Affected	Not affected	Not affected	Not affected
12:00	Affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.3 : Results Table for 15 March

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Not affected	Not affected	Not affected
08:00	Not affected	Affected	Affected	Not affected
09:00	Not affected	Not affected	Not affected	Not affected
10:00	Not affected	Not affected	Not affected	Not affected
11:00	Affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.4 : Results Table for 15 April

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Affected	Affected	Not affected
08:00	Not affected	Not affected	Affected	Not affected
09:00	Not affected	Not affected	Not affected	Not affected
10:00	Not affected	Not affected	Not affected	Not affected
11:00	Not affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.5 : Results Table for 15 March

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Affected	Affected	Not affected
07:00	Not affected	Affected	Affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Not affected	Not affected	Not affected	Not affected
10:00	Not affected	Not affected	Not affected	Not affected
11:00	Not affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.6 : Results Table for 15 June

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Affected	Affected	Not affected
07:00	Not affected	Affected	Affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Not affected	Not affected	Not affected	Not affected
10:00	Not affected	Not affected	Not affected	Not affected
11:00	Not affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.7 : Results Table for 15 July

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Affected	Affected	Not affected
07:00	Not affected	Affected	Affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Not affected	Not affected	Not affected	Not affected
10:00	Not affected	Not affected	Not affected	Not affected
11:00	Not affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.8 : Results Table for 15 August

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Affected	Affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Not affected	Not affected	Not affected	Not affected
10:00	Not affected	Not affected	Not affected	Not affected
11:00	Not affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.9 : Results Table for 15 September

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Affected	Affected	Not affected
08:00	Not affected	Affected	Affected	Not affected
09:00	Not affected	Not affected	Not affected	Not affected
10:00	Not affected	Not affected	Not affected	Not affected
11:00	Not affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.10 : Results Table for 15 October

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Affected	Not affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Affected	Not affected	Not affected	Not affected
10:00	Affected	Not affected	Not affected	Not affected
11:00	Affected	Not affected	Not affected	Not affected
12:00	Not affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.11 : Results Table for 15 November

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Not affected	Not affected	Not affected
08:00	Affected	Affected	Not affected	Not affected
09:00	Affected	Not affected	Not affected	Not affected
10:00	Affected	Not affected	Not affected	Not affected
11:00	Affected	Not affected	Not affected	Not affected
12:00	Affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

Table D.12: Results Table for 15 December

Hours	Wall A	Wall B	Wall C	Wall D
05:00	Not affected	Not affected	Not affected	Not affected
06:00	Not affected	Not affected	Not affected	Not affected
07:00	Not affected	Not affected	Not affected	Not affected
08:00	Not affected	Not affected	Not affected	Not affected
09:00	Affected	Affected	Not affected	Not affected
10:00	Affected	Not affected	Not affected	Not affected
11:00	Affected	Not affected	Not affected	Not affected
12:00	Affected	Not affected	Not affected	Not affected
13:00	Not affected	Not affected	Not affected	Not affected
14:00	Not affected	Not affected	Not affected	Not affected
15:00	Not affected	Not affected	Not affected	Not affected
16:00	Not affected	Not affected	Not affected	Not affected
17:00	Not affected	Not affected	Not affected	Not affected
18:00	Not affected	Not affected	Not affected	Not affected
19:00	Not affected	Not affected	Not affected	Not affected

APPENDIX E

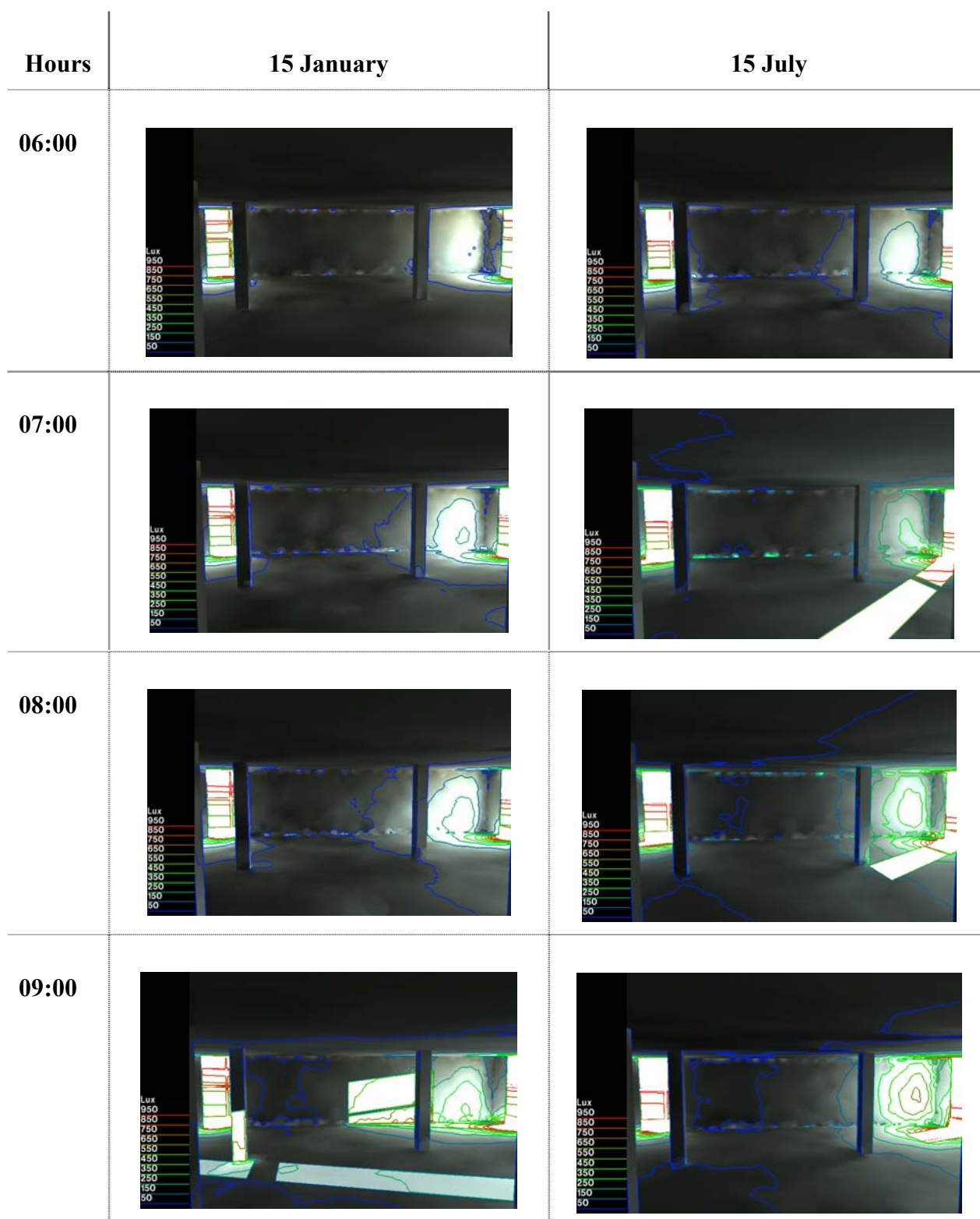


Figure E.1 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall A between hours of 06:00 and 09:00.

