A Comparison of Daylight Prediction Methods

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ABSTRACT

Daylight plays an important role in architecture. Apart from being a free source of energy that is virtually limitless, it affects the performance of human psychology. People physically become not only more active but have a positive mental state to tackle whatever the workplace throws at them. The first and the most obvious thing to understand about natural daylighting is that daylight is variable. It varies along with the seasons of the year, the time of day, and varies according to the weather. In spite of the amount of daylight penetration, making sure that not too much enters is also a challenge since it may create bigger problems such as glare or overheating.

Although using daylight is extremely economic and energy efficient it should be well designed and controlled in order to maximize these traits. One of the solutions to overcome such problems is the use of daylight prediction methods. In this research, four different daylight prediction methods are used in order to calculate the daylight factor, focusing on an overcast sky condition in a case study which was a design studio in E.M.U university of North Cyprus. These methods were explained and used in order to estimate the available daylight factor to maximize the efficiency and reduce the carbon footprint of the building. Both quantitative and qualitative comparisons were utilized in order to analyze the results. This comparison visualized the characteristic of each method. This study verified the fact that the implication of each method has different perspectives and according to the needs of the user, a decision can be made on which method to utilize. This study focused on light from an overcast sky and can be furthered by researching the effects on the daylighting with the direct rays of the sun instead of an overcast sky.

Key words: Daylight factor, Prediction method, Overcast sky.

ÖZ

Günışığı mimarlıkta önemli bir rol oynar. Sınırsız bir enerji kaynağı oluşunun yanı sıra insan psikolojisini ve performansını etkiler. Çalışma mekanının sunduğu etkilerle insan fiziksel olarak yalnız daha aktif değil aynı zamanda zihinsel olarak daha pozitif durumda olur. Doğal gün ışığı konusunda kabul etmemiz gereken şey değişken olduğudur. Yıl boyunca mevsimlere, gün boyunca saatlere ve hava durumuna göre değişir. Gün ışığının yapıya girmesi istenir ancak fazla girmesi kamaşma ve yazın aşırı ısınmaya neden olur.

Yapılar bu sakıncaları gidermek için çok iyi tasarlanmalıdır. Pencereleri gereğinden büyük yapmamak için bir çözüm günışığı tahmin yöntemlerini kullanmaktır. Bu araştırmada dört farklı günışığı tahmin yönteminin bir Doğu Akdeniz Üniversitesi Mimarlık stüdyosunda uygulanarak karşılaştırılması yapılmıştır. Karşılaştırma gerek niceliksel ve gerekse niteliksel yönlerden yapılmıştır. Bu karşılaştırma her yöntemin farklarının gözönüne serilmesini sağlamıştır. Herbir yöntemin farklı avantajları vardır ve kullanıcı koşullarına göre en uygun yöntemi seçmelidir. Bu çalışma kapalı gökyüzü varsayımına göre yapılmıştır. Araştırma açık gökyüzü koşullarına gore de irdelenmelidir.

Anahtar kelimeler: Günışığı katsayısı, Günışığı tahmin yöntemleri, Kapalı gökyüzü.

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INTRODUCTION

1.1 Description of the Thesis

One of the major factors in verifying the way in which internal environments and buildings are experienced by people is daylight. The role of daylight in day to day basis and the fact of providing internal space quality make it that important.

This is one of the reasons behind the constant need to integrate daylight into architecture, apart from high cost of fossil fuels or temporary electricity sources.

Besides being one of the most efficient sources of energy, not to mention the fact that it's completely free, there are other important aspects that should not be overlooked before entering the building.

Generally, it is considered a pleasure to have daylight inside the building unless it distracts the occupants from accomplishing their daily tasks such as glare from computer screens as this can reduce productivity of offices and creates eye strain.

Replacing artificial lighting with natural daylighting can be the best solution in terms of carbon footprint reduction and cutting costs to a minimum. It is essential to make sure that improper natural lighting or poor control doesn't give overheating or glare discomfort (Halliday, 2008).

Daylighting conditions constantly change as the years, seasons and even the day goes on. The amount of daylight available in a given space can differ with various different conditions therefore designer needs a technique to be able to predict the future of that space with an expected design strategy. Understanding the daylight and learning a reliable prediction method is necessary for an architect before designing the building (Robbins, 1986).

Daylight prediction methods help the user to calculate different issues related to daylighting. The particular topic which has been focused on in this research is **daylight factor**. “The daylight factor is the ratio of the internal illuminance to the external illuminance, available simultaneously” (Muneer, 2004).

A design studio is selected as the case study for this thesis. The calculation of daylight factor in this studio has been scrutinized by daylight protractors, Ecotect software application and the Radiance Software application. The attained values are evaluated and compared with the actual value which is obtained by an illuminance meter.

1.2 Problem Statement

In order to create a comfortable space, architects need to consider all human senses during the design of a building in order for users to communicate and operate within the rooms with ease. Careful consideration should be devoted to the penetration of the sun’s rays. This level of comfort should be benchmarked against the thermal, luminous and aesthetical aspects. This will ease the users ability to adobt to environmental changes (Araji, Boubekri, & Chalfoun, 2007).

Classroom lighting is now of great importance to the economy and the future of any country since it affects both the performance and the well-being of all students. Good lighting is not a matter of regulation. Although regulation is required, it is a matter of good design. Daylighting takes into account three factors of personal need. These are visual comfort, visual satisfaction and visual performance (Bean, 2004).

Calculations are not an end in themselves. Their aim is to help the designer choose between alternatives or to check whether a particular solution meets a condition.

There are many methods available for estimating each of the quantities such as day lighting which a designer needs to familiarize themselves with. None is ideal for all circumstances. They vary in accuracy, in generality, in time and in cost (Tregenza, 1998).

Since they are a small part of the whole design process, it is important to research about the available means of calculation.

1.3 Aim of the Research

Daylighting plays an important role in architecture. However, integrating daylight is largely influenced by the depth, shape and the spacing of the building. In order to predict the future situation of designed buildings, daylight prediction methods must be considered (Halliday, 2008).

The dilemma of which method would be more suited to the design problem still lingers therefore this research will strive to clarify the answer for the following questions;

- What are the advantages and limitations of selected daylight prediction methods?
- What type of calculations performed by these methods will be more appropriate for simulating daylight in the condition of selected case study?

1.4 Methodology

This study is initiated by explaining the importance of daylighting and the concept of daylighting prediction methods. In addition, in order to support the theoretical framework and to discover the gaps, the review of recent similar studies which have been done so far are included.

Later in the thesis, in order to collect the data needed to evaluate the methods, a case study is selected. The case study is a design studio. The reason behind selecting this case study is the fact that the design studio is occupied only during the day which makes it a perfect candidate for this research.

The studio is a part of Eastern Mediterranean University which is located in North Cyprus. It is very close and accessible and can be reached anytime of the day in case further studies are required.

Among other various types of prediction methods, three techniques are selected. These methods are as follows;

B.R.E daylight protractor method as a graphical method and Radiance and Ecotect as a computational method performed on a Personal Computer. Later in the chapters, the results of these methods are compared with the actual value which is calculated by an illuminance meter. The evaluation is both qualitative and quantitative. The collected data will be evaluated by analysis and inventory forms which are provided according to specific criteria and filled in for each individual method.

1.5 Limitation of the Study

The calculated data has been done in relation to the weather data in Cyprus. The collection of the data is relevant to an overcast and uniform sky. The comparison of the attained daylight factor value has been calculated for an overcast sky.

1.6 Impact of Daylighting in Architecture

The connection of lighting and architecture is undividable. Light helps form, space, texture and color which are all an essential part of architecture.

In addition, it is a required element for most of the functions taking place in a building to act as an aesthetical element creating visibility, comfort and environmental control (Steemers, 1994).

1.6.1 History of Daylight in Architecture

Daylighting may date back to the time when natural light was entering the mouths of the caves. “Perhaps the first civilized use was the Roman Patio house. After the 1900 daylight was in competition with the various forms of artificial light, up to the point when it appeared to be irrelevant, having as its nadir the development of “Burolandschaft” when buildings could be of infinite depth, and when even some schools and factories were built without any windows at all” (Phillips, 2004).

In other words, humans are trying to improve the quality of life by using large scale commercial energy. Although this may sound like technological progress, there are severe consequences to using such energy sources. Perhaps the most severe problem of this issue is the destructive effects on the environment. Meanwhile, large amount of heat being wasted have created pollution (Sukhatme, 1991).

Apart from these neglected issues, it appears that the circumstances are changing. The importance of daylight usage in architecture is becoming increasingly popular. The use of local resources and materials are preferred. Federal solar programs which were initiated in 1978 have put so much effort for consumer education and professional advancements in the architectural integration of daylighting concepts (Mazria, 1990).

There are many reasons behind this issue. It can be the high cost of fossil fuels, temporary electric sources or being a significant and convincing element in order to create a quality life (Phillips, 2004).

1.6.2 Role and Importance of Daylighting in Architecture

"Daylight is both a design element and an environment system" (Robbins, 1986). Daylighting in architecture has been considered as an essential aspect. Directing daylight into the building can help achieve three different necessary requirements in architecture:

- Visual comfort
- Energy efficiency
- Green building developments (Li, A review of daylight illuminance determinations and energy implications, 2010).

Daylighting is preferably the best option for illuminating a space during the day, unless regards to the function of the space can be excluded. It is a valuable source since it provides variability, intensity, color and above all else, no energy consumption. However none of these can be exactly reproduced by artificial lighting (Halliday, 2008).

There are many reasons which put forward the idea of considering daylight as a light source in architecture. Claude Robbins states few of these reasons as followed:

- Quality of the light
- Importance of daylight as a design element
- View (daylight apertures provide visual communication channels to the outside)
- Use of day lighting apertures are fire exits in emergencies
- Energy conservation resulting from the use of day light as a primary or secondary illuminant
- Energy consumption and peak demand cost savings resulting from the use of daylight
- No cost change in construction
- Opportunity to develop integrated structural and mechanical systems
- Psychological and physiological benefits not obtainable with electric lighting or windowless buildings
- The genuine desire to have natural light and sunlight in a room or space (Robbins, 1986).

1.7 Concept of Day Light Prediction

Apart from being a great source of light, daylighting has been known as one of the most powerful elements of architecture by means of either art or science.

Although daylight plays an important role in architecture, there are some consequences regarding daylight integration into architecture.

Day lighting keeps changing during the years, seasons and even during the day. The amount of daylight available in one space can differ with many conditions.

Besides being a variable source of energy, daylighting has some other critical facts. For instance, in buildings with large glazing areas, some other issues may occur. There can be severe discomforts due to either glare or overheating (Burberry, 1997).

With increasing interest and need for using natural lighting rather than an artificial one, multilateral day lighting is considered.

The multilateral day lighting can be achieved by increasing the size of windows, adding more windows or window walls, skylight, etc.

By using multilateral day lighting, the area sources of natural lighting increases.

However these actions will create a larger ratio of brightness inside the building which needs to be controlled to prevent upcoming problems such as glare inside the building.

In order for a designer to be able to evaluate the level of visual comfort and energy efficiency of the expected space, the designer requires a method to estimate or predict the approximate illuminance for any point within the internal space (Li, A review of daylight illuminance determinations and energy implications, 2010).

Daylight fenestration can have an influencing fact upon this evaluation. Fenestration is an architectural term explaining the penetration of daylight through any openings or skylight into the building (Hillbrand, 2002).

Several factors can affect the quality and availability of the daylight inside a building:

- The nature and brightness of the sky.
- The size, shape and position of the windows.
- Reflections from internal surfaces.
- Reflections and obstructions outside the room (Light readings, 2004).

In order to create a comfortable space, architects need to consider all human senses during the design process in order for users to communicate and operate efficiently within the building. This level of comfort should be thermal, luminous and aesthetical. This will provide users the ability of getting along with environmental condition changes (Araji, Boubekri, & Chalfoun, 2007).

Although daylight like the other environmental factors needs to be controlled, the fact that it is changing its character from day to day or even during the day makes it difficult (Ralphs, 2007).

Since there are many factors affecting the quantity and quality of daylight entering the inner side of building, what would be the solution that takes into consideration all these factors? When this question is answered, that is when daylight prediction or simulation method can become practical.

In order for a designer to be able to introduce natural light into a building and control it appropriately, daylight calculation or prediction methods must be utilized.

These methods help introduce daylight into a building and find an appropriate way of controlling it. Since they provide the user the chance of simulating or predicting the future conditions of the building space, it can assist the users in order to avoid wrong design, in order not to waste energy and money.

1.8 Development of Daylight Prediction Methods

Although daylight is one of the main resources of energy, its utilization and preference rather than using artificial lighting which cost a substantial amount were ignored for decades.

The reason behind the fact that these methods weren't popular was that prior to the Second World War, daylight predictions within rooms was impractical and was not considering the inner reflectance.

However, in 1973 various design tools have been developed. Since then they have adopted much simpler methods that were user friendly. Computerized tools were developed under federal research initiatives. These tools also utilize the traditional calculation methods such as the three-dimensional scale models and calculation procedures to predict daylight (Mazria, 1990).

By mid 1980's, only a handful of daylight prediction software were able to predict illumination levels in daylighted spaces. According to an evaluation in 1988 by Ubbelohde et al. he demonstrated that none of the software back then was capable of predicting the simplest of real daylighting designs. Between 1988 and 1998, computer methods were developed and several major methods were introduced to users such as Radiance which will be studied in this research (Ubbelohde & Humann, 1998).

1.9 Research Background

Early daylight studies were limited to estimating the daylight penetration inside the rooms where a simple rule of thumb method was often used (Tregenza, 1998).

In 1975, the concept of average daylight factor was suggested by Longmore. This value points out the visual sufficiency of the daylighting in space for daylighting calculation as a whole rather than at any particular point (Li, 2010).

Up until 1998, in reviews about daylighting prediction methods, computer calculations have been generally mentioned as a subset of lighting design software or energy simulation software. These reviews have been appeared as articles on performance of individual software in the lighting press, computer graphics publications and architectural journals (Ubbelohde & Humann, 1998).

Although the number of publications regards to daylight prediction method comparison is very little, there have been some studies attempting to evaluate and compare different prediction or simulation methods (Ubbelohde & Humann, 1998).

Furthermore there have been some similar studies on same methods which have been studied in this research.

Ubbelholde and Human (1998) did a study on comparison of four daylighting software. These softwares are: Lumen Micro, Lightscape, Super lite and Radiance. They evaluated the comparison as followed;

“ Some can accurately predict quantitative daylight performance under varying sky conditions and produce handsome and accurate visualizations of the space. The programs differ significantly, however, in their ease of use, modelling basis and the emphasis between quantitative predictions and visualization in the output.” (Ubbelohde & Humann, 1998). Moreover, Reinhart has also done lots of studies on comparison of daylight prediction methods. Reinhart and Herkel (1999) evaluated five Radiance based simulations. The result from this comparison revealed the fact that having a time consuming method doesn’t prove to be more accurate. Instead, the sky luminous efficacy model and whether if both hourly direct and diffuse illuminances are considered makes the method accurate. These methods are not capable of inputting weather data with time steps below one hour (Reinhart & Herkel, 1999).

Meanwhile Sethi(2003) studied and evaluated Ecotect as a designer friendly simulation software. This study which was picked as the best student author paper by SBSE (society of building science educators) led to this result: The simulation software used, has the ability to simulate daylighting and solar exposure and may further be used in other areas of thermal, acoustic, lighting analysis etc. This is helpful as a design tool when these decisions are interdependent.

In Velux daylight symposium (2007) Bodart defines the advantages and limitations of Radiance and daylight factor protractors. He explains daylight protractor as a method which needs few input parameters and has fast result. However this method is limited to static and quantitative metrics and is not suitable for spaces with complex geometry, material and sky condition and has a low accuracy. On the other hand Radiance software has its own advantages and drawbacks. It can work well for spaces with complex material since it has well developed material library and provides the user with accurate, dynamic, quantitative and qualitative results. In return, it is a time consuming method in regards to learning and calculation (Bodart, 2007).

Apart from different comparisons which have been done, there are some studies about the development of methods and how popular they are.

One of the first programmes of the International Energy Agency was established in 1977, which was the solar cooling and heating programme. This unique programme works with collaboration of experts on related topics from all over the world. Among different tasks and surveys which have been done so far, there are some studies and online surveys related to daylight prediction methods (Solar,Heating and cooling programme:International energy agency).One of these researchers named Christoph F. Reinhart has done various studies about daylight protractors, Radiance and Ecotect. Reinhart did an online survey on the use of daylight simulation. The key findings from this survey can be categorized as followed (Reinhart, 2004):

Types of users who apply daylight prediction methods are:

- Architect
- Lighting designer

- Interior designer
- Energy consultant
- Engineer
- Researcher
- Manufacturer

And these methods produce various types of outcomes:

- Interior illuminance
- Daylight factor
- Photo realistic images
- Interior luminance
- Electric lighting use
- Glare indices
- Daylight autonomy

After using daylight prediction methods, the result can affect several aspects in design of the particular space. These aspects are as followed:

- Shading type/control
- Window size
- Glazing type
- Lighting controls
- Building orientation
- Interior surface properties

- Room dimensions

According to another research which took place in Victoria University of Wellington, Wellington, New Zealand in 2007 has shown that the best method to estimate the illuminance in a space in pre-construction stage will be through daylight prediction. Up until now, these methods have been complex, expensive and time consuming, especially when they represent illuminance for all 365 days of the year. Therefore the number of users for these methods is not many. However recent developments have made these methods more practicable to be used regularly, in particular to calculate all the hours of the standard daylight year (8am-5pm) (Stewart & Donn, 2007).