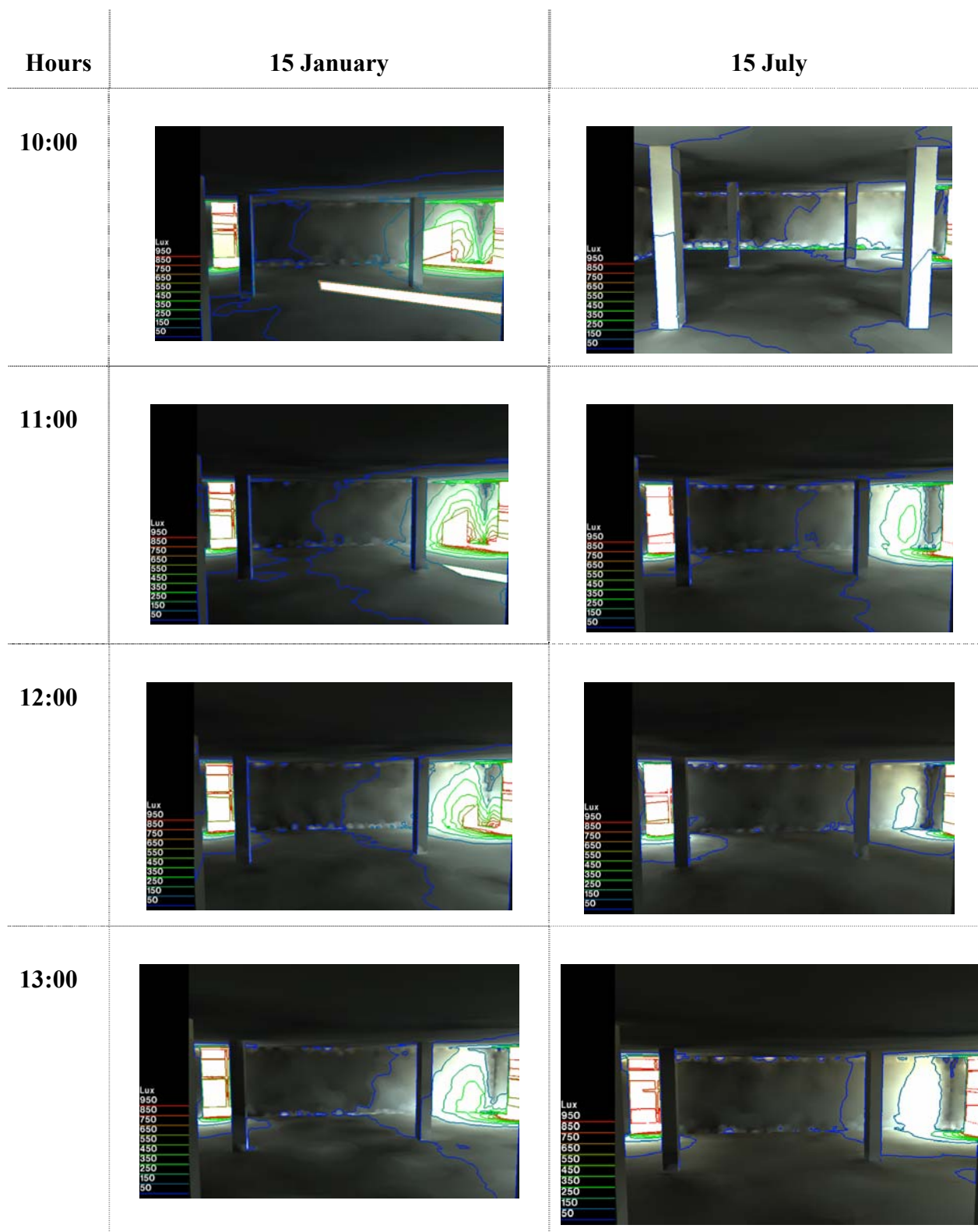


Figure E.2 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall A between hours of 10:00 and 13:00.