However it should be mentioned that none of these studies state which method is the best, since each individual has its own advantages and limitations therefore the decision on selecting the proper method differs according to many aspects.

In fact, daylight prediction methods are developing with the purpose of better calculation in order to examine the effectiveness of any daylight design strategy.

All these researches state that Calculations are not an end in themselves. Their aim is to help the designer choose between alternatives or to check whether a particular solution meets a condition. There are many methods available for estimating daylight. None is ideal for all circumstances. They vary in accuracy, in generality, in time and in cost. So this survey will help find the proper method in order to predict daylight for a specific design studio (the case study) with defined weather conditions in regards to the weather of Cyprus.

Chapter 2

COMPARISON OF DAYLIGHT PREDICTION

2.1 Case Study: A Design Studio in the City of Gazimagusa

The case study for this comparison is a design studio located in the Architecture department of Eastern Mediterranean University campus in Gazimagusa.

“Gazimagusa is one of the five existing districts in the Northern Cyprus. Northern side of Cyprus is known as Turkish Republic of Northern Cyprus.

Cyprus is the third largest island in the Mediterranean and it has Mediterranean climate which is warm and rather dry, with rainfall mainly between November and March. In general, the island experiences mild wet winters and dry hot summers. Variations in temperature and rainfall are governed by altitude and, to a lesser extent, distance from the coast. Hot, dry summers from mid-May to mid-September and rainy, rather changeable winters from November to mid-March are separated by short autumn and spring seasons” (Geography of Cyprus).

According to Cyprus meteorological agency which is directly related to Cyprus municipality, due to the geographical location of North Cyprus, there is an abundance of solar energy. On a normal summer day, on average, there is about twelve hours of sun light whereas on a winter day there is about 5 hours of sunlight. Average daily amount of solar energy in the year is 417.3 cal/cm^2(Calories per

Square Centimeters). In July, average daily maximum is 622.2 cal/cm^2 of solar energy. In December, the minimum average daily solar energy has a value of 214.5 cal/cm^2 (Kuzey Kıbrıs'ın genel hava durumu).

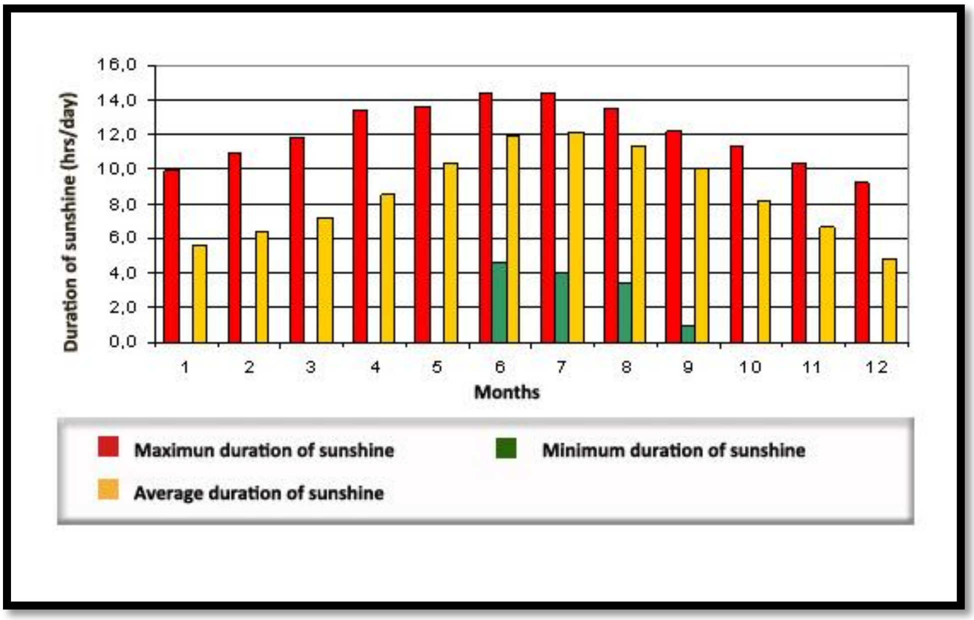

Figure 1: Sunshine period in North Cyprus (Kuzey Kıbrıs'ın genel hava durumu)

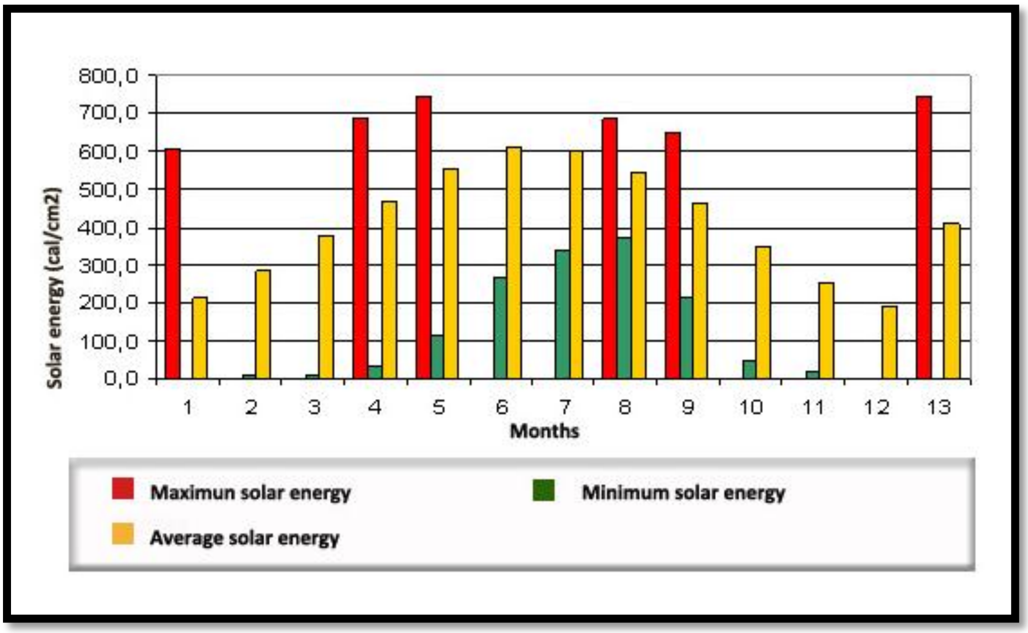

Figure 2: Solar energy in North Cyprus (Kuzey Kıbrıs'ın genel hava durumu)

2.2 Methods of Daylight Prediction

“Physiologically and psychologically it is beneficial to let daylight into buildings. It is more efficient to utilize natural lighting sources than artificial ones particularly during day time which there is available natural light (Light readings, 2004).

Although daylight like the other environmental factors need to be controlled,

One of the problems being faced in controlling it is the fact that its characteristics are changing day in and day out and even several times during the day. (Ralphs, 2007).

That’s when daylight prediction methods become a great asset to a design. These methods will help estimate the fenestration of daylight through the openings pre-construction in order to control this energy in the most efficient way.

Good daylighting is not something that can be considered after finishing the design or while building the project.

In order to have the efficient design its necessary to analyze the daylight that would be available in that specific space (CLEAR, 2002).

There are different methods for day lighting analysis however they can be divided into three different categories:

- Computer simulations
- Graphical methods
- Physical scale models

This research was conducted in order to determine a study on daylight simulation/prediction methods which play a significant role in development of designing energy efficient buildings. The advantages and disadvantages as well as the reliability of these methods were also a part of the objectives.

In order to answer these research goals, four prediction methods are compared in order to provide a chance to find the better solution that is more appropriate to the condition of the expected case study. These methods were performed for two different types of sky which are uniform sky and overcast sky.

One of the applied methods is from the graphical method category and two of them from the computer simulation category. Furthermore, an indoor and outdoor on-site evaluation is done by using an illuminance meter device in order to compare the results attained through these methods.

These prediction methods provide the user with different types of values such as:

- Illuminance (Lux)
- Luminance (cd/m^2)
- Sky component (%)
- Daylight factor (%)

This study focuses on the daylight factor values. In the design of a building, the sufficiency of the daylight fenestration is very important. It should be taken into consideration in terms of interior daylighting or daylight factor. In addition it is becoming progressively more common to be computed when basic drawings of the design are prepared (Longmore, 1968).

In order to compare the daylight factor value attained by the selected daylight prediction methods, a design studio in architecture department of E.M.U was selected as case study. There are two reasons behind this decision. Firstly, according to the function of this space, most of the activity in classrooms is taking place during the day. Secondly according to one study, in classrooms where there is more daylighting, student's ability to learn progressed 20% faster in mathematics and 26% faster in reading than similar students in classrooms with poor daylighting (Kats, 2003).

The existing studio in Gazimagusa is analyzed by the mentioned types of calculation methods and the results of the applied methods are compared.

The comparison is taken by means of the inventory forms which are provided accordingly and filled for each individual method.

2.2.1 Graphical Calculation

There is a wide range of graphical methods in order to calculate available daylight inside a specific space which can be done manually.

These methods were achieved from computational simulation. Since graphic is the most common method for architects and designers, it can develop their project during design process. Plus being easy to apply, graphic methods reveal the relative effect of different design factors and provide the user with extra insight to their design strategy in order to improve the idea.

2.2.1.1 B.R.E Day light Protractors: Introduction to the Method

One of these graphical methods is daylight protractors. The particular type of the protractors which were used in this study was B.R.E daylight factor protractors.

These types of protractor help the designer examine the sufficiency of daylight at a stage where scale drawings are available.

Although the original set of these protractors can still be applied, newer versions have been introduced. Same principles were applied for the latest versions, however they are more accurate in their construction and more recent data such as glass transmission has been imported into the equation. The recent versions are the results of experience of using the original one; meanwhile the principle of the method is same. Each protractor includes two semi circular sets of scales. The top section is made for calculating sky component and bottom scale is for calculating window correction. Longmore (1968) explains the operation base of B.R.E protractors:

“The daylight at a point in a room is essentially a function of the angular sub tenses of the window and of the principal reflecting surfaces at the point, of the angle which the incident light makes with the reflectance plane and of the angle of elevation of the patch of sky visible from the point. Thus the daylight can conveniently be evaluated in terms of these angles” (Longmore, 1968).

The Building Research Establishment (BRE) developed this set of protractors which give direct reading of the sky component in percentages. There are 10 different protractors, five of which are used for the uniform sky and five for the International Commission on Illumination (CIE sky) (Burberry, 1997).

Table 1: B.R.E protractors types (Longmore, 1968)

	(Uniform sky)	**(CIE sky)**
Vertical glazing	1	2
Horizontal glazing	3	4
Slope 30 degrees to Horizontal	5	6
Slope 60 degrees to Horizontal	7	8
Unglazed openings	9	10

In this research, the type of the opening is vertical glazing. That's why both protractors 1 and 2 are used. As it is shown in table 1, protractor number 1 is related to a uniform sky and protractor number 2 is related to an overcast sky. There are total of four types of sky assumptions. These sky types are explained below.

Standardized sky models

Daylighting keeps changing during the years, seasons and even during the day. The amount of daylight available in one space can differ with any condition.

Although these changes are interesting, they make a designer's job more difficult.

Since there is no exact permanent condition for the sky, the accurate calculation will be much more complicated. However, architects and engineers need to build a sky model in order to start the primary steps of estimating.

The Commission International de 'Eclairage (CIE) created a series of sky models which can be very valuable for the designers or engineers while utilizing natural lighting into the building (CLEAR, 2002).“These sky models are as explained and illustrated as followed:

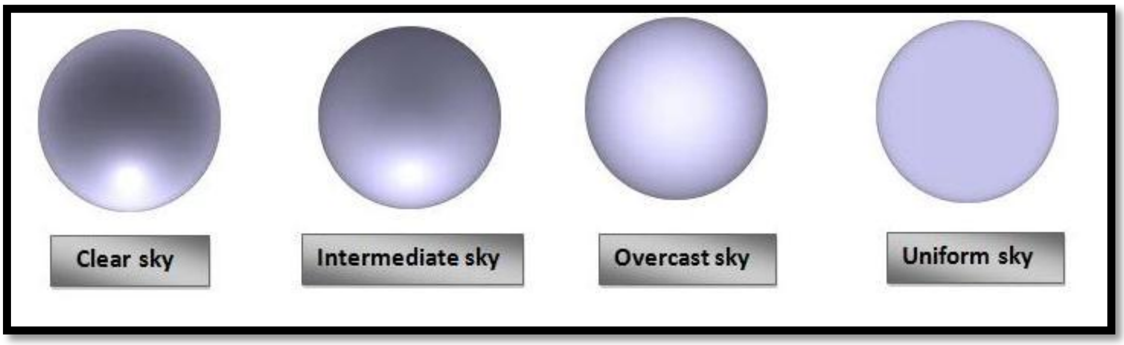

Figure 3: Sky types (www.learn.londonmet.ac.uk)

Clear sky

The luminance of the standard CIE clear sky varies over both, altitude and azimuth. It is brightest around the sun and dimmest opposite it. The brightness of the horizon lies in between those two extremes.

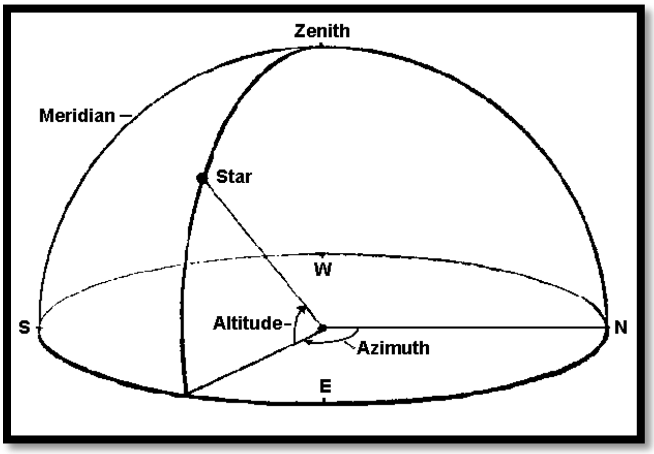

Figure 4: Altitude and azimuth (http://www.johnpratt.com)

Intermediate sky

The standard CIE intermediate sky is a somewhat a hazy variant of a clear sky. The sun is not as bright as with the clear sky and the brightness changes are not as drastic.

Overcast sky

The luminance of the standard CIE overcast sky changes with altitude. It is three times as bright in the zenith as it is near the horizon. The overcast sky is used when measuring daylight factors. It can be modeled under an artificial sky.

Uniform sky

The standard uniform sky is characterized by a uniform luminance that does not change with altitude or azimuth. It remains from the days when calculations were done by hand or with tables. “Today, it is still used for Rights of Light cases” (CLEAR, 2002).

2.2.1.1.1 Method Explanation

In this research, since the condition of the case study was considered as an overcast sky and then a uniform sky for a vertical glazing type of window, protractor number one and the protractor number two were used. Same principles were applied with different protractors.

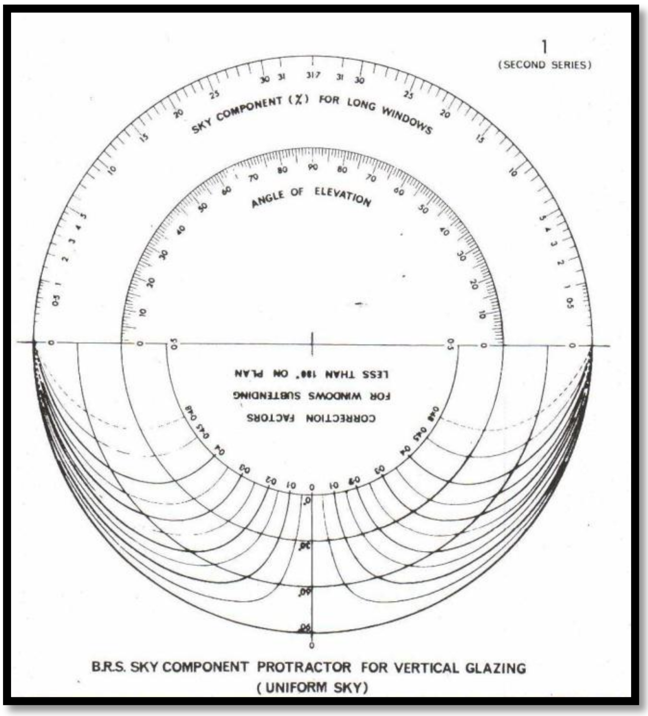

Figure 5: B.R.E sky component protractor for vertical glazing number 1 (BRE)

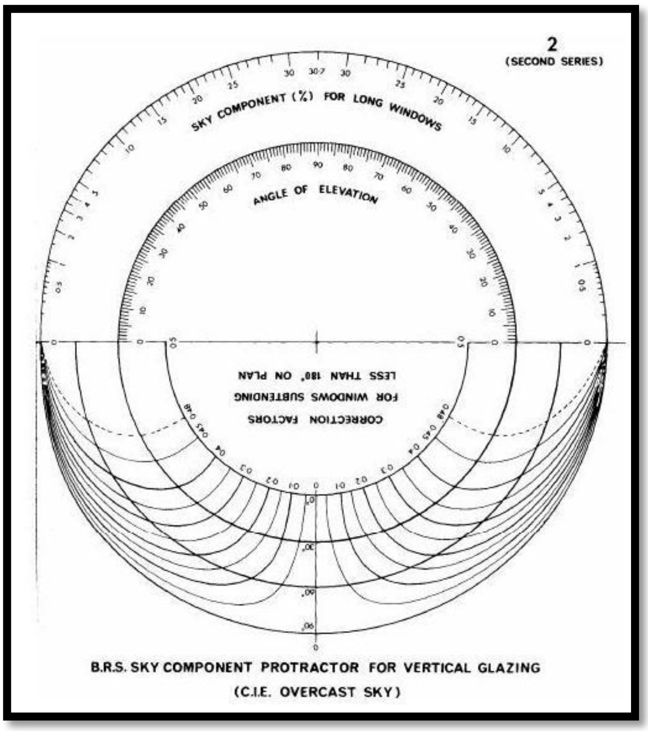

Figure 6: B.R.E sky component protractor for vertical glazing number 2 (BRE)

Longmore explains the operation basis of B.R.E protractors as followed:

"The daylight at a point in a room is essentially a function of the angular sub tenses of the window, and of the principal reflecting surfaces at the point, of the angle which the incident light makes with the reference plane and of the angle of elevation of the patch of sky visible from the point. Thus the daylight can conveniently be evaluated in terms of these angles" (Longmore, 1968).

Daylight factor is the percentage of external illumination from an unobstructed sky at a point on a horizontal plane in a room (Li, 2004).

DF is the sum of the following components (Daylight factors: Split Flux):

Sky component (SC): It is directly from the sky, through an opening such as a window.

Externally reflected component (ERC): It is the light reflected off the ground, trees or other buildings.

Internally reflected component (IRC): The inter-reflection of (SC) and (ERC) off other surfaces within the room.

That means that daylight factor can be estimated by a simple formula (Muneer, 2004):

DF = DC + ERC + IRC

Therefore the following steps were done in order to calculate the daylight factor with the help of the aforementioned protractors.

At the first step in the section of the room, the working plane is drawn and the considered point is plotted. Then the edges of the window are connected to that point.

Now the protractor with the scale A facing up, is placed on the selected point on the working plane.

The difference of values where the lines intersect the outer perimeter is the **initial sky component**.

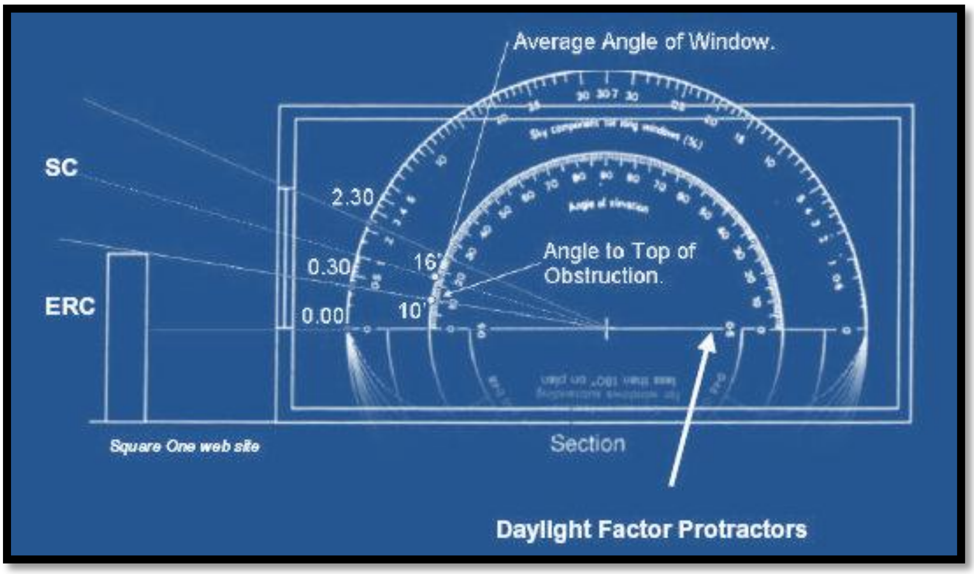

Figure 7: Step one (Reinhart C., 2005).

Also the average of the inner value of the angles will be the **corrected sky component**.

The next step is the same process on the plan as before. On the same point with same distance from the window however, this time the protractor is placed with the scale B parallel to the window. The semi-circle that corresponds to the correction factor value which was achieved in earlier steps is selected.

The values along the inner semi-circle where the limit lines intersect the semi-circle are taken. If both points are on one side of centre line the values are added together, if they are both on separate sides they will be subtracted. This value will be the **correction factor**.

If there is no outside obstruction there will be no **externally reflected component**.

And if there is any, the sky component should be multiplied by the reflectance of the material and if it’s not clear, since the condition is overcast sky type it can be multiplied by 0.2 (Moore, 1885).

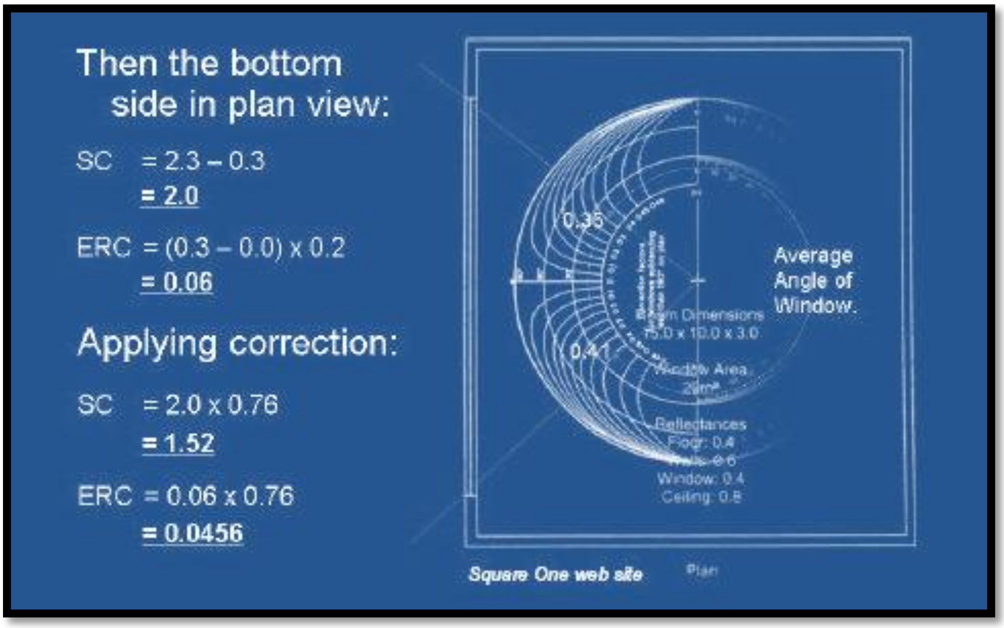

Figure 8: Step two (Reinhart C., 2005)

Then in order to calculate **internally reflected component,** simply the following formula is filled.

$$IRC = \% \quad \frac{0.85 \; A_p}{A_{is}\,(1- \; \rho_1\,)} \; x \; (K_C \; . \quad \rho_{wf} + 5\; \rho_{wc})$$

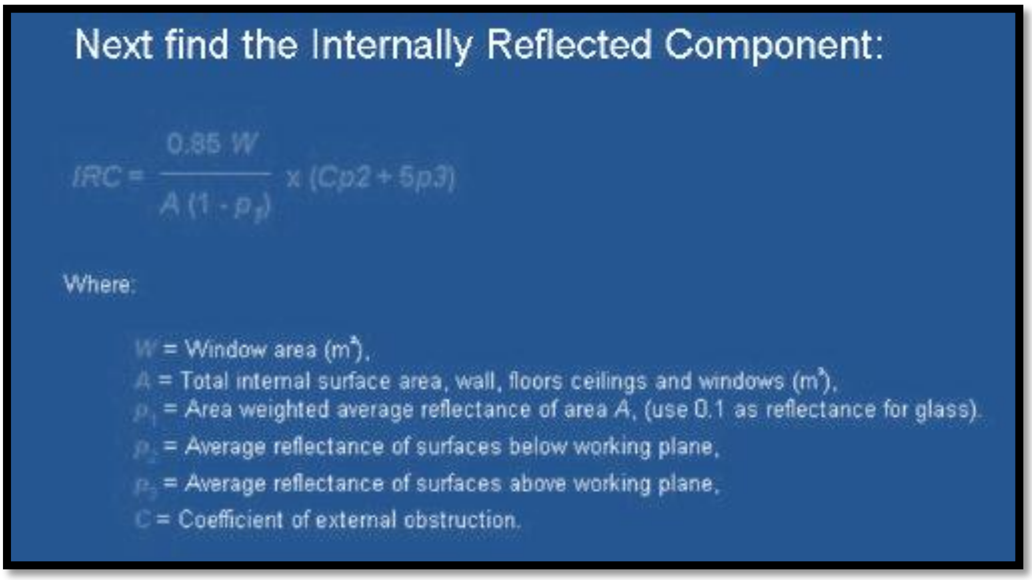

Figure 9: Step three (Reinhart C., 2005)

After finding three of the components, they are simply added up to calculate the **daylight factor**.

Figure 10: Step four (Reinhart C., 2005)

Therefore the daylight factor can be calculated manually by means of B.R.E protractors.

The attained value for the daylight factor is true for the case where there is no glass window or a frame is present therefore, there should be additional corrections to be applied to the achieved daylight factor value.

These correction factors are related to the type of glass used, cleanness of the window and the light transmission reduced by the frame. These corrections are crude values attain a more accurate estimate.

These values are shown in table 2, 3 and 4.

2.2.1.1.2 Method in Practice

The selected point is right in the middle of the room. Analyzing the case study by means of B.R.E protractors is described as followed:

Calculation for an overcast sky

Figure 11 illustrates the section of the design studio and values where the lines intersect the outer perimeter of the protractor. The addition of these values is the **initial sky component** value.

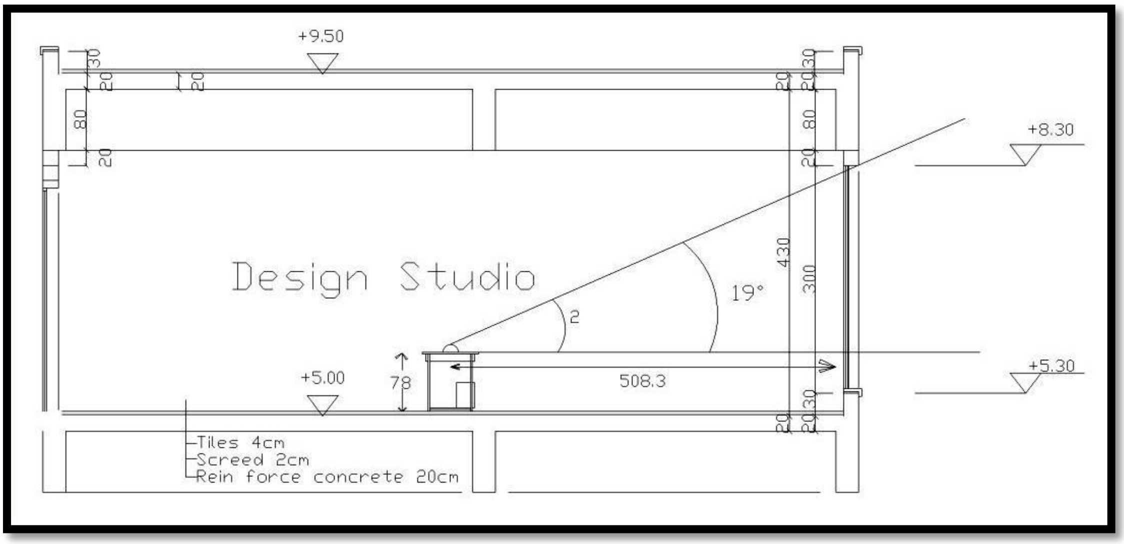

Figure 11: Section of the design studio (by author)

Therefore the achieved value is as followed:

Initial sky component = 2

Next step as it was mentioned in **method explanation** section is finding the sky component **correction factor.** The circle corresponding to "Average angle of window" on B part of protractor was found. The intersection of lines from the window sides on plan gives the sky component correction. The corrections were read from the scale on the inner most circles.

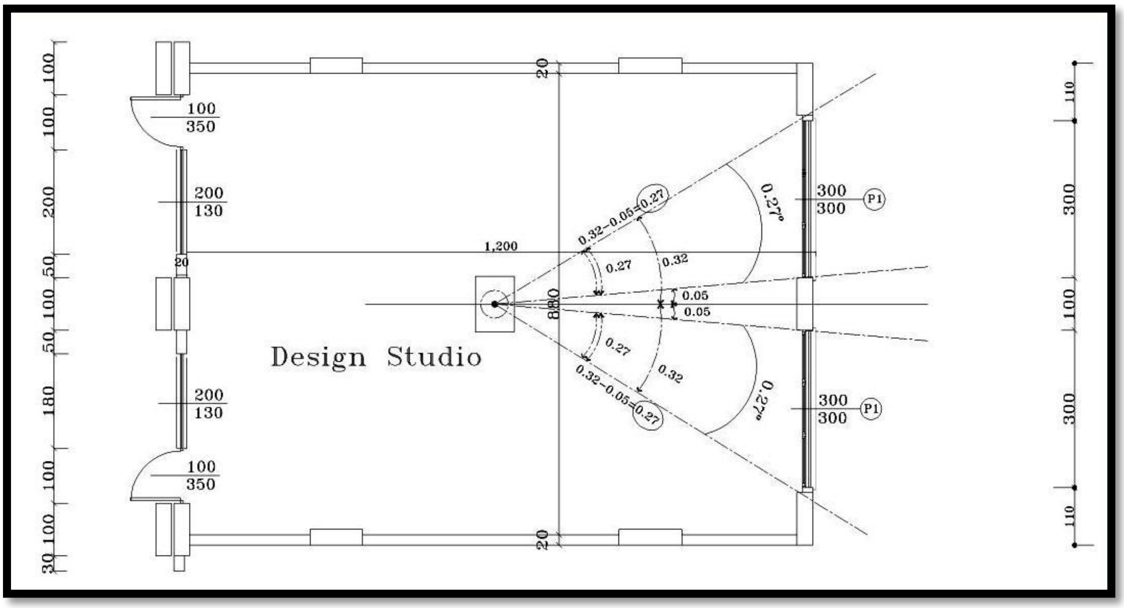

Figure 12: Plan of the design studio (by author)

According to the values found from the plan, the correction factor is as followed;

Correction factor = 0.27 + 0.27= 0.54

Therefore the **Sky component** is as followed;

SC = iSC x CF = 2 x 0.54 = 1.08

Finding out the **externally reflection component** is involved in the next step which is zero in this case study since there is no object surrounding the design studio.

In order to calculate the last component which is **internally reflection component,** the values which were achieved in the previous steps were put in the formula. The formula is as followed;

$$IRC = \% \quad \frac{0.85\ A_p}{} \ \times (K_C \ . \ \rho_{wf} + 5\ \rho_{wc})$$

A_{is} (1- ρ_1)

A_{p} = 2 x 9 = 18 m²

	Ceiling	Floor	Side & Back Walls	Window	Window Wall

$$\rho_1 = \frac{(105.6x0.55) + (105.6x0.4) + (141.04x0.55) + (18x0.07) + (11.61x0.55)}{380.61} = 0.487$$

$$\rho_{wf} = \frac{(0.78x24x0.0.55) + (105.6x0.4)}{380.61} = 0.138$$

$$\rho_{wc} = \frac{(3.52x24x\ 0.55) + (105.6x0.55)}{380.61} = 0.274$$

So the value of IRC is as followed:

$$IRC = \% \frac{0.85 \times 18}{380.61(1- 0.487)} \times (39 \times 0.138 + 5 \times 0.274) = 0.661$$

Therefore the **daylight factor** value is:

DF = SC +ERC + IRC = 1.08 + 0 + 0.661 = 1.741

“In this method it is required to do more correction for the glass type, cleanness of the window and the light transmission reduced by the frame” (Daylight factors: Split flux method). According the table 2, 3 and 4 the corrected daylight factor is as followed;

Corrected DF = 1.741 x 0.8 x 0.85 x 0.8 = 0.947

Table 2: Correction factor on the DF for the window cleanness (C_{wc}) (Longmore, 1968)

Environment	Window Slope	Room use: Clean	Room use: Dirty
Clean Environment	Vertical	0.9	0.8
	Sloped	0.8	0.7
	Horizontal	0.7	0.6
Polluted Environment	Vertical	0.8	0.7
	Sloped	0.7	0.6
	Horizontal	0.6	0.5

Table 3: Correction factor on the DF for the glass light absorbance (C_g) (Longmore, 1968)

Glass Type	Correction Factor for glass, C_g
Normal Flat window glass	1.00
Wired security glass	0.95
Translucent glass	0.80 – 0.95
Double glazing	0.85
Transpared plastic plates	0.65 – 0.90

Table 4: Correction factor on the DF for the prevention of light by window frame (Longmore, 1968)

Window Type	Correction Factor for window frame, C_f
Metal Windows	0.80 – 0.85
Metal Window in timber frame	0.75
Timber window	0.65 – 0.70

It is necessary to mention that the step of daylight factor correction was performed only in this method since the other methods which were used in this study are for the purpose of using in early design stages. The case studies are considered as new built environments without fading or pollution. Although by importing more detailed values to the software, the accuracy of the correction can be possible.

Calculation for a uniform sky

Same principles are applied. However in this case, daylight protractor number one, which is special for uniform sky, is used.