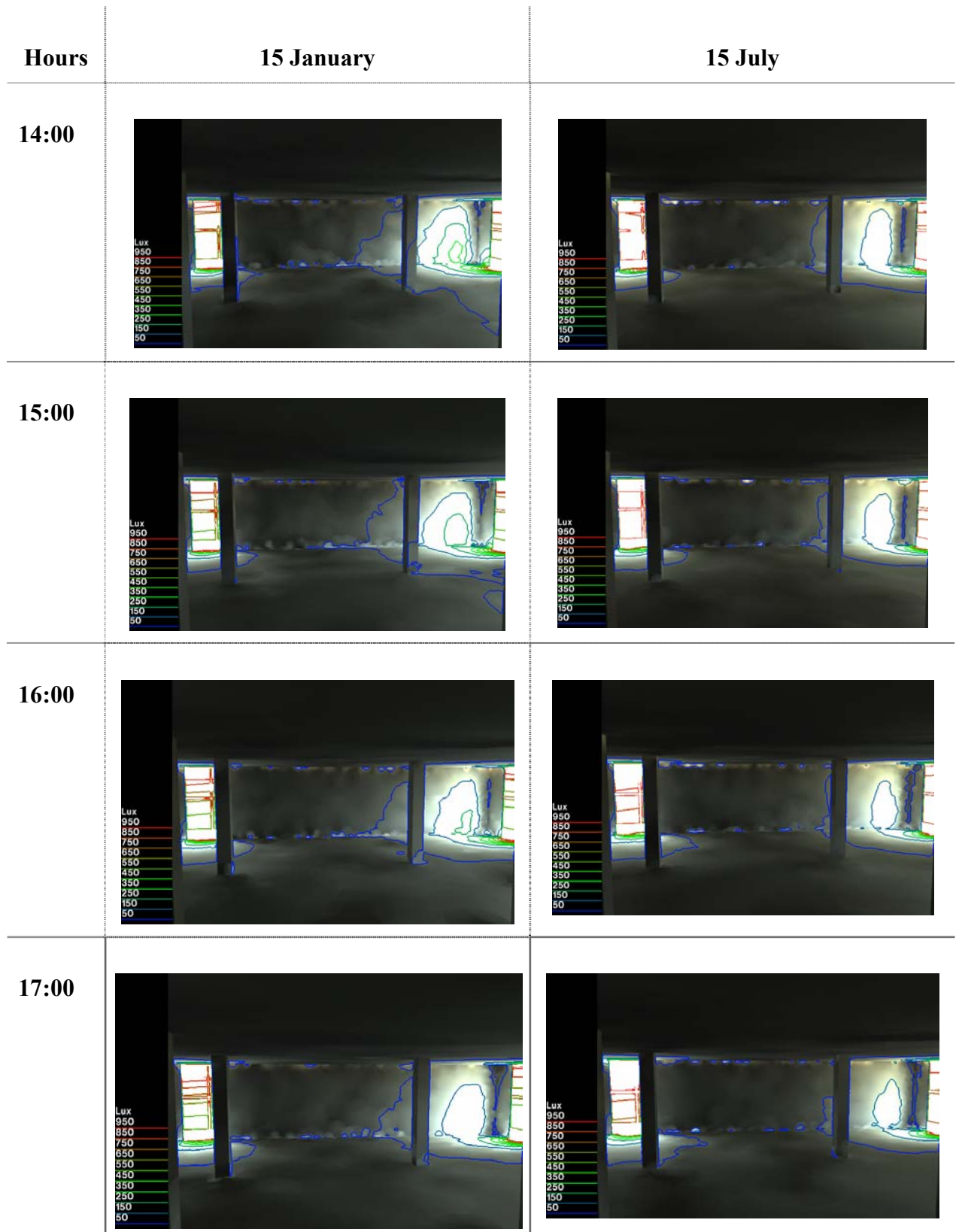


Figure E.3 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall A between hours of 14:00 and 17:00.

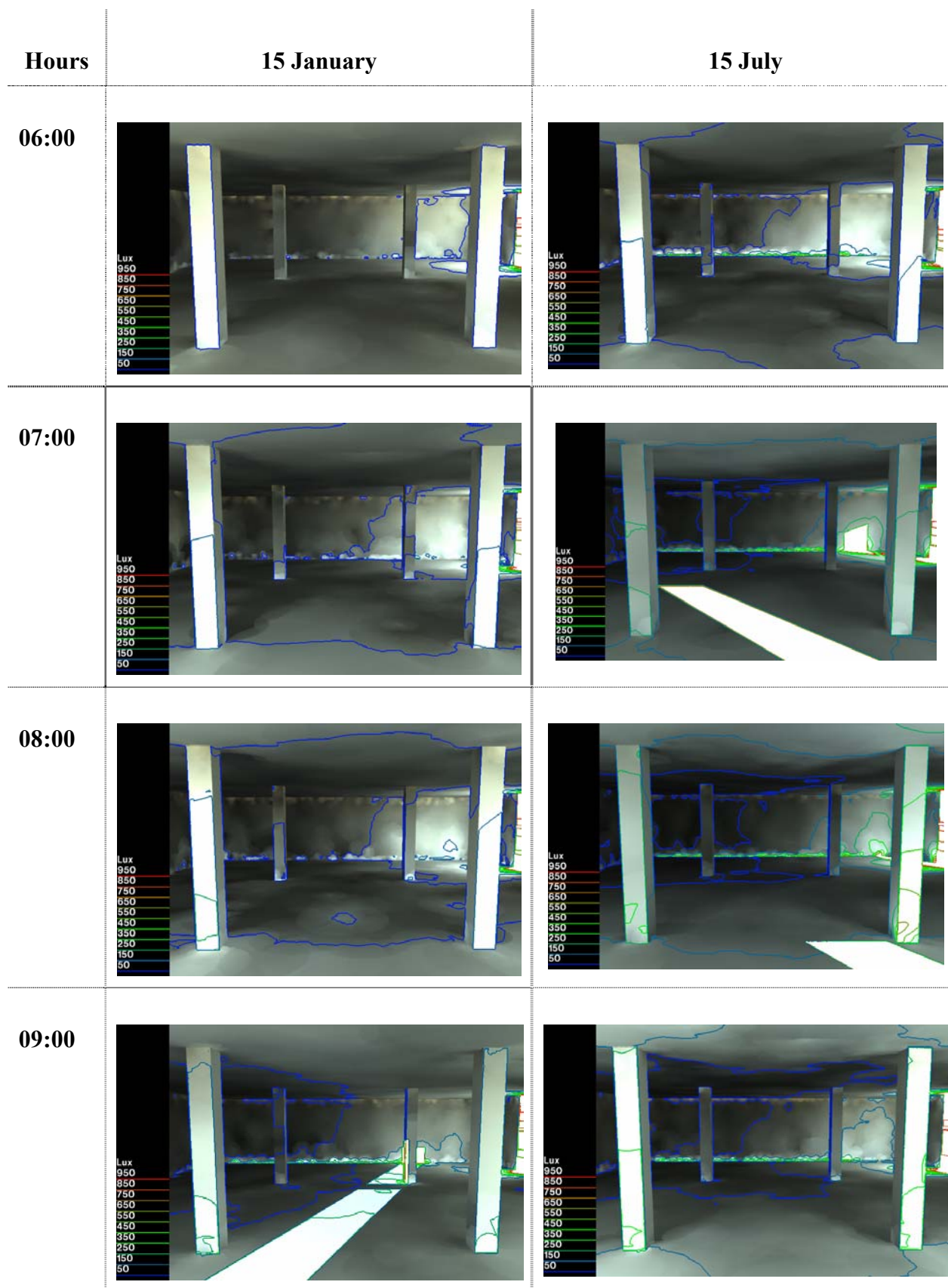


Figure E.4 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall B between hours of 06:00 and 09:00.