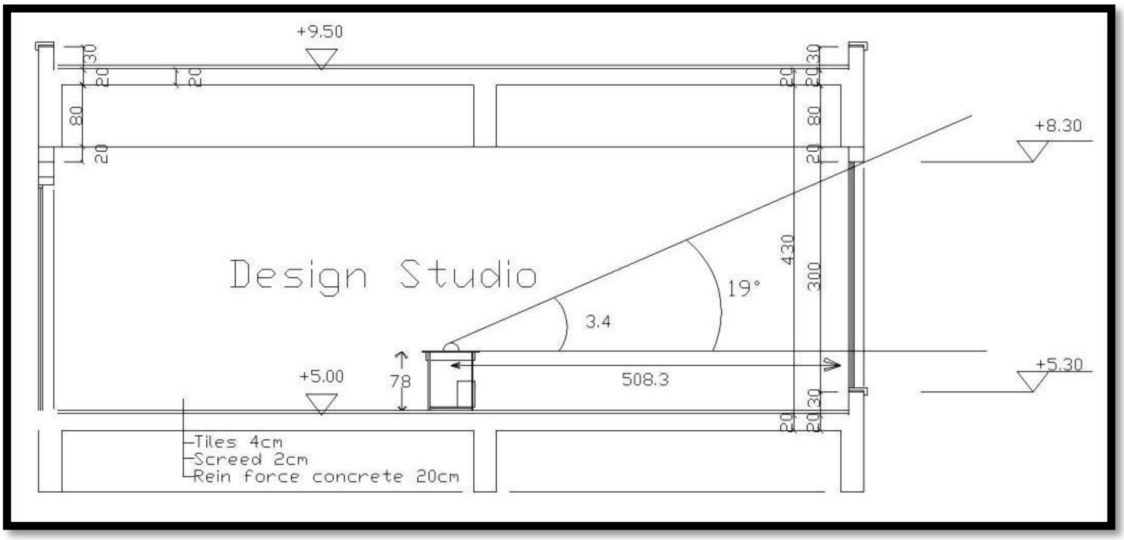

Figure 13: Section of design studio (by author)

Initial sky component = 3.4

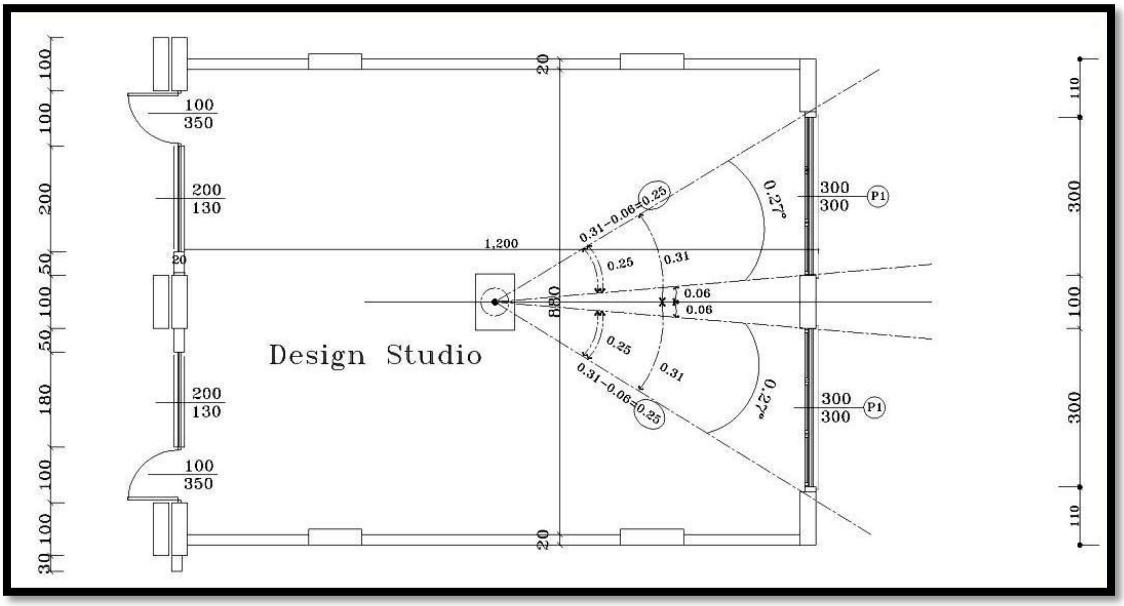

Figure 14: Plan of the design studio (by author)

According to the values found from the plan the correction factor is as followed:

Correction factor = 0.25 + 0.25= 0.5

Therefore the **Sky component** is as followed:

SC = iSC x CF = 3.4 x 0.5 = 1.7

IRC value is also same, therefore the **daylight factor** value is:

DF = SC +ERC + IRC = 1.7 + 0 + 0.661 = 2.361

The corrected daylight factor according to table 2, 3, and 4 will be:

Corrected DF = 2.361 x 0.8 x 0.85 x 0.8 = 1.284

2.2.2 Computer Calculation

The performance of day lighting in a building can be analyzed by various computational methods.

Different steps should be considered during the simulation in order for a designer to be able to evaluate the daylight inside the building (Goulding, Lewis, & Steemers, 1992);

- There are different types of sky such as: overcast, clear, average etc. According to the type of sky there will be a simulation of the light source plus the location of the sun.
- The outdoor environment plus any obstruction or external elements and the light reflection from any particular surfaces should be considered.
- Transmission of light through any daylighting devices, louvers etc.
- The existing light reflection of any particular surface.
- Presentation of the final light distribution in different terms such as daylight factor or illuminance etc.

Nevertheless, most software has a much simpler process by making less detailed assumptions such as (Goulding, Lewis, & Steemers, 1992):

- Generally just one room is going to be studied.
- An assumption will be made that the form of the space will have a simple geometry such as a rectangular shape with less than twenty flat surfaces.
- Some of the software assumes the surfaces to be mostly diffusing, whereas other software considers the mirrors and other types of surfaces.

- The quality of light reflection simulation is different in each program.
- There are different results depending on the software. Some are in the form of isolux or daylight factor curves. Some have graphical improvements and number of them use color graphics and rendering in order to present the pictures of the rooms.

The analysis of the case study is done by two different computer methods which are Ecotect and Radiance.

2.2.2.1 Autodesk Ecotect Analysis 2010: Introduction to the Method

Ecotect analysis 2010 is a detailed program which helps the user build a rough model of the chosen space, simulate different conditions related to the space , measure and improve environmental factors such as (Products:Ecotect Analysis 2010);

Shadows and reflections: it displays the sun's position and path relative to the model which changes according to the date, time, and location by inputting the particular weather data file to the software. It also display shadows over the model and view how sunlight enters through openings and moves around within a space and many other detailed analysis related to reflectors (Products:Ecotect Analysis 2010).

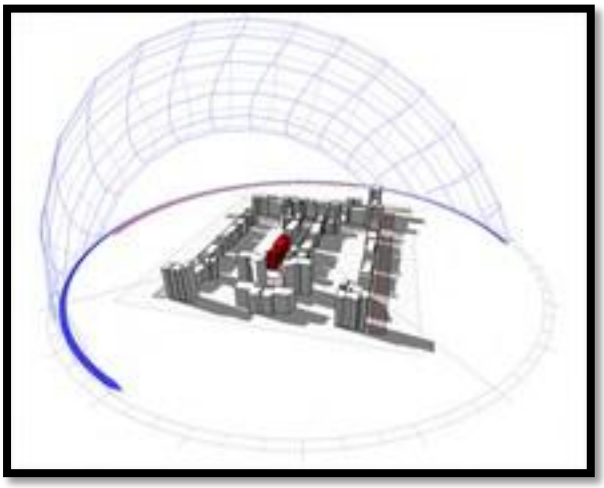

Figure 15: Shadows and reflections (Products:Ecotect Analysis 2010)

Shading design: With its three dimensional modeling ability, it provides the chance of creating various shading devices whilst examining and calculating the amount of solar radiation that will hit any part of the design (Products:Ecotect Analysis 2010).

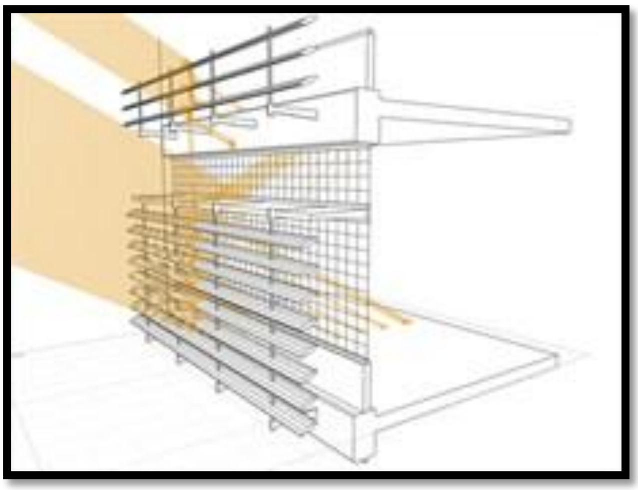

Figure 16: Shading design (Products:Ecotect Analysis 2010).

Solar analysis: It creates an overview of the whole building with the sun being a part of the overview and any solar radiation that goes through the openings or any other source. It can calculate solar availability over any spot according to the time, date and season (Products:Ecotect Analysis 2010).

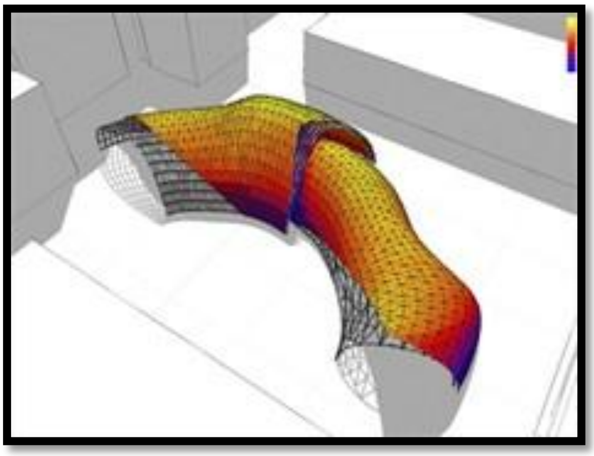

Figure 17: Solar analysis (Products:Ecotect Analysis 2010).

2.2.2.1.1 Method's Explanation

Since this calculation was a software based method, it was very complex and a great deal of research went into learning how to operate the program in order to start using the software and obtains the desired results.

After learning the software, a three dimensional model of the design studio (case study) was created which includes the real material of any surface of the space plus any obstruction or artificial lighting if existed.

The second stage was finding the weather data related to the location of the building and import it to software in order to be able to find the exact sun location on a specific time and date. This data can be obtained free of charge through the US Department of Energy website in a special format capable of being imported to the software.

At this stage the software provides a three dimensional image of the building's surrounding and any existing solar radiating through the building as it is shown in Figure 18.

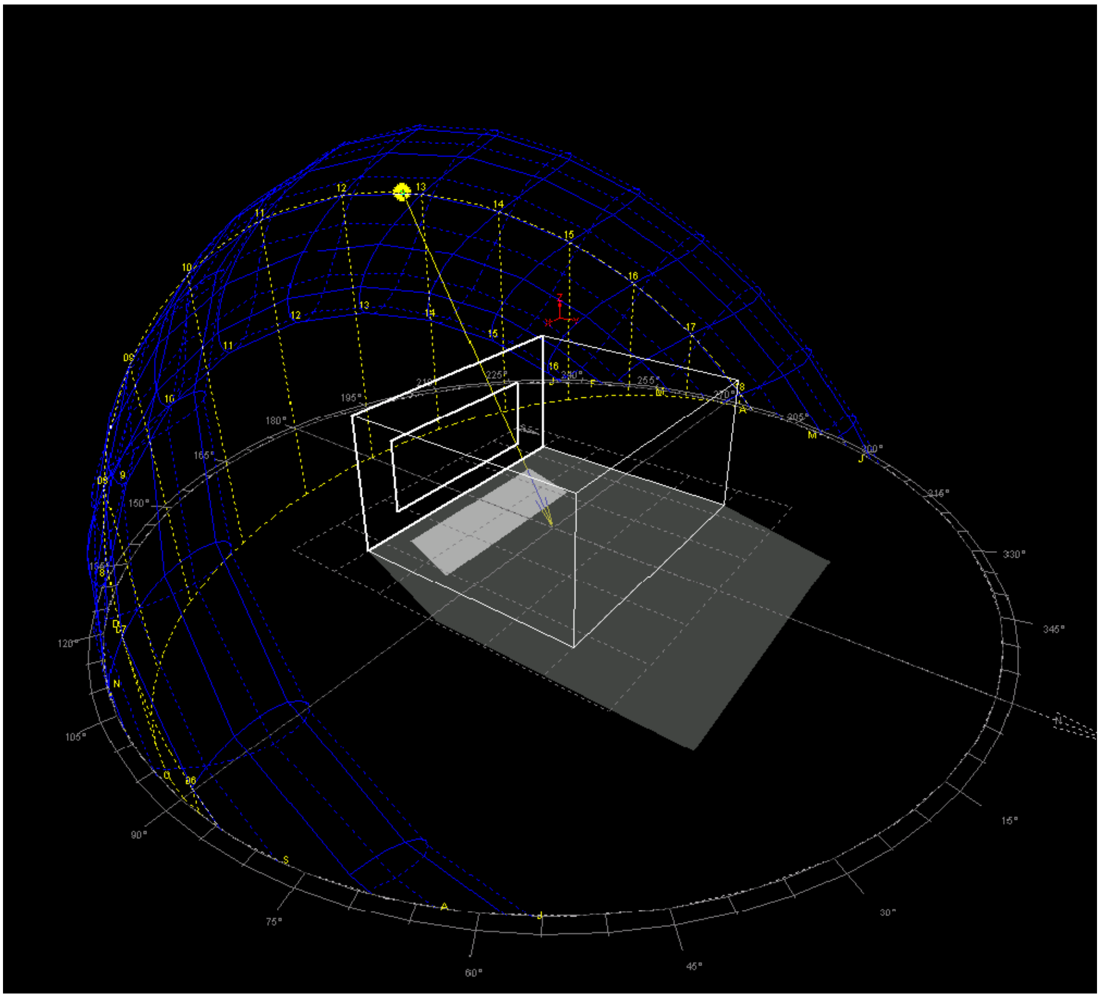

Figure 18: Resulting building design form (Reinhart, 2005)

At the next step, more daylight analysis will be shown including how to calculate the Daylight Factor.

As it is shown in Figure 19, different colors illustrate the different level of daylight factor inside the room. The percentage of daylight factor in different zones is shown in the legend.

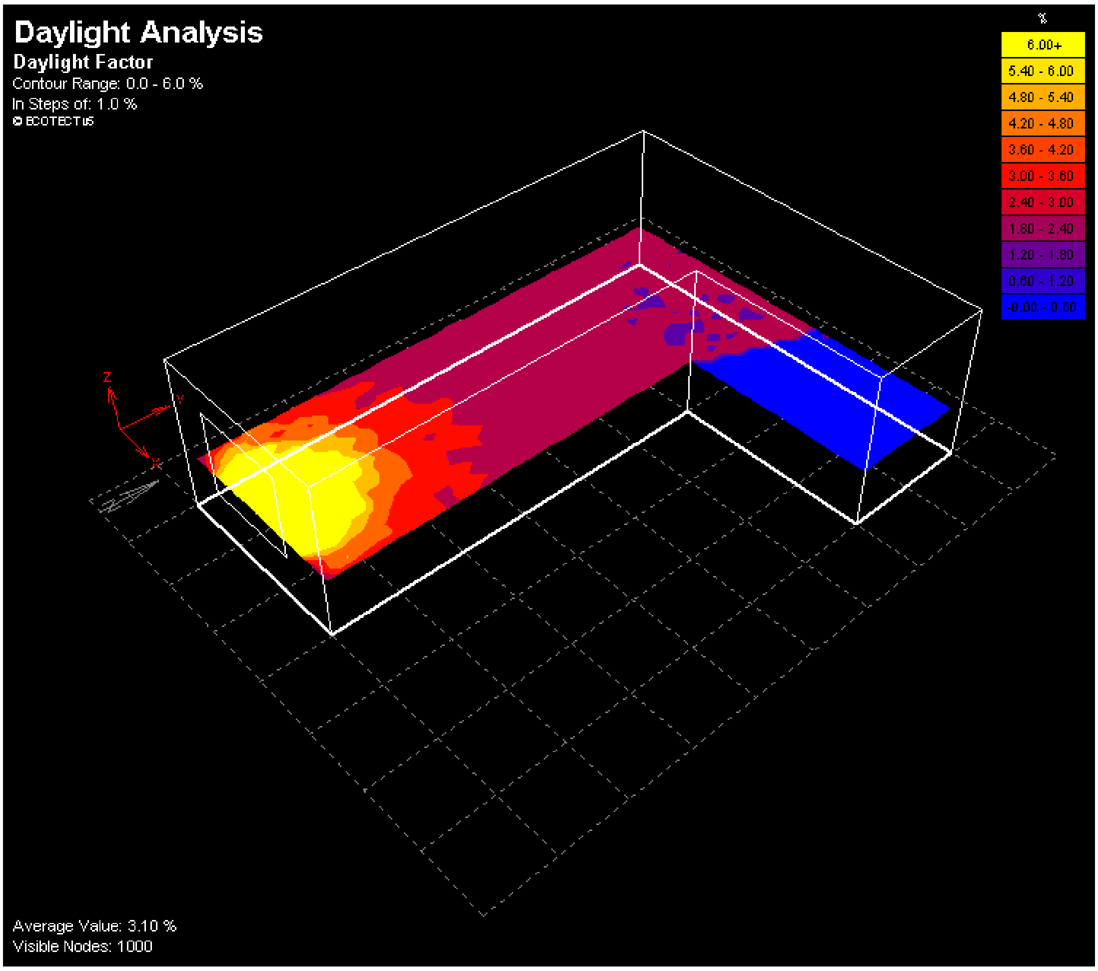

Figure 19: Daylight analysis (Reinhart, 2005).

A question may arise asking what exactly the sky assumption of this software is.

The answer to the question is that this software does not only provide users the chance of calculating the daylight factor, but it has the possibility of selecting different sky conditions to suit their needs.

Lastly, the software provides a photoelectric sensing effect screen, which visualizes and performs advanced calculations of the daylight factor for any specific point defined by its user. Detailed charts are created as shown as shown in Figure 20.

“This photoelectric sensing effect screen produced two graphs that linked potential annual lighting energy savings with the zone average daylight factor. One graph assumes the ability to dim the lighting based on the current level whilst the other assumes lights are simply switched on or off as appropriate.

The aim of this analysis is to give an indication of likely savings. Obviously the exact type of installed control system and its settings will ultimately determine savings; however this calculation will tell if it is worth pursuing such a design solution” (Autodesk Ecotect Analysis 2010 help). According to the graph the designer has the opportunity to follow the percentage of daylight factor available on any point at any time of the year.

Figure 20: Photoelectric sensing effect chart (by author)

It is obligatory to mention that one of the biggest advantages of this software is that after modeling and providing the right information of the room such as the weather data, there is the possibility of exporting that model according to the required needs into several other programs to continue the calculations.

Different software selections are as followed:

- VRML
- RADIANCE/DAYSIM
- POV-Ray
- AUTOCAD DXF
- WINAIR4 (CFD)
- HTB2 (THERMAL)
- ENERGYPLUS
- ESP-r
- DOE-2 / eQuest
- SBEM / SAP 2005
- NIST FDS (CFD)

2.2.2.1.2 Method in practice

Calculation for overcast sky

At first, the three dimensional model of the building was created as it is shown in Figure 21.

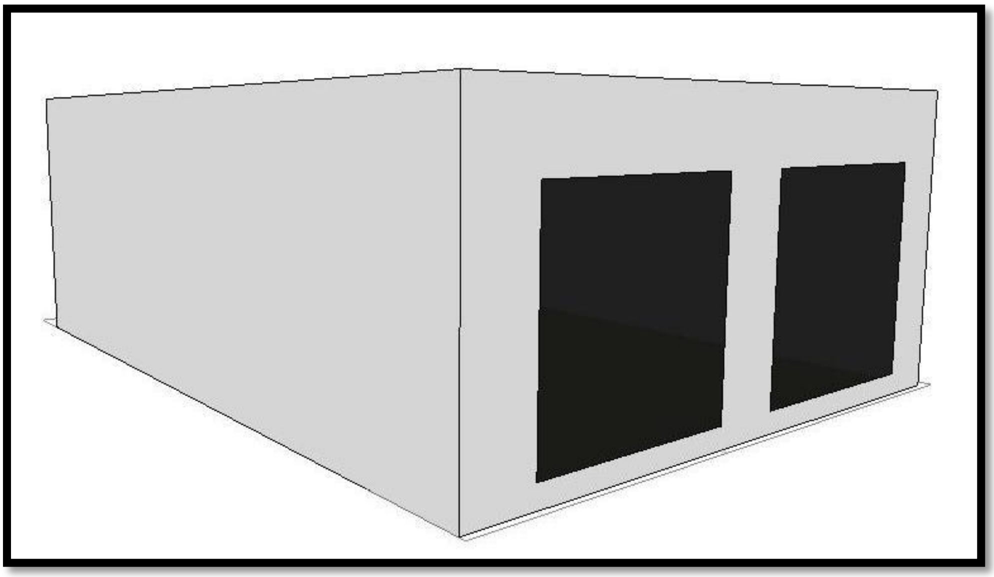

Figure 21: 3D model of the case study (by author)

The existing materials of case study are applied to the model element surfaces. As illustrated in Figure 22, the material type, the thickness, the density and many other details can be applied to the model. However, this step doesn't make any difference in the appearance of the model since this software is not for the purpose of design or decoration.

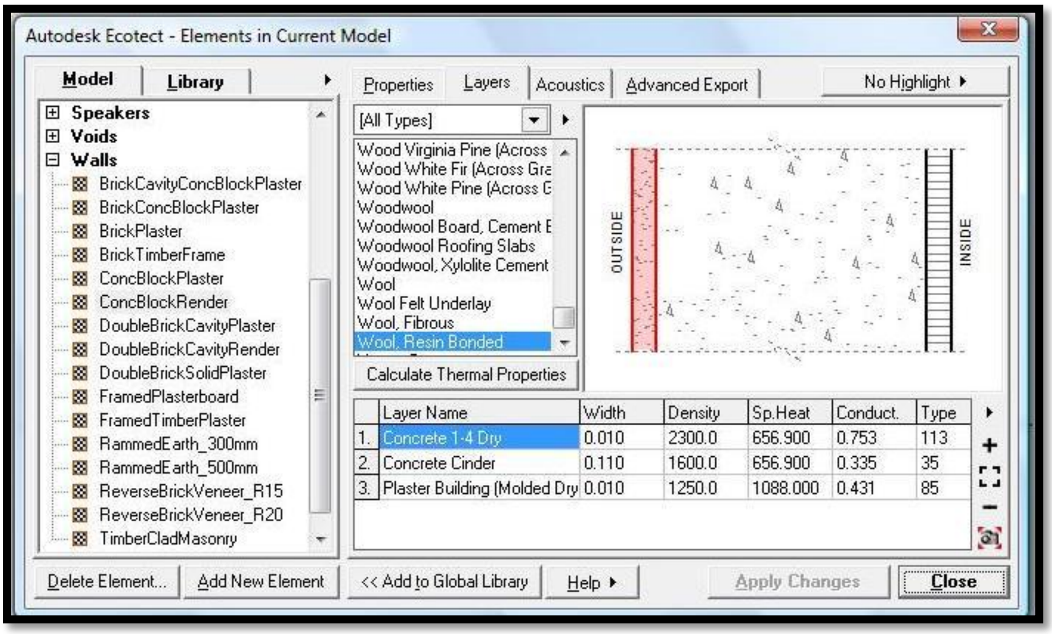

Figure 22: Material assignment (by author)

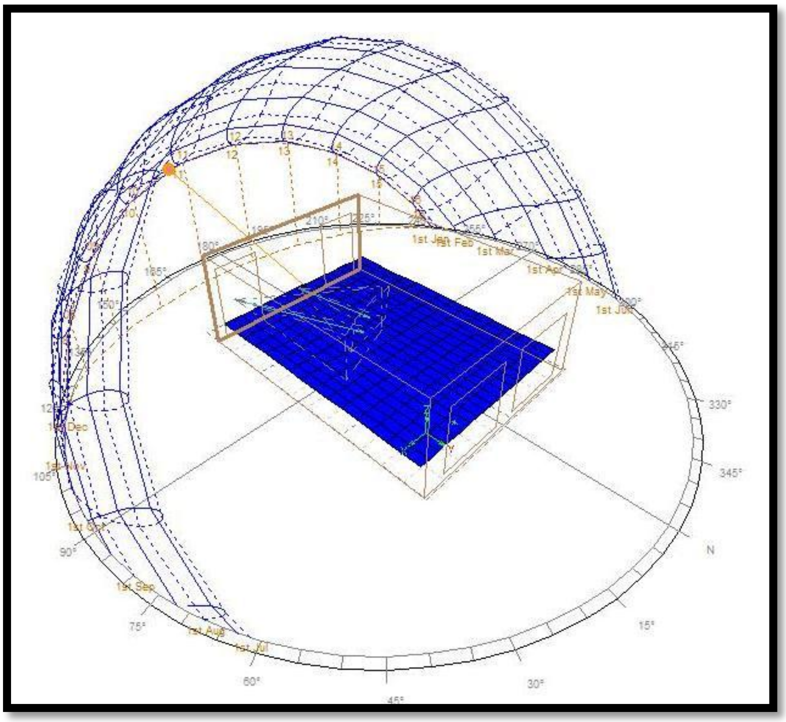

Figure 23: Daily and annual sun path in 3D editor window (by author)

At this stage, the question may still linger about how the user can define the weather and climate changes of that particular space?

Ecotect easily guides the user to a website named **Energy plus energy simulation software** and navigates to a section named “weather data”. After loading the weather data of the location of the case study, following images are created which illustrates the daily sun path as well as annual sun path.

The windows of this studio are facing north. However, since the sky assumption of this study is overcast sky, it really doesn’t make any changes in calculating the daylight factor.

Although it is required for the studies which are done according to other sky conditions, but it is not in the scope of this research so it is not necessary.

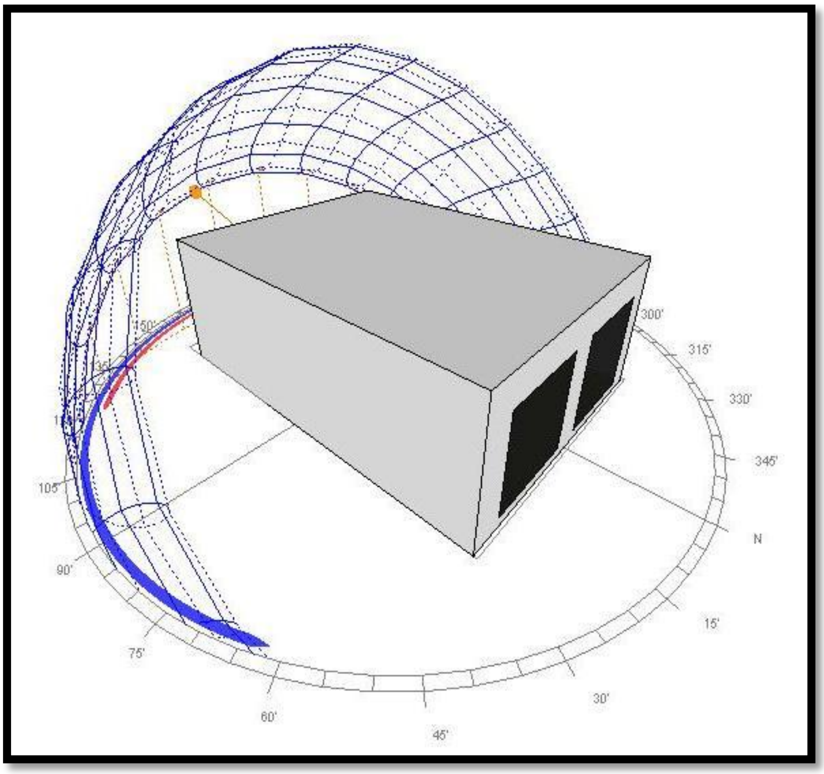

Figure 24: Daily and annual sun path in the **visualize** window (by author)

The software provides the chance of analyzing the case study through different fields such as thermal analysis or acoustics etc.

However, since the base of this analysis is occurring around the lighting field, only the daylight analysis will be focused on.

The result of this analysis is visualized in two different forms.

First type as shown in Figure 25 is the same 3D model as well as visualizing the percentage of existing daylight factor by various colors on the specific plane during different times of the day or year.

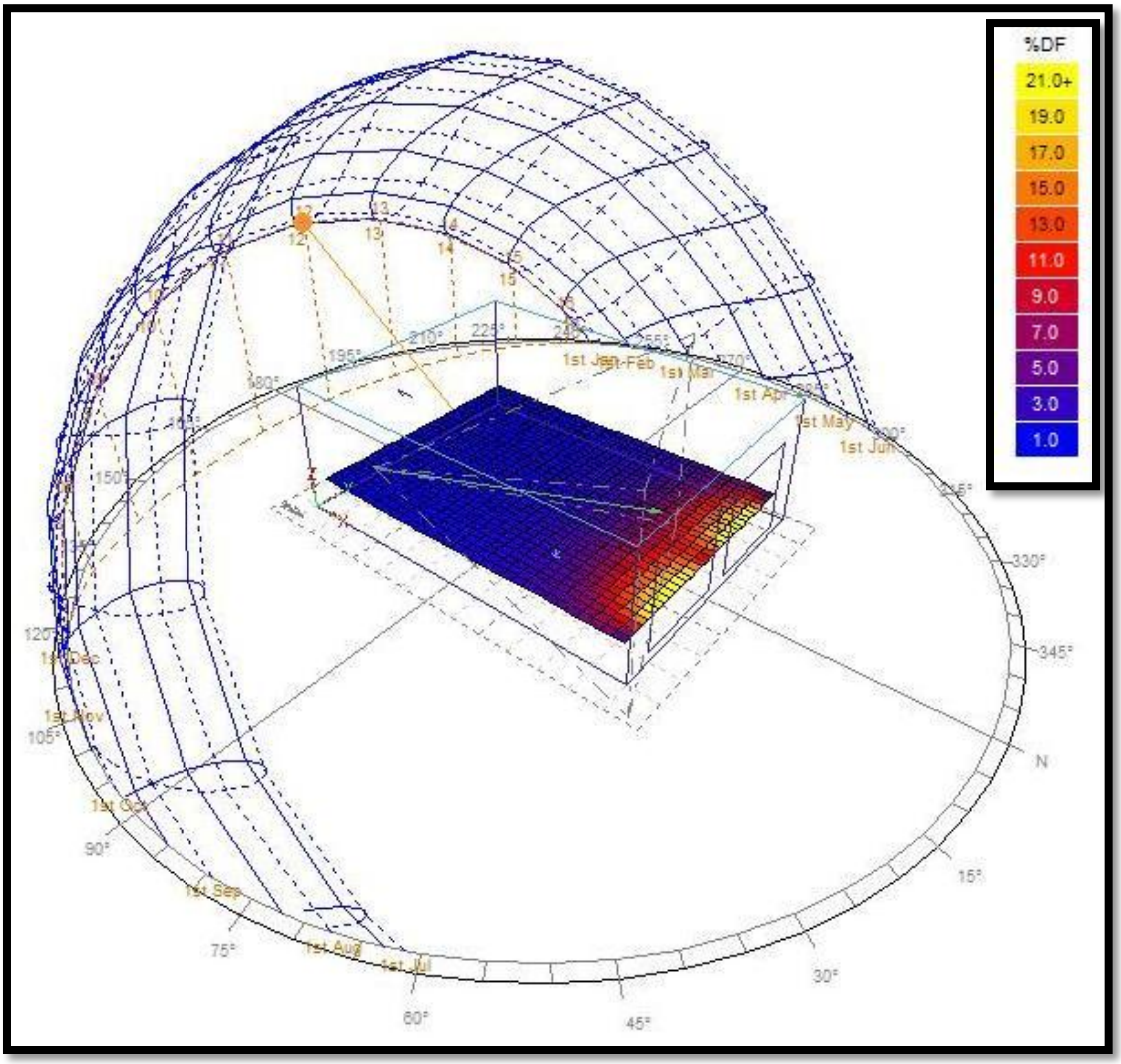

Figure 25: Daylight factor analysis for overcast sky (by author)

The second type of daylight analysis is the more advanced way of calculation in this research. This type is the same photoelectric sensing effect chart which was mentioned in **method explanation** section.

The result of this advanced day lighting calculation is shown in Figure 26.

At this stage, it’s possible to calculate the daylight factor at the centre zone of any particular point. So the calculation was done for the exact same point, located in the centre of the room where the B.R.E protractors calculation method was done.

The illuminance for this calculation was 400 Lux. Since the case study is a design studio, Ecotect automatically assigned a valid value to the office or workshop type of space. The daylight factor percentage is highlighted in Figure 26.

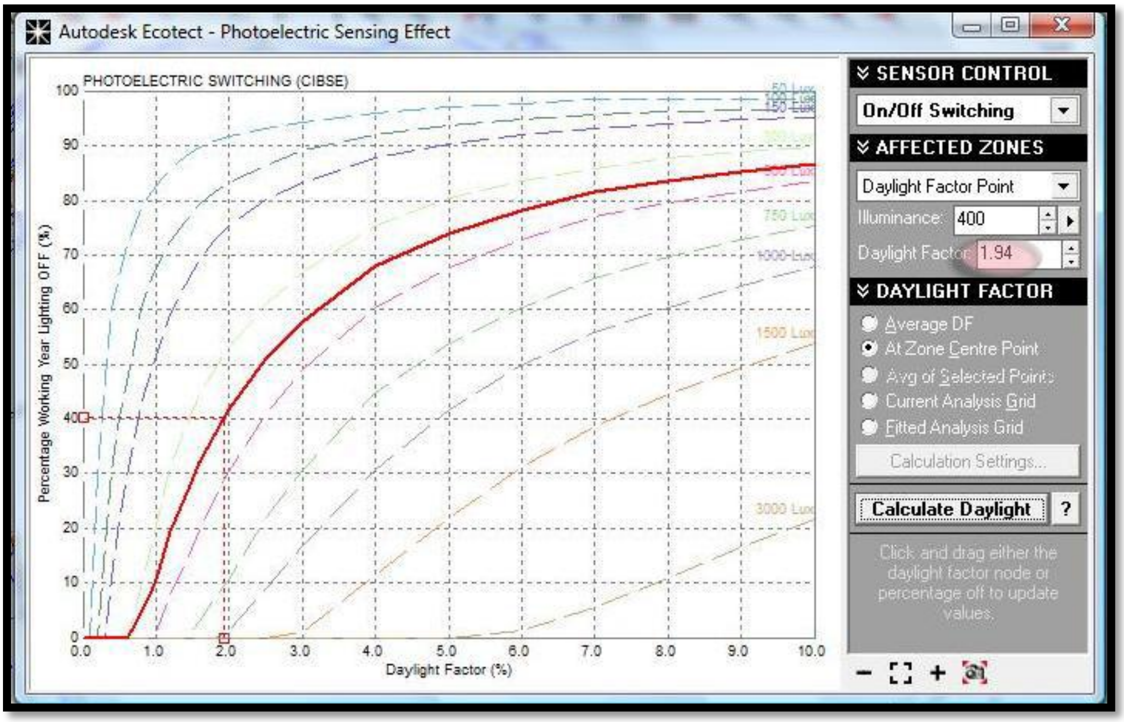

Figure 26: Daylight Photoelectric sensing effect chart for overcast sky (by author)

As it's illustrated, the daylight factor value for the selected zone which is the selected point in the centre is as follows;

DF = 1.94

It is necessary to mention that changing the illumination level in this software does not alter the final daylight factor value given. The illumination can be changed according to the preferred study function and condition.