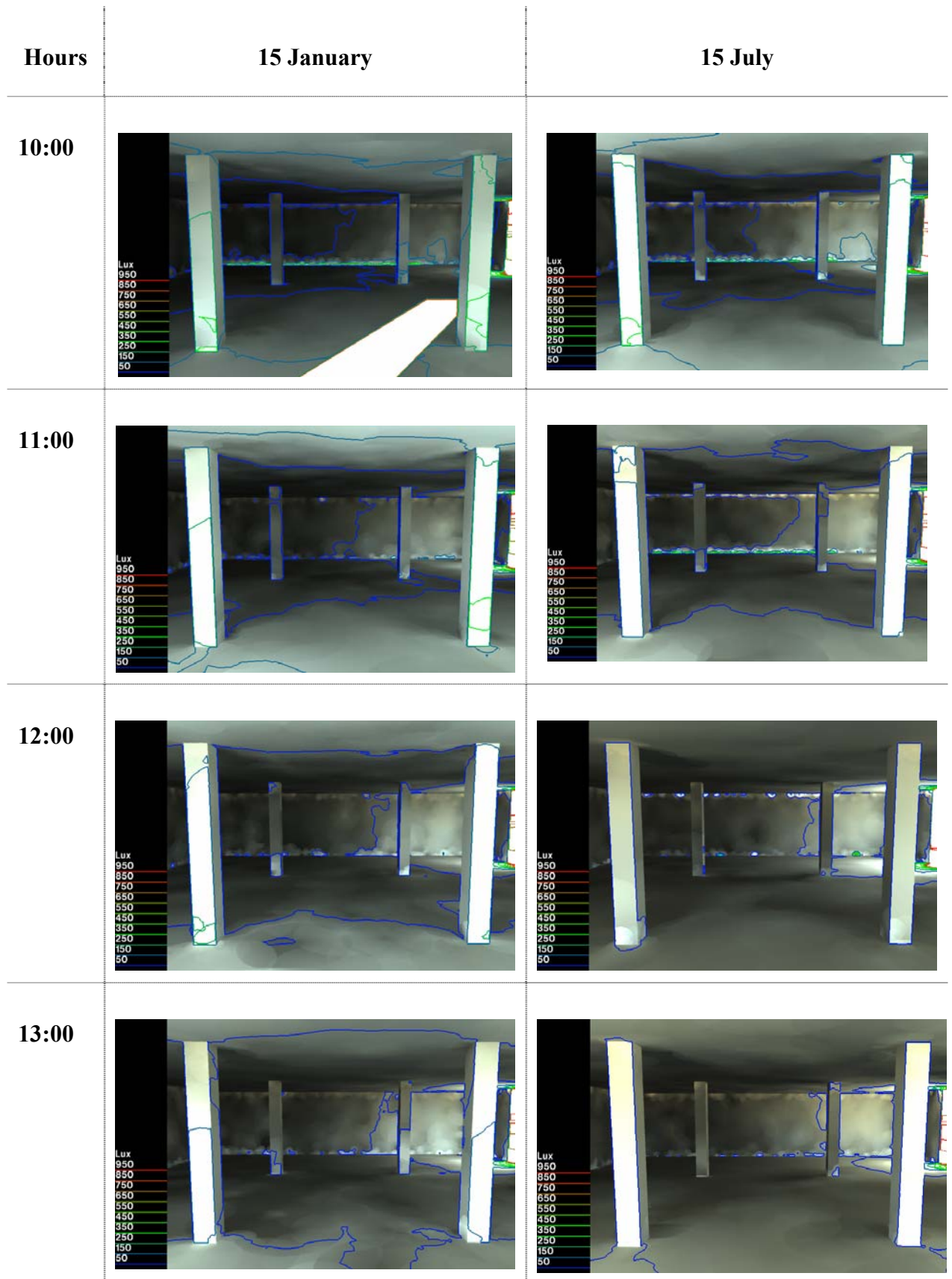


Figure E.5 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall B between hours of 10:00 and 13:00.

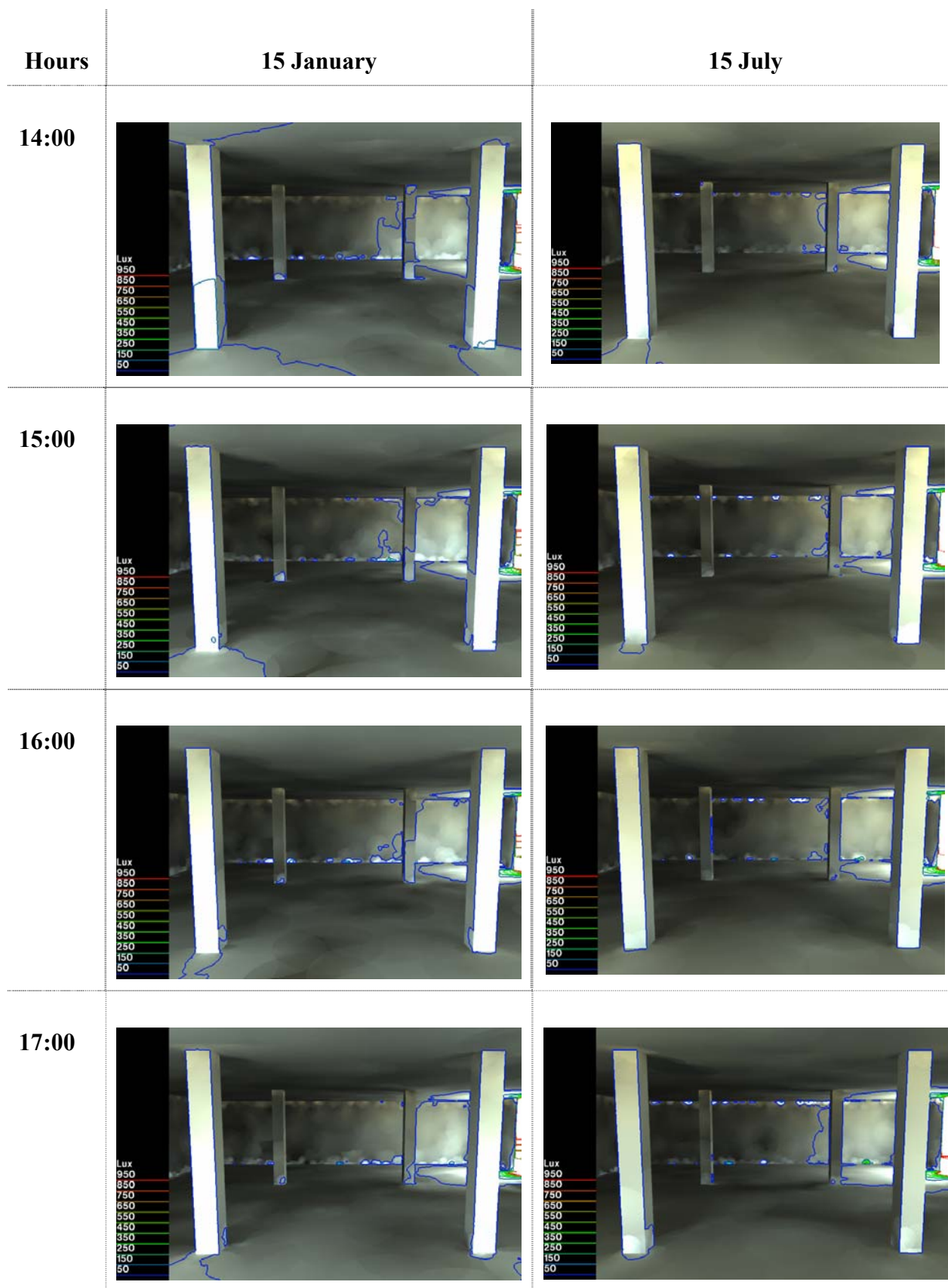


Figure E.6 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall B between hours of 14:00 and 17:00.

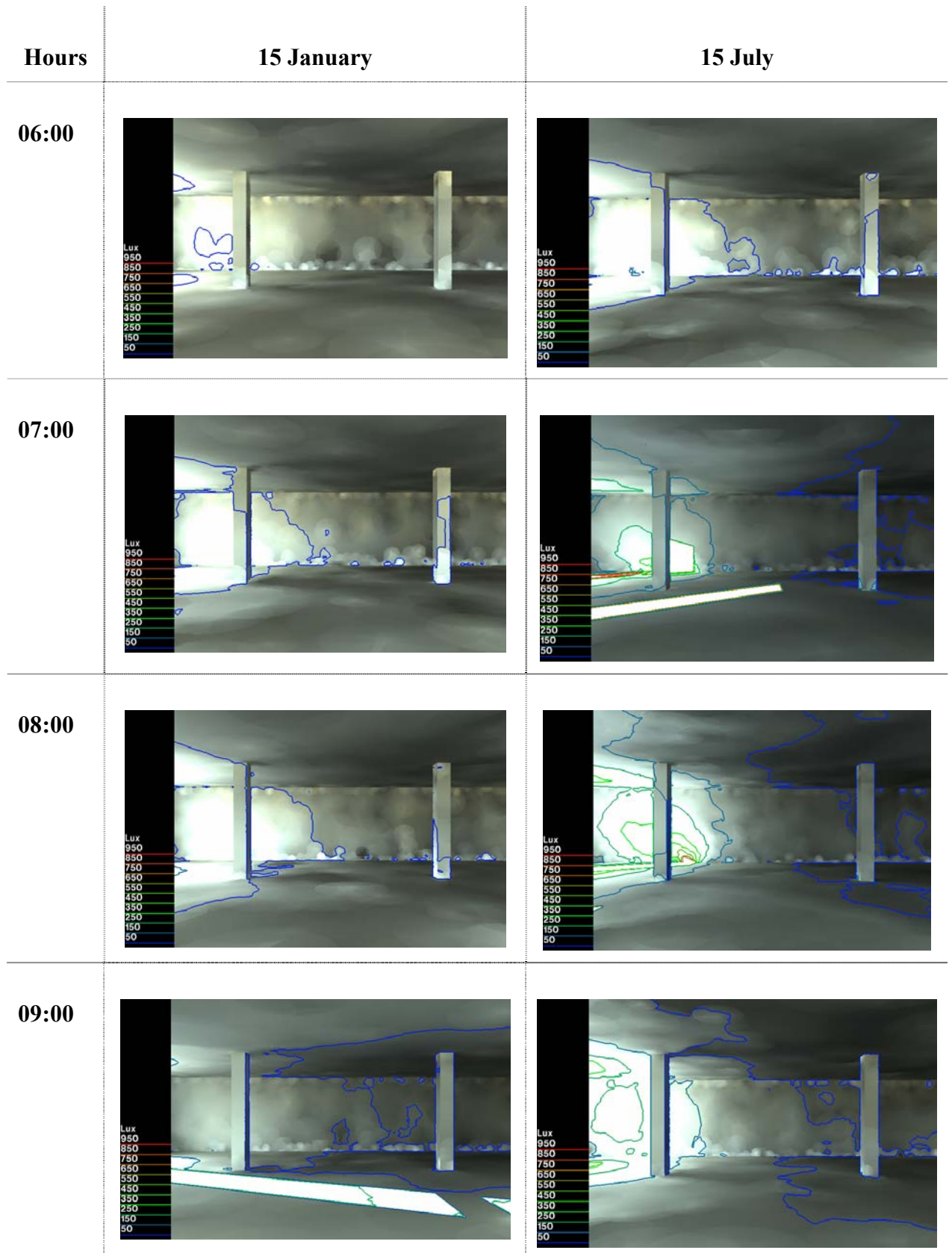


Figure E.7 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall C between hours of 06:00 and 09:00.