Calculation for uniform sky

This is effortless since the model of the building with imported information such as weather data and material is ready.

In the calculation details, type of sky will be defined as overcast.

Daylight factor analysis is shown in Figure 27.

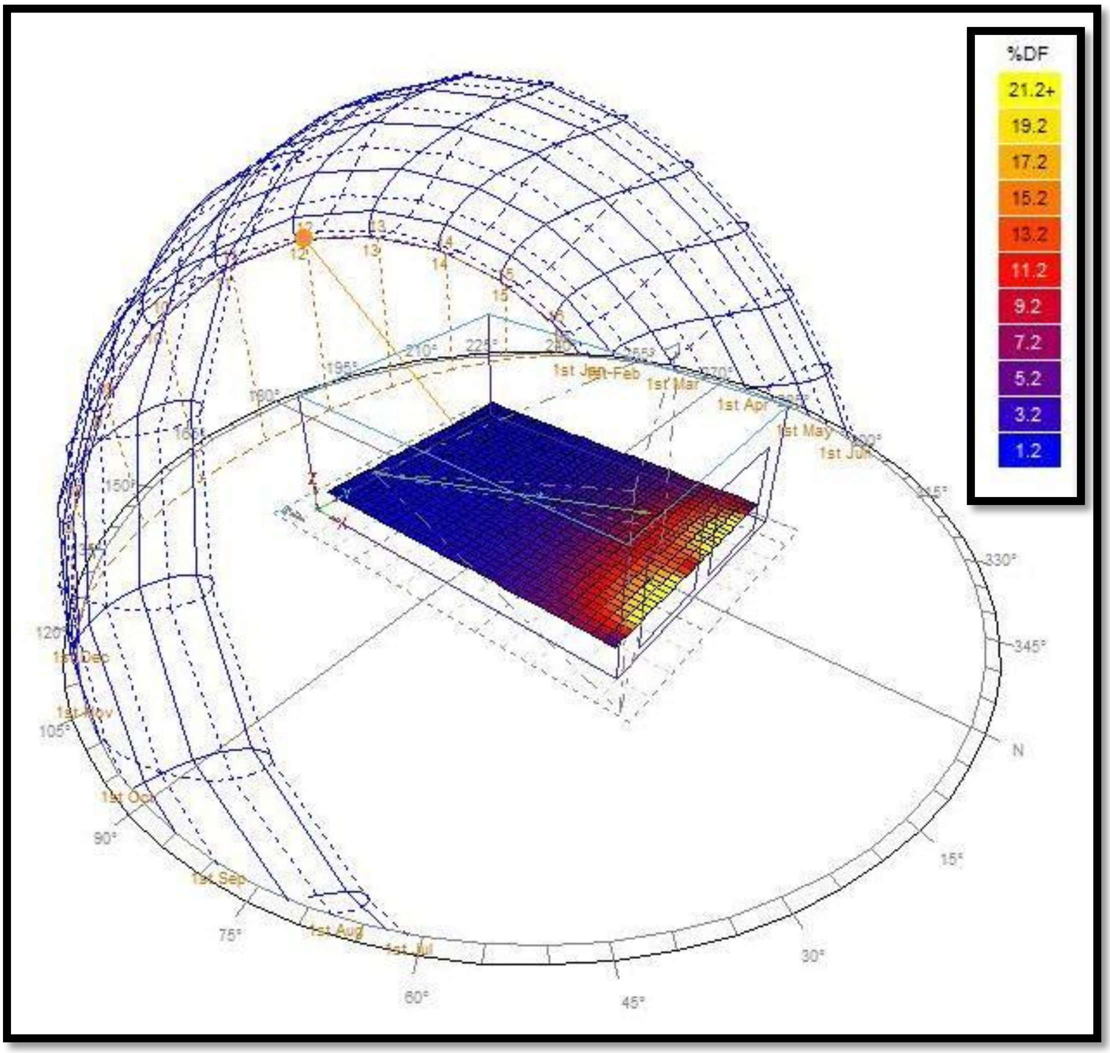

Figure 27: Daylight factor analysis for uniform sky (by author)

Daylight factor percentage calculated for uniform sky is same as overcast sky value as it is shown in the figure below.

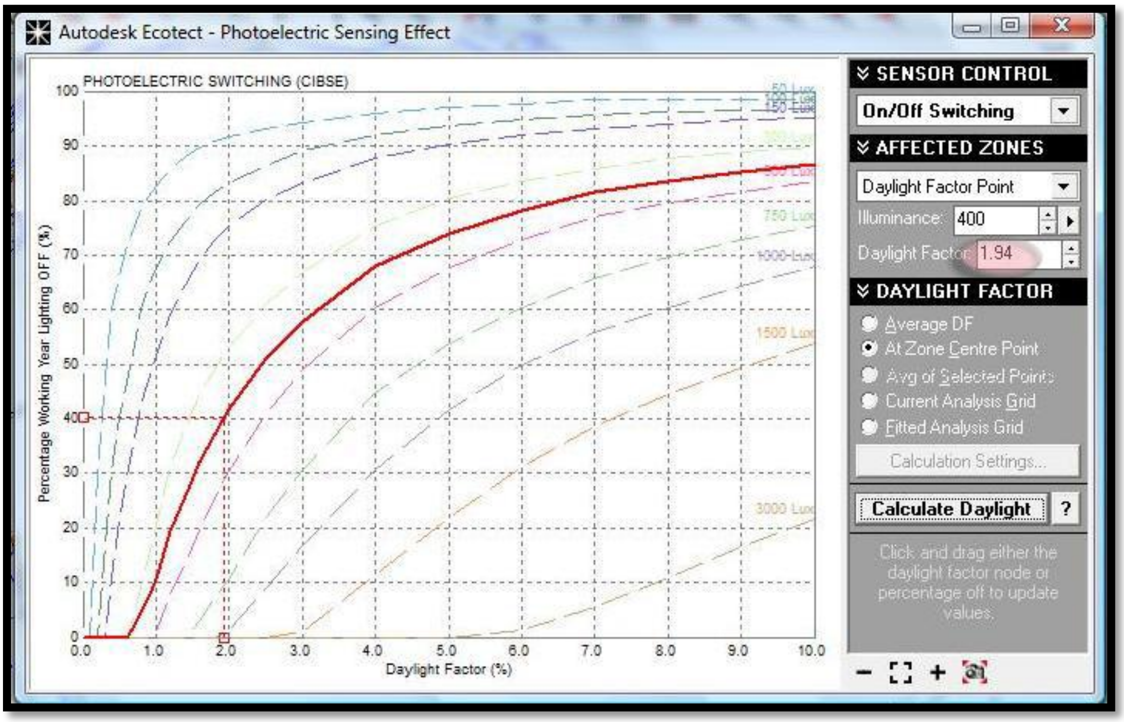

Figure 28: Daylight Photoelectric sensing effect chart for uniform sky (by author)

As displayed above, the daylight factor value for the selected zone which is the located point in the centre is as follows;

DF = 1.94

2.2.2.2 Radiance: Introduction to the Method

“The Radiance software is a distributed ray tracing package developed by Greg Ward Larson, then at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. The software implements a distributed, or "stochastic", ray tracing method, which is optimized to simulate the diffuse distribution and transmission of light in the built environment” (Lighting Design Glossary).

This software can create photorealistic images. It does not store subjective brightness values, however it considers the luminance on all visible surfaces and will lead the process to achieve the day light factor value (Lighting Design Glossary).

Figure 29: Ambient bounce image (Basic radiance tutorial)

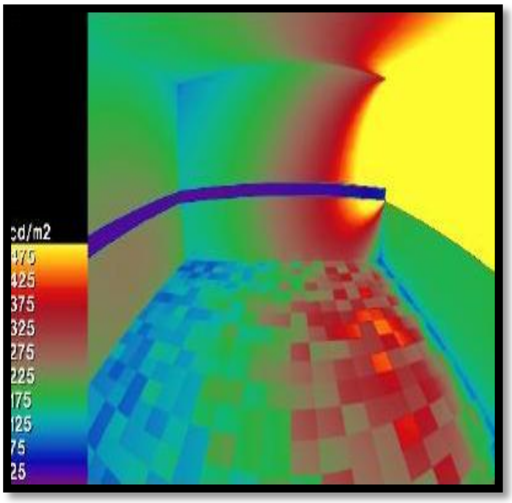

Figure 30: False color image (Basic radiance tutorial)

2.2.2.2.1 Method Explanation

In this study, instead of re-inputting and reconstructing the prediction model from scratch, the model of the studio in Ecotect software can be exported directly into Radiance for more complex and physically daylight simulation and photorealistic images. Therefore, as a result, similar images as shown in Figure 29 and 30 were created. In addition to the images, the chance of calculating daylight factor on any point of any surface is presented to the user.

2.2.2.2.2 Method in Practice

The created model in Ecotect software including the applied material on the surfaces was exported to the Radiance software.

A number of photorealistic images were created. These images were produced according to the camera positions set inside the room within Ecotect.

It simulates the existing condition of daylight radiation through the building from each point of view.

The captured images are a group of various different purposes taken for overcast and a uniform sky. Each individual image has its own purpose.

The first image which was created by Radiance enables the user to read the percentage of daylight factor. The values can be attained by clicking on a particular point on any surface of the image, then the daylight factor at that point appears as shown in figure 31 and 32.This image shows that the further away a surface is from the window edge, the percentage of the daylight factor decreases. The accuracy of the location of the chosen points is not very high since it’s just a perspective image of the interior of the room, but it estimates the right value if clicked on the right point.

On the other hand in order to estimate the daylight factor on the exact selected point same as the others, an object as table was created in the exact same place with same height in Ecotect and was exported to Radiance. Therefore by clicking on the center of this object a rough value of daylight factor can be achieved. Since the output characteristics of this method are purely images which work with the quality of daylight and daylight factor, they do not represent the exact quantity.

As it is shown in figure 33 and 34 the daylight factor value is 2.2% for overcast sky and 3% for uniform sky.

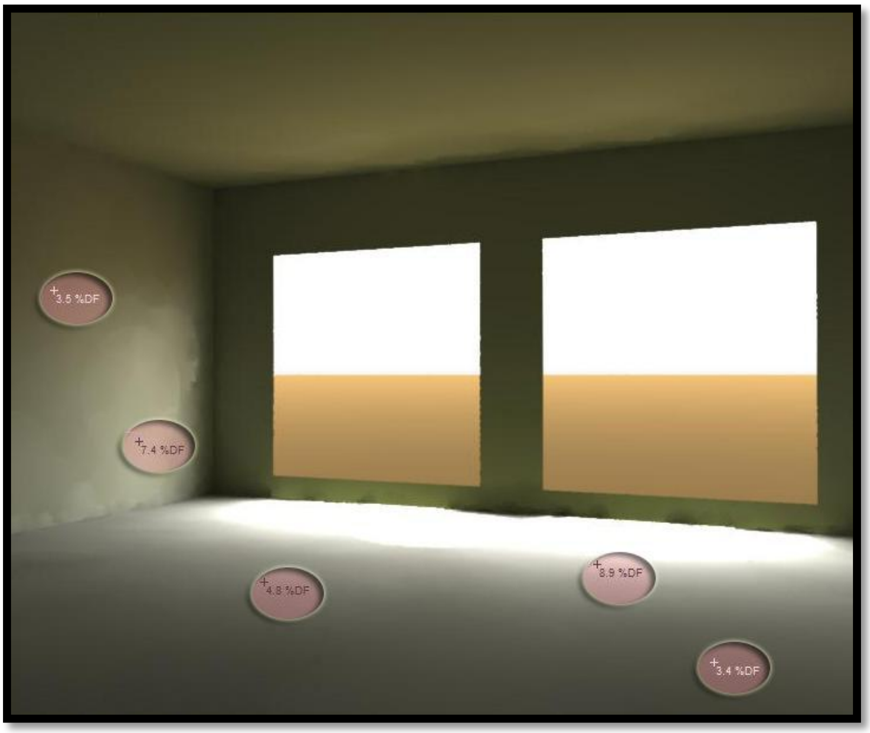

Figure 31: Basic image created by Radiance for overcast sky (by author)

Figure 32: Basic image created by Radiance for uniform sky (by author)

Figure 33: Daylight factor value in Radiance for overcast sky (by author)

Figure 34: Daylight factor value in Radiance for uniform sky (by author)

Human Sensitivity as it is shown in figure 35 and 36 is another type of image which is “Similar to an exposure adjustment but uses nonlinear and linear filters to mimic human visual perception. This tool compresses the dynamic range so that most of the details in a high-contrast image may be displayed simultaneously, similar to the visual experience one may have in the actual space” (Mischler, 2003).

Figure 35: Human sensitivity image for overcast sky (by author)

Figure 36: Human sensitivity image for uniform sky (by author)

In addition, this image is an abstractive way of visualizing the contrast of light and shade which human eyes can see by looking from that point of view towards the window. It simply manipulates the way human eyes catch the brightness of daylight. It is brighter closer to the window where daylight penetrates into the building and is darker towards the back of the room which is darker.

False color as it is shown in Figure 37 and 38 is also one of the images being produced by Radiance. This image enables the user to visualize invisible daylight radiation by using certain colors to create a contrast in order to ease the readability of the image (Solar systematics).

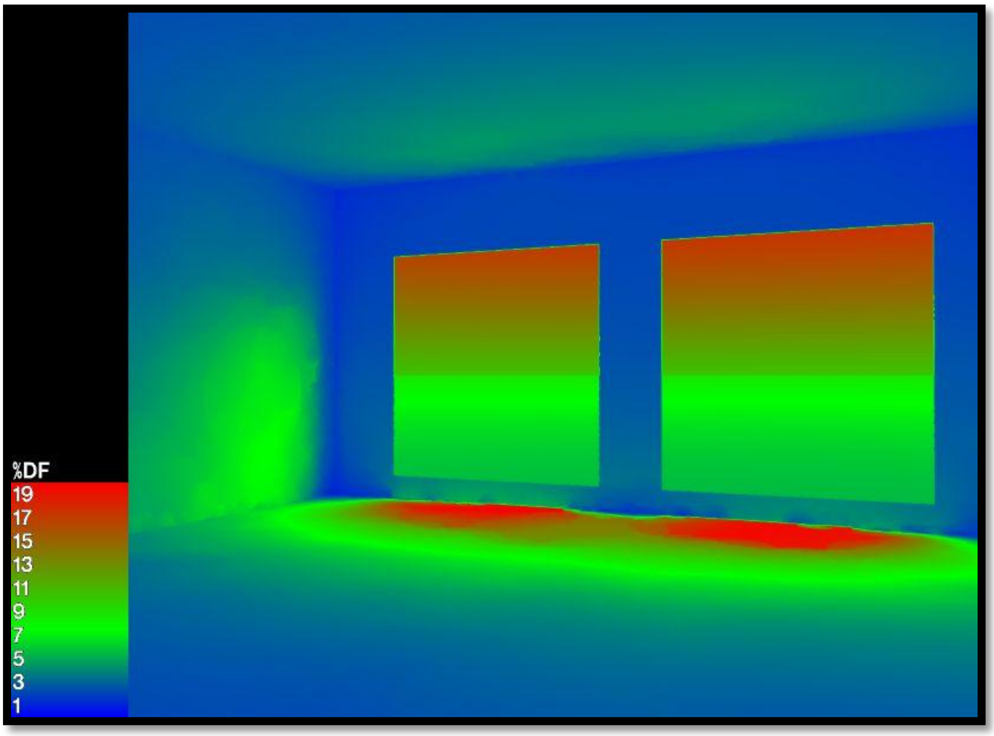

Figure 37: False color image for an overcast sky (by author)

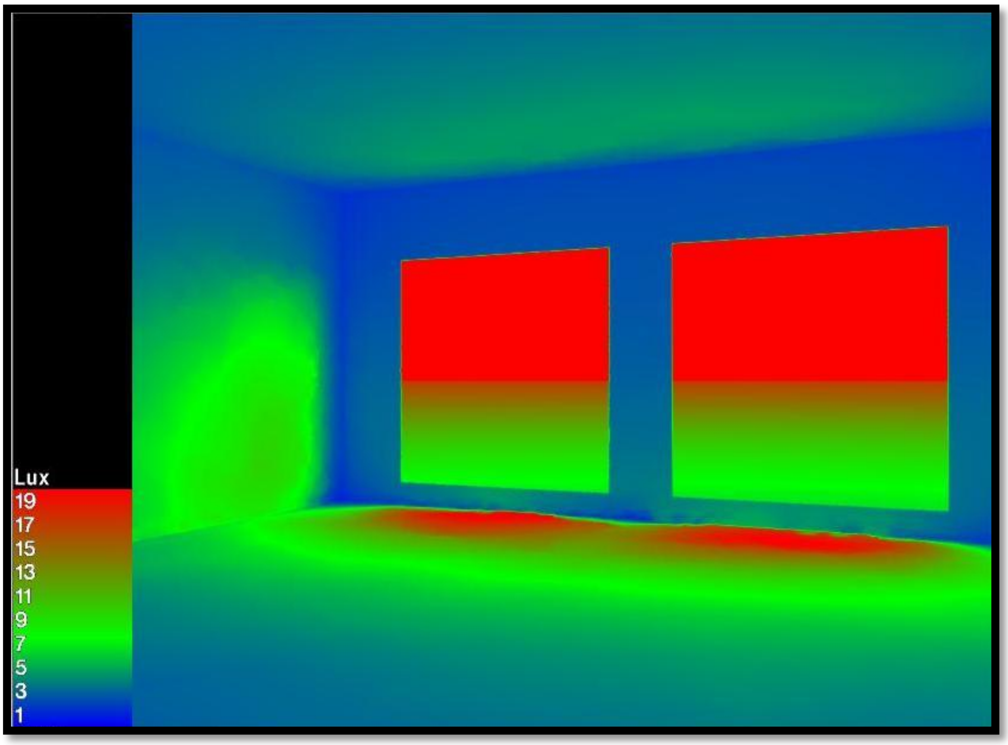

Figure 38: False color image for a uniform sky (by author)

And the last image produces **contour lines.** As shown in Figure 39 and 40 “contour line image is similar to false color. Both output images with quantitative measurements. Contour line draws demarcation lines in equal steps, according to number of divisions specified, between zero and the maximum value. Unlike false color the resulting image will contain colored lines of equal value overlaid upon the true color luminance or illuminance image” (Mischler, 2003).