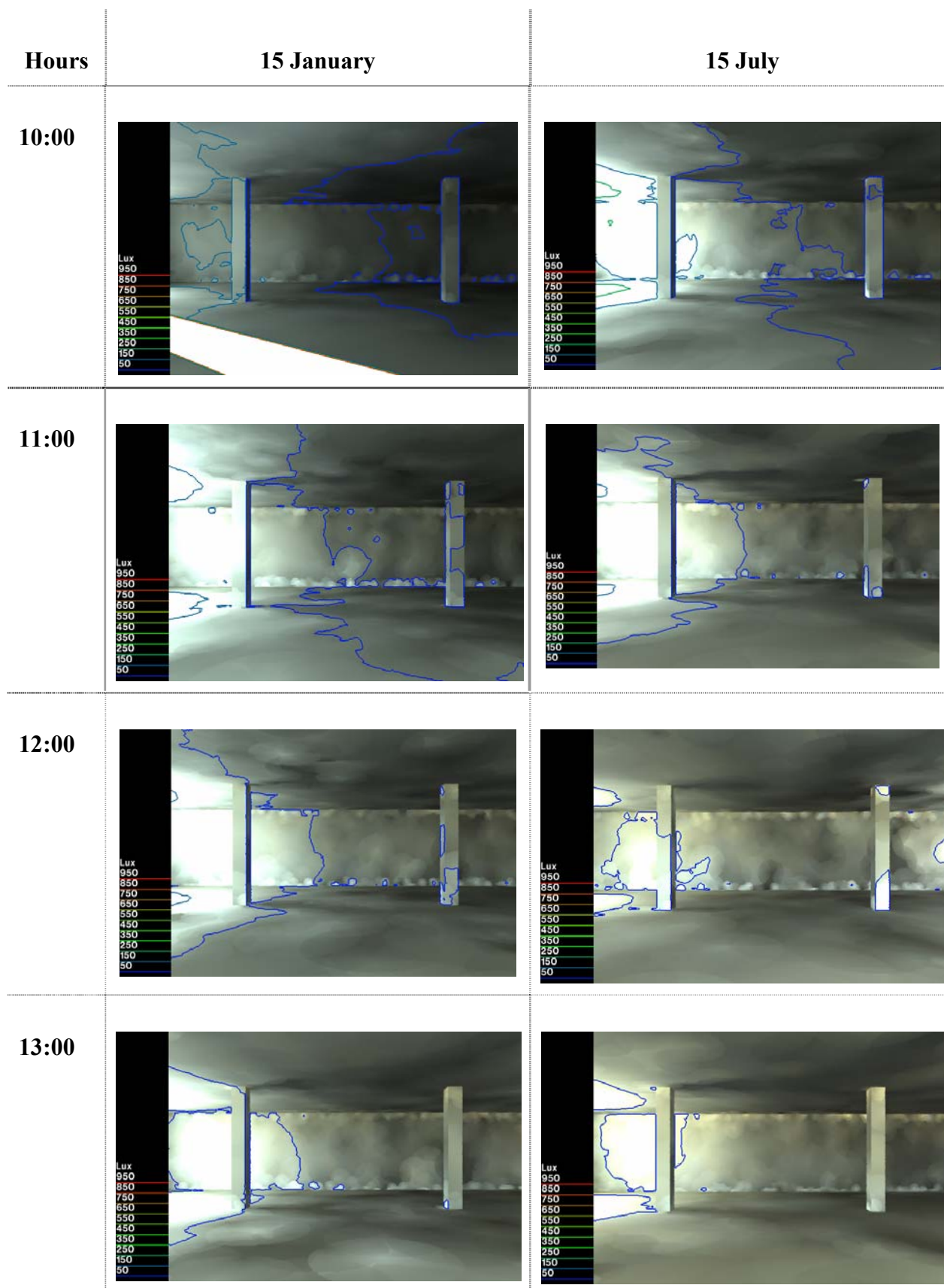


Figure E.8 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall C between hours of 10:00 and 13:00.

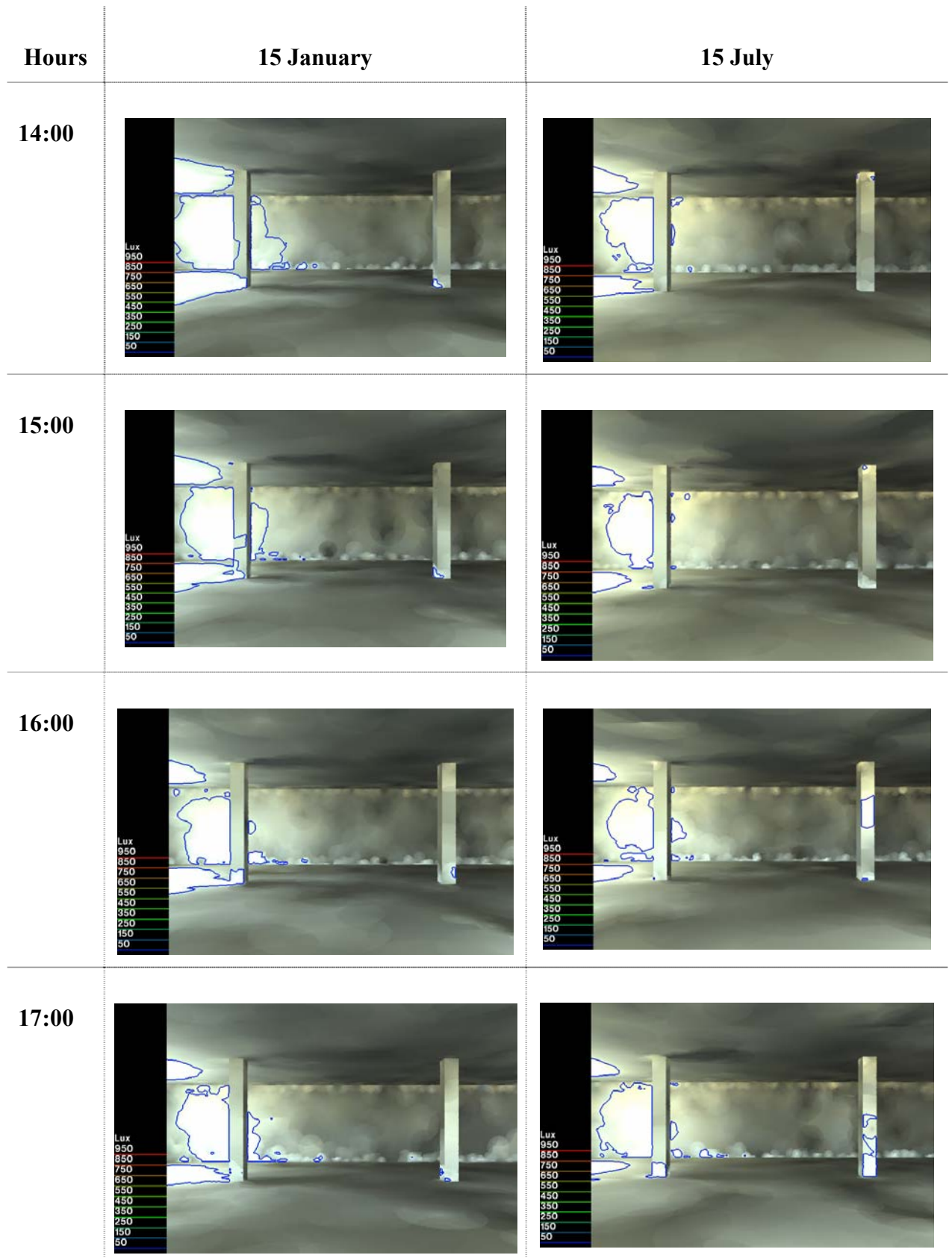


Figure E.9 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall C between hours of 14:00 and 17:00.

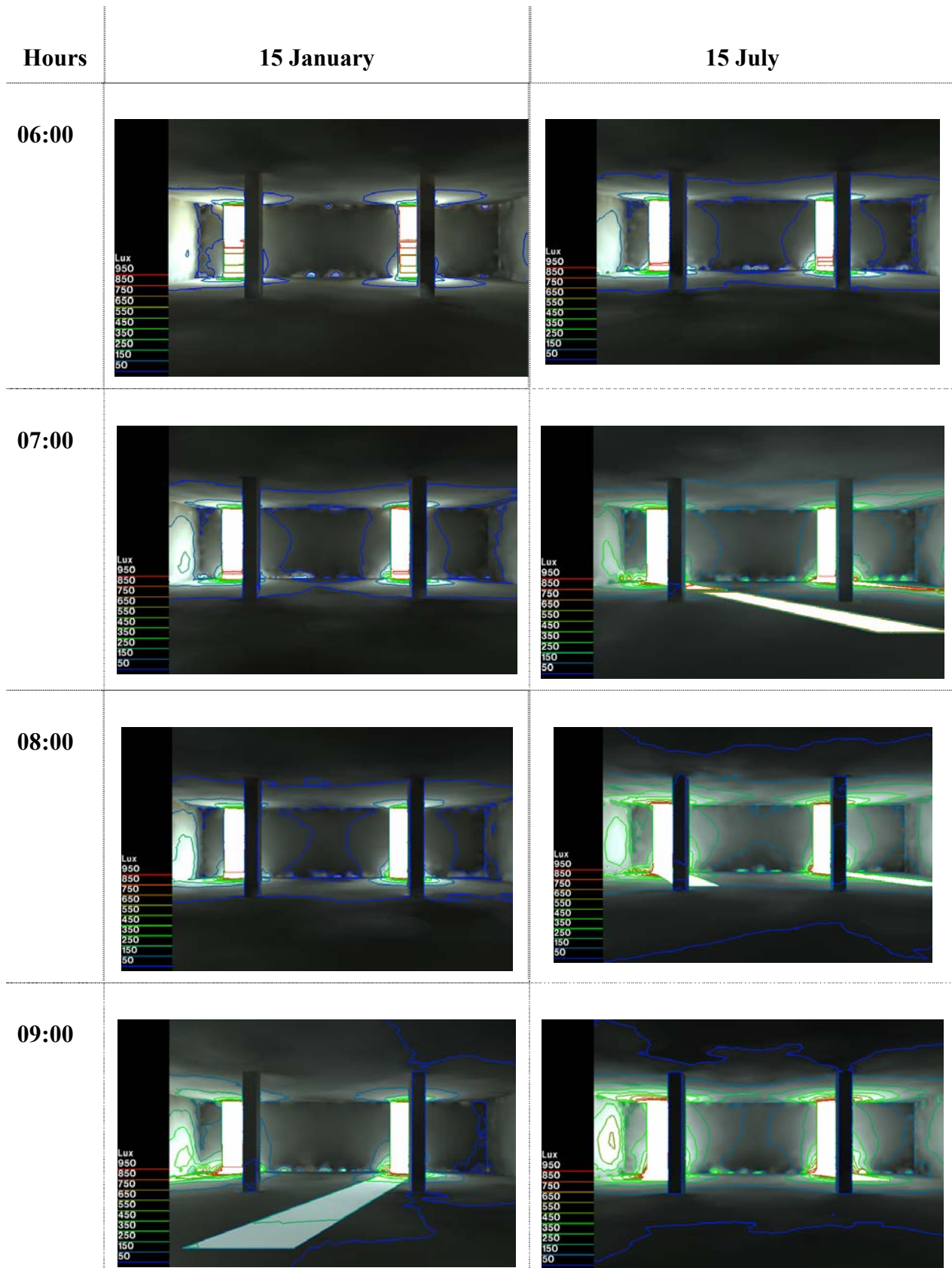


Figure E.10 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall D between hours of 06:00 and 09:00.