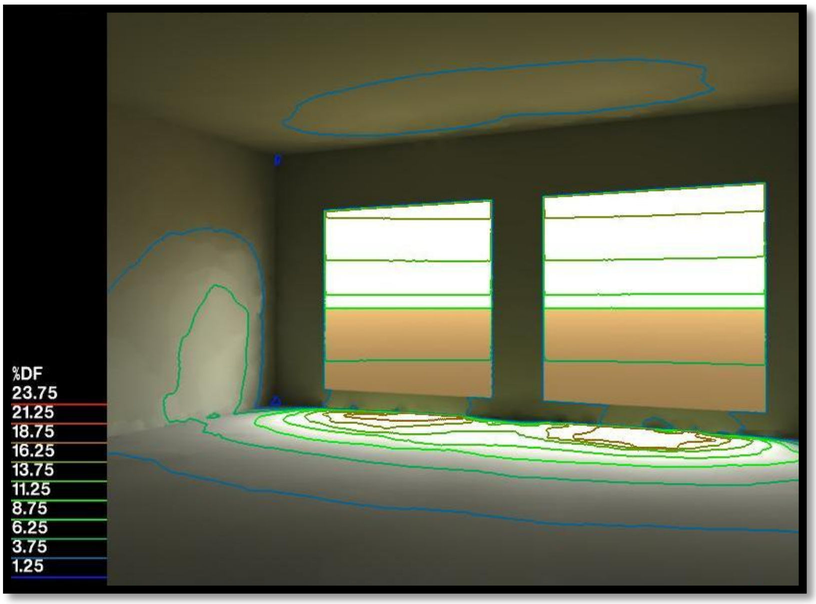

Figure 39: Contour line image for overcast sky (by author)

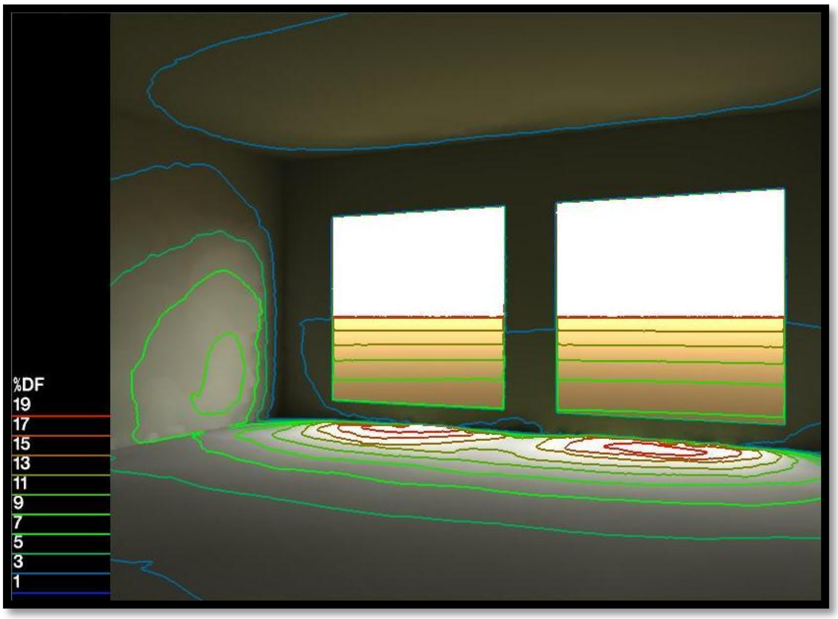

Figure 40: Contour line image for uniform sky (by author)

Since the results of this software are in the form of images, there is no chance of creating a particular zone or spot for exact calculation the same way as Ecotect does. Although it does an excellent job by enabling the user to stimulate the specific space which was captured by the placed camera to envision how it is going to look.

2.2.3 On-Site Evaluation

There are a wide range of devices which can be utilized in order to calculate the daylight factor either within or outside the building. These illuminance meters have been developed with the help of significant technological advances.

Illuminance Meter T-H1: Introduction to the Method

There are various versions of the illuminance meter device that has been developed through the years.

The particular type which is used in this research is called **Illuminance Meter T-H1.**

This device is a light measuring instrument which was introduced in 1979.

Figure 41: Illuminance meter T-H1 (by author)

"Light meters measure illumination in different terms such as luxes (lx). A lux is equal to the total intensity of light that falls on a one square meter surface that is one foot away from the point source of light. Most light meters consist of a body, photo cell or light sensor, and display" (Lux meters).

This device is from a company called Konica Minolta Sensing. This company has a reputation for the reliability and longevity of their instruments.

The question of why this specific model was chosen for this research may come up. The reason is that these devices are quite pricy and the only available model for this research was this particular model. The reliability of this model is unprecedented.

2.2.3.1 Method Explanation

Each light measuring device provides the user with an instruction manual booklet, which explains step by step how to do the measurement.

The device should be laid down horizontally on a flat surface. All the artificial lights should be turned off. If there are any obstructions covering the openings to the outside should be removed. The user should try to read the device from as far away as possible, this is due to the fact that the heat and the color of the users clothing could affect the measurement and give inaccurate readings.

The measurement should be repeated then the average value should be calculated to get an accurate reading for a specific time of day when the measurement occurred. In addition to the date and time of the day, condition of sky and type of weather should be noted as this can influence the measurement as well.

2.2.3.2 Method in Practice

The device is small, light and portable therefore, there is the chance of carrying it to the design studio (case study) and carry on the measurement at any time.

Measurements are taken once for an overcast sky and another for a clear sky.

The measurement is done at the point situated in the centre of the room, in exactly the same position as the other methods. In addition to the interior point calculations, it is also performed outdoors on an opening adjacent to the studio windows. The result of this calculation is shown in table 5.

Table 5: On site evaluation using light measurement instrument (by author, 2010)

Sky type	Date	Weather data & Outdoor situation	Time	Indoor value	Time	Outdoor value
Overcast	8-Jun	•Somewhat rainy •Thunder •Outdoor calculation facing bushes	•13:43 •13:44 •13:45	-357 Lux -361 Lux -359 Lux ✓ Average value: 359Lux	•13:46 •13:47 •13:48	-21375 Lux -2 1425 Lux -21400 Lux ✓ Average value:21400Lux
Uniform	22-Jun	•No cloud •Sunny •Slightly windy •Outdoor calculation facing bushes	•13:43 •13:44 •13:45	-690 Lux -700 Lux -695 Lux ✓ Average value: 695Lux	•13:46 •13:47 •13:48	-104022 Lux -104000 Lux -103978 Lux ✓ Average value:104000 Lux

Since this study focuses on the calculation of the daylight factor and the attained result from the other methods is daylight factor percentage, it is necessary to convert these values from illuminance (Lux) to daylight factor (%).

The process of conversion is simple. Since the outdoor and the indoor illuminance value are available, they will be applied into daylight factor formula as followed:

DF= (Ei/Eo) x 100%

Where,

Ei= illuminance due to daylight at a point on the indoor's working plane

Eo= simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky

Since average illuminance value of indoor and outdoor are achieved, these will be the converted values.

$DF_{\text{Overcast Sky}}$ = (359/21400) x 100% = 1.67

$DF_{\text{Clear Sky}}$ = (695/104000) x 100% =0.66

2.3 The comparison of the Simulation Methods

The case study of this research is analyzed with four different methods.

One of these methods is the **graphical technique**, two of them from the **computer technique** and the last is the actual measurement method.

The evaluation of the collected data will be compared in terms of quantity and quality.

With a quantitative comparison, the attained daylight factor value from protractors, Ecotect and radiance will be compared with the value attained illuminance meter values.

The qualitative comparison will be done by evaluating different aspects which influenced the process of each individual method.

In addition to the comparisons few tables will be created in order to summarize the answers, achievements and the results. These tables provide the chance of visualizing the results right next to each other and have the opportunity of a better comparison.

It must be stated that the comparison, final table and anything stated about these methods are the results of individual observation and personal opinions.

2.3.1 Quantitative Comparison

Since the calculations of daylight factor are done by four different methods, different values are achieved and will be compared.

At this stage of the research, the process of each method is explained and compared with the others. The attained values which are calculated with the help of these methods are shown in Table 6 as followed:

Table 6: Attained daylight factor values (by author)

Method name	Daylight factor value	
	Overcast sky	Uniform / clear sky
B.R.E daylight protractor	Without DF correction=1.74 With DF correction=0.947 %	1.284 % (Uniform sky)
Ecotect software	1.94 %	1.94 % (Uniform sky)
Radiance	2.2 %	3.10% (Uniform sky)
Measurement values	1.67 %	0.66 % (Clear sky)

As shown in Table 6, the attained values are not exactly the same.

The reason behind this difference can be explained further by investigating the difference between each method. This can be the result of a different principle which each individual method carries on.

There are some similarities in the way that these methods are performed. The following conditions were exactly the same in each method:

- The design studio is carefully measured and same exact dimensions are applied to all methods.
- All of these methods use an overcast sky for the calculation.

- The existing material of the design studio is studied and applied to each method.
- The selected point for all the methods is in the centre of the room.

On the other hand, the differences in the process of these methods can be categorized as such:

Environmental Condition

Whilst calculating with the daylight protractor, the only data in terms of environmental condition that can be applied is the condition of the sky. This is done by selecting the proper protractor related to the condition of sky. The process of this method can be achieved simply by filling out the specific formulas which were stated in the previous section. On the other hand, in Ecotect and Radiance, not only can the type of sky be defined, but also the weather data related to the location of the case study can be imported to the software. The weather data can be obtained from the US Department of Energy website in a special format capable of being implemented within the software. The weather data covers various aspects related to the weather however the latest update of the weather data of Cyprus for this software was 2001. Also the available data verifies the location as Cyprus-Larnaca which is not the exact location of the research, but the closest available weather data to the case study. The different data available are shown in Figures 42, 43 and 44.

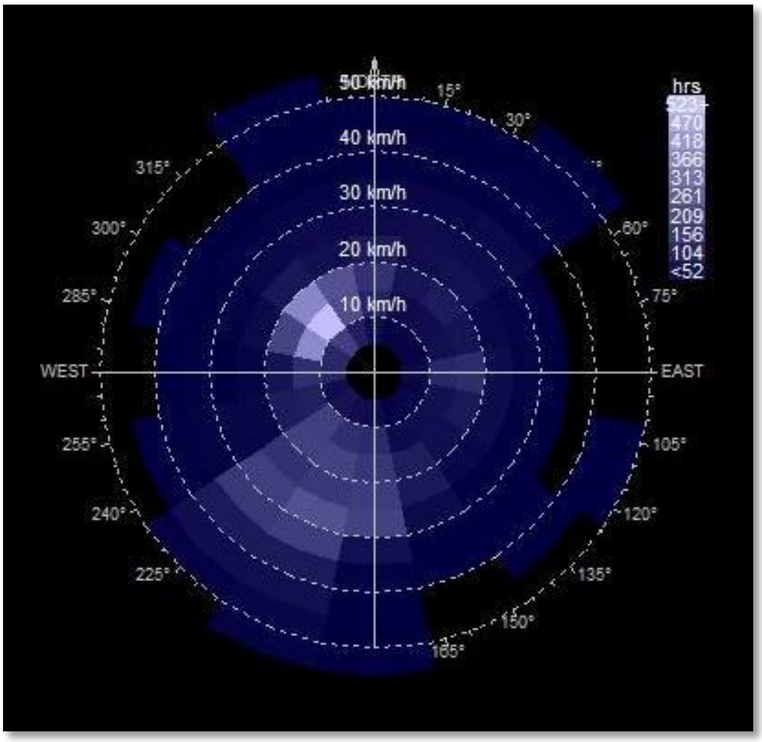

Figure 42: Prevailing winds: wind frequency (hrs) (By author)

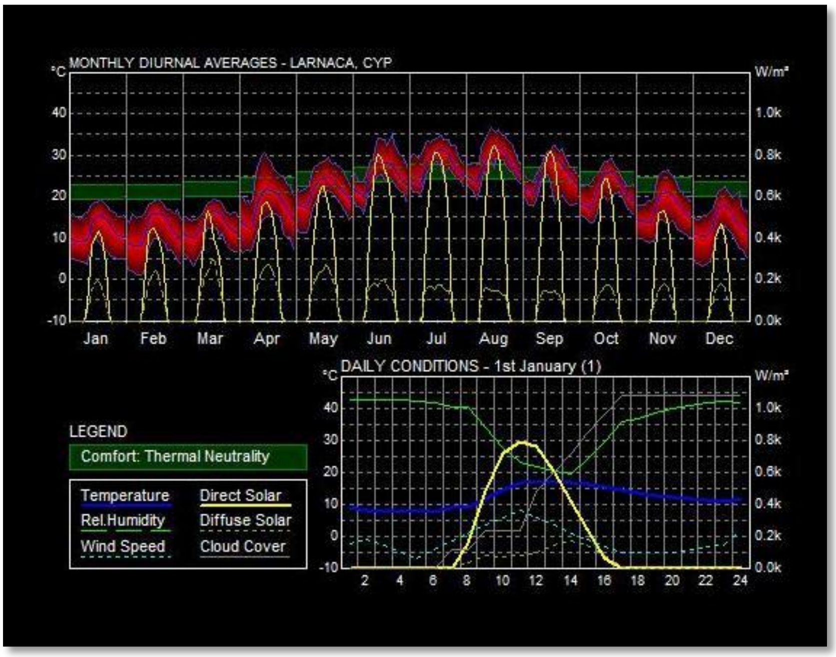

Figure 43: Hourly and daily data (by author)

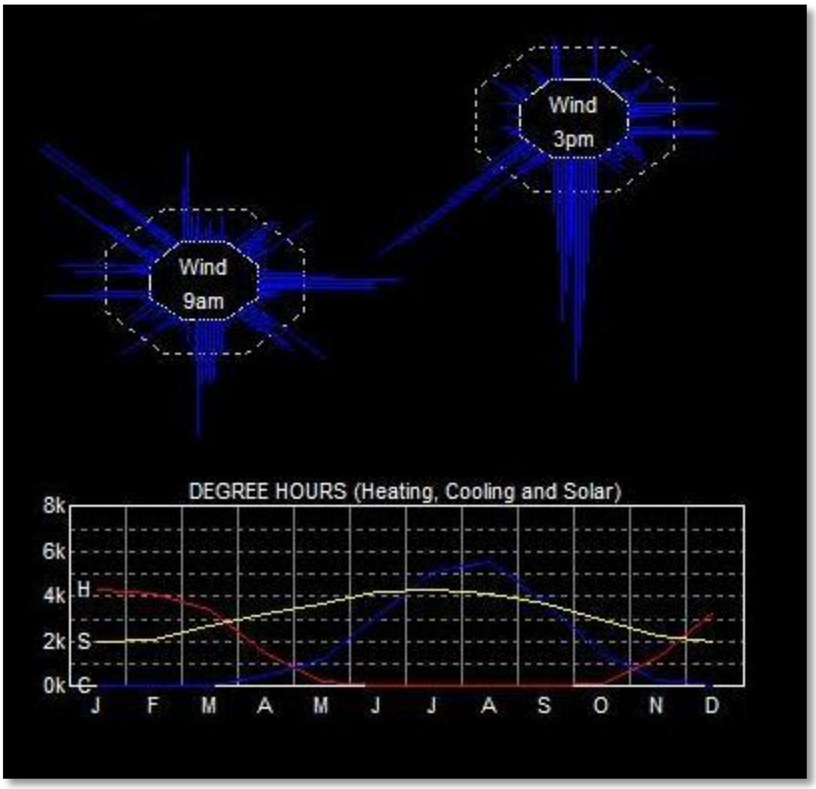

Figure 44: Monthly data (by author)

On the other hand, illuminance meter is located at the actual site to get the real weather result which are up-to-date and may be more reliable than any other method solely because of that reason. For example, in this study, as it is mentioned in method explanation section, the sky condition is overcast and weather was somewhat rainy with thunder. Because of the irregularity of the weather, the data attained from the illuminance meter changes constantly.