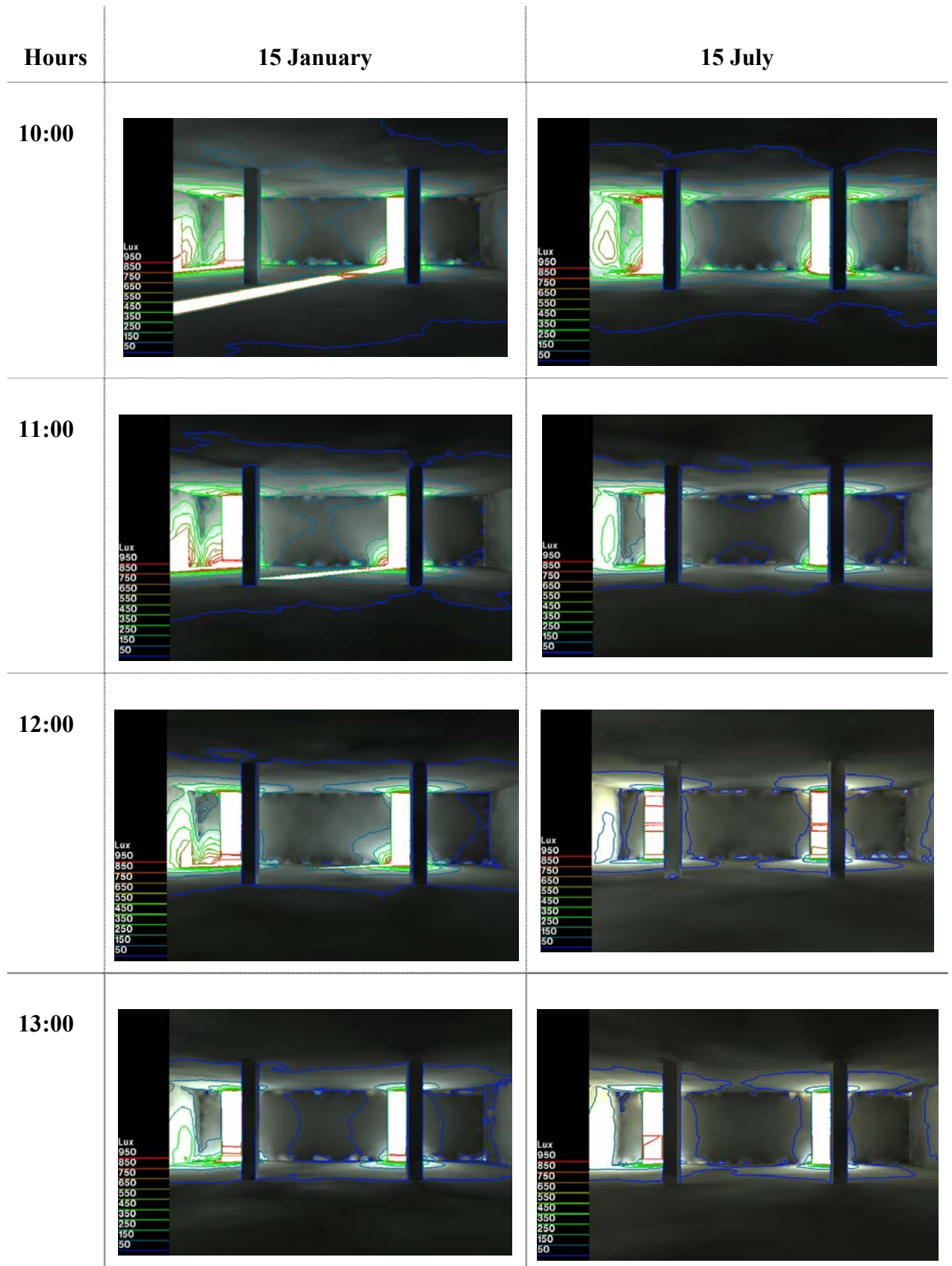


Figure E.11 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall D between hours of 10:00 and 13:00.

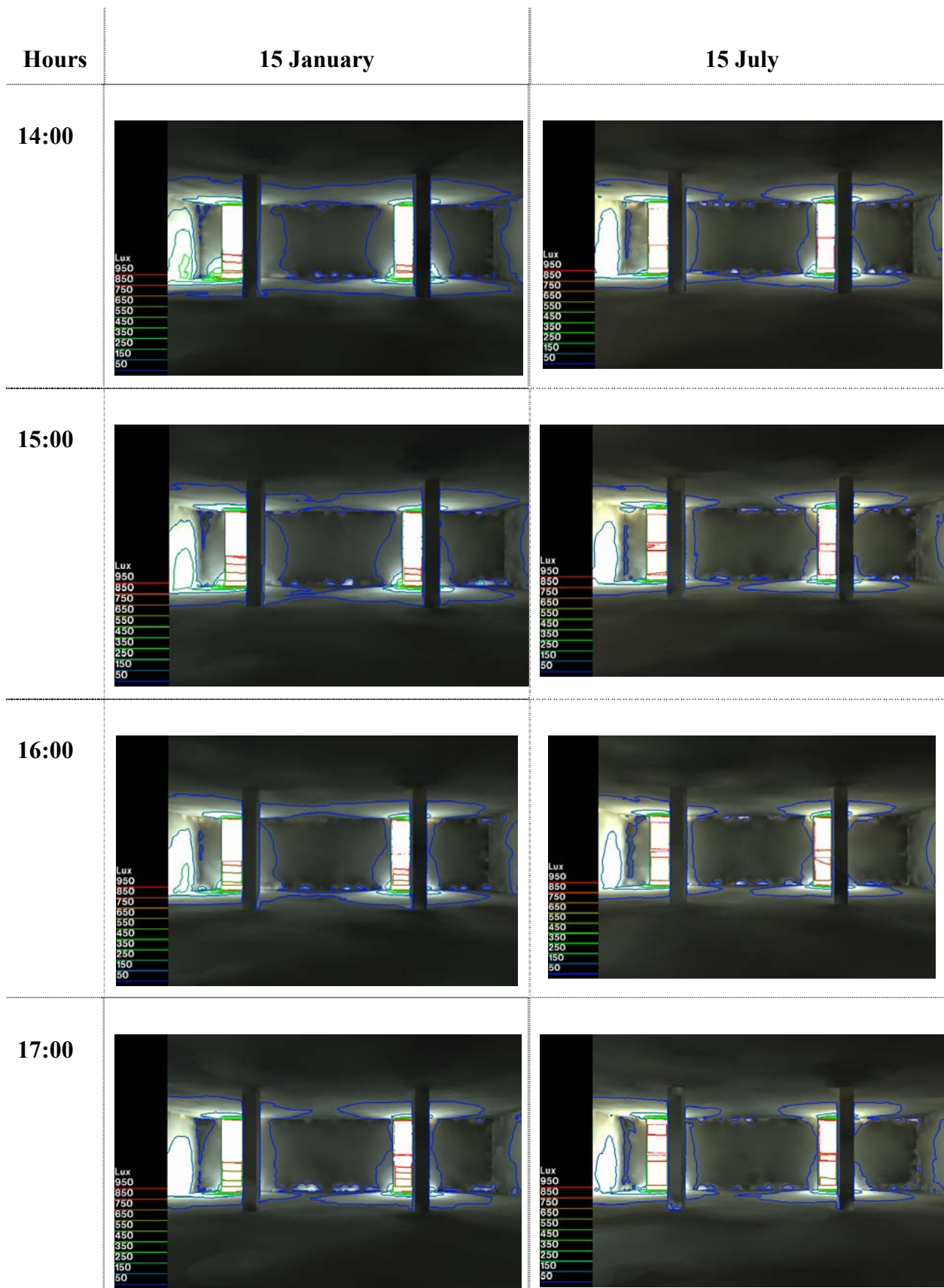


Figure E.12 : Comparison of winter and summer daylighting conditions on sample days 15 January and 15 July for Wall D between hours of 14:00 and 17:00.

CURRICULUM VITAE



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Universities and Colleges attended:

- Bursa Şükrü Şankaya Anatolian High School, 2002
- Gazi University Faculty of Architecture, Department of Architecture, 2006
- Hochschule für Technik Stuttgart, Department of Building Physics, Erasmus Exchange Student, 2007-2008 Spring Term

Publications:

- **Şener F.**, Yener A. K., 2007; Lighting Criteria in Museum and a Case Study of Istanbul Naval Museum, 4. *National Lighting Symposium*, 13-15 December, İzmir, Turkey.
- Yener A. K., **Şener F.**, 2007; Lighting of Museum and Exhibition Spaces, *Professional Lighting Design Magazine*, PLD, pp: 51-52.
- **Şener F.**, Yener A. K., 2008; Investigation of Library Buildings from Visual Comfort Points Of View and Evaluation Of A Case Study, *Balkanlight 2008 Conference*, 7-10 October, Ljubljana, Slovenia.
- **Şener F.**, Yener A. K., 2008; Lighting Criteria in Libraries and Investigation of ITU Architecture Faculty Library from Lighting Criteria points of view, 7. National Lighting Congress, 27-28 November, Istanbul, Turkey
- Yener A. K., Güvenkaya R., **Şener F.**, 2009; Visual Comfort And Energy Efficiency in Primary School Classrooms - Investigation of a Case Study, *International Building Physics Conference 4, IBPC 4*, İstanbul, Turkey (accepted)