Time and Date

The time and date doesn’t alter the difference in the value attained by daylight factor protractors. After selecting the proper protractor according to the type of opening and definition of sky, the process can be carried on and time and date doesn’t affect the result of calculation. However, as illustrated in Figure 45, the exact time and date that the illuminance meter calculation was done, have been applied to Ecotect.

Although it does not make any alterations to the daylight factor, it changes the position of the sun, daily and annual path in three dimensional images.

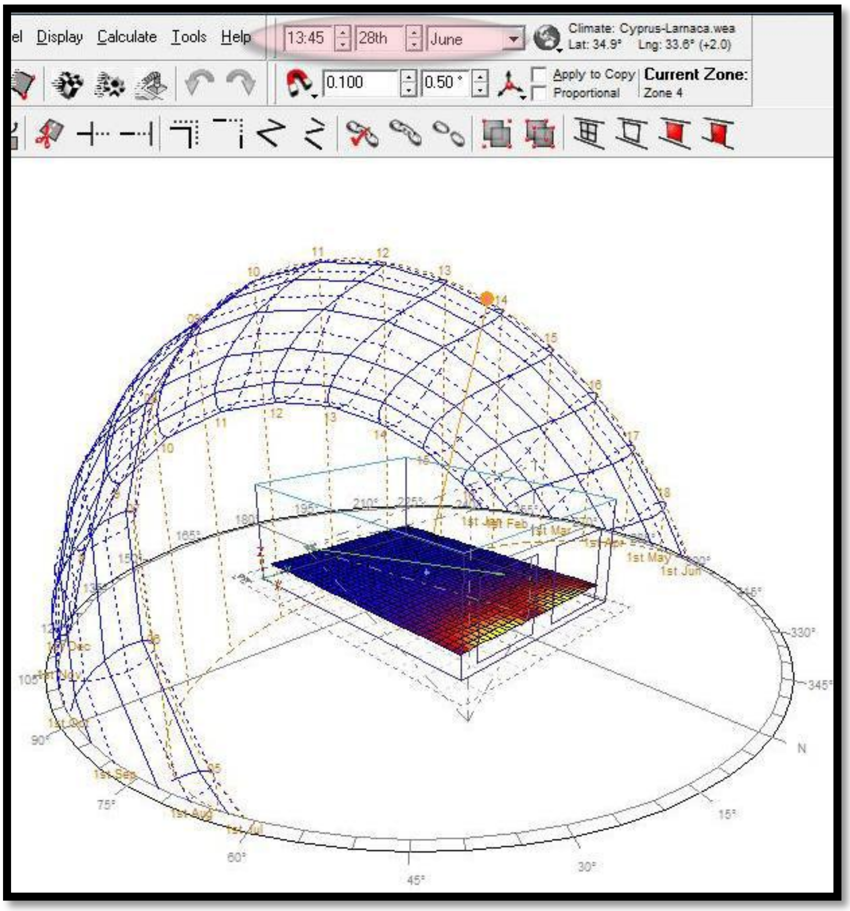

Figure 45: Applying time and date to Ecotect

In Radiance as well, time and date doesn’t influence the result.

On the other hand, time and date plays a very important role in the calculation process of the illuminance meter and can influence the calculation result. Any slight change during a specific time of the day can alter the final results by an immense amount.

Material

In the daylight protractor method, the only information related to material is the reflectance. In this research, the material reflectance of any surface were looked up and applied to the formula. However, Ecotect defines various aspects for each individual material assigned to any existing layer of the case study model. These properties shown in Figure 46 are material color/reflectance, emissivity, roughness, solar absorption, visual transmittance and thermal decrement not only for interior but for exterior as well.

U-Value (W/m2.K):	1.830
Admittance (W/m2.K):	3.340
Solar Absorption (0-1):	0.502
Visible Transmittance (0-1):	0
Thermal Decrement (0-1):	0.79
Thermal Lag (hrs):	5
[SBEM] CM 1:	0
[SBEM] CM 2:	0
Thickness (m):	0.130
Weight (kg):	211.500

	Internal	External
Colour (Reflect.):	(R:0.553)	(R:0.553)
Emissivity:	0.9	0.9
Specularity:	0	0
Roughness:	0	0

Figure 46: Material properties in Ecotect (by author)

Radiance as well has a variety of choices for material in the material library. However when exported from Ecotect to Radiance, some discrepancies may arise such as material not being compatible.

The illuminance meter has the chance of calculating the real environment factors with real materials. Therefore every single material property such as reflectance or roughness will be considered in the calculation process automatically.

The other difference in terms of material is the way these methods deal with use of the room.

In another words, with the daylight protractor method, at the end of the calculation, there are some correction factors that should be multiplied by the attained value.

Few tables are available as it was shown in table 2, 3 and 4 to find these correction factors. These data are related to window cleanness, glass light absorbance and prevention of light by its frame. In spite all, these values are just crude numbers in order to have a safer estimation that is closer to the real value. This can be a reason behind the difference between the uncorrected and corrected daylight factor values compared with the others. The uncorrected value is closer to the others, especially the illuminance meter value. However, the corrected value is much different compared to the other achieved values.

In Ecotect, the process is different. There are no crude factors. However, similar actions can be performed. For example, in this research, when the surface materials are selected and applied, the surface color can be selected to resemble the real surface color. If any surface such as the wall or floor of the case study are darker than what it should be in regards to cleanness and room use, similar colors were applied in the method.

In Radiance none of these terms are defined and there is no crude value to correct the last value. In fact the calculated value is just a rough estimation.

However during the calculation with the illuminance meter, there was the advantage of operating inside the space with the exact environment. Therefore, cleanness of room, window cleanness, glass light absorbance and prevention of light by frame were calculated without human intervention and without the need of guestimates.

Virtual versus Real

Daylight protractors calculation takes place with the means of two dimensional drawings such as plan and section. Also, Ecotect's capability of modeling provides the user a virtual three dimensional model of the building. Output characteristic of Radiance are purely images which work with the quality of daylight and daylight factor However, in contrast with the calculation process of the protractors and Ecotect, Ecotect functions with a virtual case, whereas the illuminance meter deals with the real building. In some cases even before constructing the building, a temporary scale model of the building can be constructed and placed under an artificial sky (manmade) as shown in Figure 47. Then the illuminance meter can be placed in the model and calculate the daylight factor. Although this method is mentioned, it is not put to practice in this research.

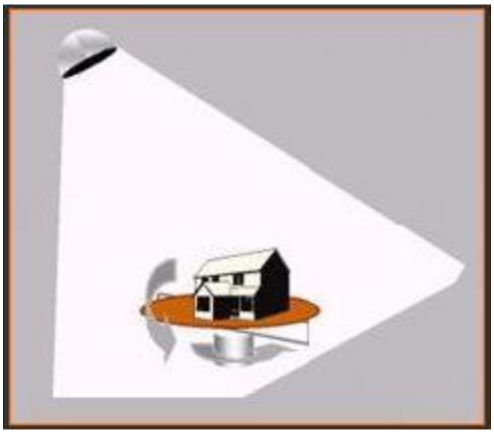

Figure 47: Scale model under an artificial sky (Bodart, 2007)

As explained previously, the process of each method is different. Daylight factor protractor method **predicts** the daylight factor value whereas Ecotect and Radiance software predicts and **simulates** the day light factor value and the illuminance meter does an on- site **calculation**.

These differences during the process of the calculation of these methods can create varying results. None of these differences provide conclusive evidence that any of these methods are better than the other. Each individual method according to these comparisons has both advantages and disadvantages. The importance of this comparison is to understand which method is the most suitable way of calculation for a specific condition.

2.3.2 Qualitative Comparison

Apart from the varied daylight factors attained, there are other aspects influencing the process of design which were faced during the calculation.

Type of User

All of these methods are suitable to be used during the design process by whoever implements daylight into their design decision. Types of users can be divided in two groups:

- Designers such as lighting designers, architects, interior designers and students.
- Engineers and energy consultant.

Time Consumption

Using B.R.E protractors is fast, as long as the user knows how to use them efficiently. However, Ecotect and Radiance are software solutions which have a rather long learning curve. They are time consuming to learn but give out results quiet quickly if the user knows how to operate the program.

Alternatively, light measuring devices hardly take any time since all user has to do is place it on the desired surface point and the value can be read instantly.

Output Characteristic

The outcome of B.R.E. protractor calculation and light measuring instrument is outputted as a numerical data. The characteristic of the output in Ecotect varies depending on the user's preference. It is capable of outputting images, numerical data, and charts. It also provides the chance of exporting the collected data into other software in order to continue the calculations or collect further information such as the type of shading devices or acoustics. Radiance creates various types of images with individual information unique to each image, but unfortunately the software is unable to precisely mark and calculate an exact point on a plan. It only allows the user to mark a location in the image provided with no measurement capabilities.

In contrast with Ecotect and Radiance, daylight protractors and the illuminance meter has no visualization ability in their output.

Ease of Use

The complexity level of B.R.E daylight protractor method is moderate to easy. The method explanation is widely available though books and internet sites. It is relatively easy to utilize them. Illuminance meter device is very easy to use as well. Each device provides the user with an instruction manual which makes the application really simple.

However the other methods are more complex. Since they are complex software capable of outputting enormous amounts of data, it requires a vast amount of time to learn enough to achieve good results when applied to the case study. Although there are books and online tutorials which can be downloaded to aid in learning the basics, they have a variety of details and steps to apply before the final result is outputted and sometimes personal touches need to be added which renders the tutorials useless.

Expenses

B.R.E protractors are available in books or any online sources completely free in most cases. Radiance is also downloadable for free from online sources. However, Ecotect license should be purchased in order to be fully activated which adds to the cost of the design of a building. A trial can be used but is limited to a specified time limit. Whereas illuminance meters are kind of pricy and the only way of experimenting with one is to purchase it.

Modeling Basis

Since B.R.E protractors are graphical tools, they help the user perform the calculation, but although they are a great light measuring method they don't provide any modeling. Radiance is also incapable of modeling however it creates three dimensional images. Ecotect on the other hand has three dimensional modeling abilities in basic levels, but enough to provide a simple model of the case study. It also provides the user the chance of entering or zooming into the interior side of the building as well as rotating it or putting a camera in any corner in order to get perspective images. And illuminance meter is just a calculation device incapable of modeling. Also an artificial sky and scale model is needed in order to use illumination meters for prediction.

User Friendly

All of these methods are user friendly. It is just a matter of time before learning and using them to get real life predictions. However, Radiance is easier to use due to the fact that it can easily import data through Ecotect so all the work is already performed. Since the material library of Radiance is well developed, the combination of Radiance and other software such as Ecotect can help achieve a more accurate result.

Human Error

B.R.E. protractor method is graphical calculation therefore the fact of performing a numerical calculation by a human can affect the accuracy of the results simply by misplacing numbers. However Ecotect and Radiance are computer calculations, therefore there is no human error possible if all the desired points are marked out correctly. It is necessary to mention that all the details and inputs are keyed in directly by humans so yet again the exactness of the result can differ according to how accurate the user is. Furthermore, the illuminance meter is a digital measurement device and it’s accurate, although the results may yet again differ according to where the user is standing and what color clothing the user is wearing. In this research the illuminance meter booklet explains the accuracy _/+ 2% C.I.E. standard, _/+ 1 digit in last changing display position.

Simulation Ability

Since B.R.E protractors are just graphical tools, there is no possibility for a simulation. The same drawback applies to the illuminance meter. Radiance is a computer program which simulates the condition of the room as perspective images. Ecotect on the other hand has a wide variety of simulating options for the required space. In addition to the modeling capabilities, a 360 degree view of the space is possible.

Support

B.R.E protractors method has a variety of samples that can be found through different types of sources. While completing this method, there is a chance of verifying and checking the result for improved accuracy. Illuminance meter devices have been developed through the years so some of the older versions have been discontinued.

Although the other methods have tutorials, they are not as simple and as common as B.R.E protractors.

That is why it is not always possible to get any support to properly verify the process and the answers.

Applicability

B.R.E protractors can be applied at a stage where only scale drawings are available.

Ecotect and radiance are applicable in the early stages of a design to determine the best types of choices, materials and dimensions of openings.

The illuminance meter can be used in two different stages.

An artificial sky and scale model is needed in order to use illumination meter for daylight condition prediction of the specific design strategy or when the building construction is done, in order to **calculate** the available illuminance in that space.

2.4 Visualization of the comparison

After comparing these methods a table is created in order to summarize the comparisons and evaluate the results according to different topics which affected the process, and the result during the analysis of the case study.

Table 7: Evaluation of the qualitative comparison (by author)

The comparison	B.R.E. Daylight protractors	Autodesk Ecotect Analysis 2010	Radiance	Illuminance meter (T-H1)
Type of user	Designer/architects/engineer/Energy consultant/students...	Designer/architects/engineer/Energy consultant/students...	Designer/architects/engineer/Energy consultant/students...	Designer/architects/engineer/Energy consultant/students...
Rapidity	Fast results	Time consuming	Time consuming	Fast results
Type of outcomes	Numerical data	Numerical data, Charts,3D models, Images	Numerical data,3D images	Numerical data
Complexity	Easy-Moderate	Moderate-Hard	Moderate	Easy
Expenses	Free	Licensed must be purchased(Not free)	Free	Not free, Must be purchased
Level of 3D modelling	None	Some	Some	None
User friendly	Yes	Yes	Partly	Yes
Human error	Possible	Hardly	Hardly	Hardly
Simulation ability	None	Some	Some	None
Support	Possible	Partly possible	Hardly possible	Partly possible
Applicability	At the end of scale drawing	Early design stages	Early design stages	Early design stages After construction

The intention of this table is to get a closer look at the different aspects facing the user during calculation. In other words, this table may be of a little help to any user who decides to put into practice each studied prediction method and have an idea of these methods before selecting or using them. Therefore the user will have a chance to pick a method which satisfies their needs as time is a factor in building design.

Chapter 3

CONCLUSIONS

There are various topics on TV, in the newspapers, books and many other resources about global warming, loss of fossil fuels, loss of energy, Economic problems and so on. There are many reasons behind these problems. Pollution, overusing of energy, production of non recycling material are all a part of it. Perhaps the most upsetting fact of it all is that it can all be avoided by people if they take a small amount of their time and think about the impact its having on Mother Nature. Using renewable energy and reducing the production of artificial energy can be one solution to life's problems.

Architects and engineers can play a significant role in avoiding above problems in many terms.

One of the ways they can do is through the use of daylighting. Optimizing natural daylight that enters the building and integrating that into architecture can be another way to save. Neglecting the use of daylighting in design strategies can cause severe physical and psychological problems to the environment and to the people in the building.

Overlighting problems can also have a negative effect on the performance of human beings with downsides such as glare, overheating inside the building and very bright interiors.

Poor daylighting design can even affect the outside of the building in terms of external comfort and energy efficiency. That’s why orientation, overhangs and shadings are also important.

Although daylight plays an important role, like any other environmental factor, it needs to be controlled to avoid such drawbacks.

Daylight always changes during the year, during the season and even during the day. Therefore, controlling it is not an easy job. It is required to predict the condition of the effects of daylight in the pre-construction stage of a building.

One of the solutions is to apply a daylight prediction method. This would give the designer a chance to predict or simulate the future situation of the specific space.

In this research, four different daylight prediction methods were explained and applied to the case study.

The comparison of these methods is not just to prove which method is the best technique but rather show a way to pick the right method for the right application that is needed and what factors will affect the result of these processes. In fact, this comparison assists the user in order to have an idea about each method before using it to find out which one is more suited to the requirements of their research.

Therefore in this research a table was created which visualizes the comparison in order to explain the characteristics of each method according to different aspects.

With the advancement of digital technology, daylight prediction method is developing into an interesting prospect not only in terms of research but also in practice in which computer-based project plays a vital role. There are a lot of software and plug-inns available in the market today that is owned and dominated by different companies such as CAAD (Computer-aided architectural design). They provide high end functionality at a high-end price but they also offer great conditions for academic and educational institutions.

Finally, this research concludes that it would be better if people understand the importance of natural energy resources and its role in a day to day situation. Also as an architect, it is necessary to learn any method that can help the future of the environment to preserve it for many more generations to come. If daylight is properly designed and well controlled along with minimizing the usage of artificial lighting and optimizing the natural daylighting by integrating it into the buildings can keep the environment cleaner and less polluted.

Last but not least, basic patters of the sun movement are very important, and are worth dedicating conscious attention to the behavior of the sun's rays. In regards to this fact, there are two cases that should be considered. One of them which were investigated in this research is **light from the overcast sky**. This research can be carried on by inspecting the other case which is the **direct rays of the sun**.

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