FEASIBILITY STUDY ON TUBULAR SKYLIGHTS TO BE USED IN SRI LANKAN OFFICE BUILDINGS

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Degree of Master of Science in Building Services Engineering

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Building Services Engineering

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DECLARATION

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……………………………..

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(Dr. Asanka Rodrigo)

ABSTRACT

Tubular Daylight Guidance technology can deliver natural light in to a space in a building where daylight is limited with an internally mirrored pipe system using the phenomena called total internal reflection. This research has been conducted to identify the potential and feasibility of applying Tubular skylights in a Sri Lankan office building. The research has focused on the existing technologies and evaluated three models of Tubular skylights designed to be used in office applications. Computer simulations have been carried out to evaluate the light out puts of different lighting arrangements made with Tubular skylights. Energy evaluations have been carried out for the cases require artificial lighting to keep constant illuminance levels. Economic evaluations have been carried out with life cycle cost calculations to evaluate the economic feasibility.

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First, I pay my sincere gratitude to Dr. Asanka Rodrigo who encouraged and guided me to conduct this study and on preparation of final dissertation.

I would like to take this opportunity to extend my gratitude to my superiors in the Central Engineering Consultancy Bureau and professionally qualified engineers in the industry who gave their co-operation to conduct my research work successfully.

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LIST OF ABBREVIATIONS

UK United Kingdom
SLL Society of Light and Lighting
TDGS Tubular Daylight Guidance Systems
HLS Hybrid Daylight/Electric Systems
DGS Daylight Guidance Systems
ELS Electric Lighting Systems
HRE Heat Replacement Effect
EDCS Effective Daylight Capturing Surface
UV Ultra Violet
TS1 Tubular Skylight with 250mm diameter
TS2 Tubular Skylight with 350mm diameter
TS3 Tubular Skylight with 525mm diameter
USA United States of America
CIBSE Chartered Institution of Building Services Engineers
DNI Direct Normal Irradiance

1 INTRODUCTION

1.1 Background

The visual effect of lighting is an important part of the total living or working environment. Daylighting is a crucial and critical issue in modern architecture. Daylight gives illumination for indoor activities and visual connection between interior and exterior environments, and brightens the internal spaces. Building occupants prefer natural light and an outside view. For a good interior environment, as much natural glare free light as possible is essential [1]. Although every building has different functions, it is compelling to use daylight as a primary or a secondary light source for the benefits of energy, productivity, and health. It is expected that proper use of natural light for lighting purposes in buildings can be an effective means of saving energy and reducing the environmental impact.

Although it is becoming increasingly difficult to provide the light required for various activities from daylight alone due to the increased building density, partial use of daylight can still significantly reduce lighting and cooling loads and improve occupant's preferences, visual relief, and pleasing effects.

Conventional windows can provide daylight about 5 m into a building. But since daylight levels decrease asymptotically with distance from the window, a disproportionate amount of daylight and associated heat gain must be introduced into the front of a room to provide small amounts of daylight at the rear. The most effective daylighting strategies could be to optimize building orientation and form as well as to optimize window size and placement. Due to overcrowded urbanization, however it is increasingly difficult to use strategies that let natural light penetrate deep into the interior space. Fortunately, emerging technologies are available that allow sunlight into the core interior of multi-storey buildings, although optical sunlighting systems as a remote illumination source can be traced back as far as the late 1800s.

A number of recent developments in optical lighting systems offer renewed opportunities for reliable optical daylighting sources with broad applicability and high effectiveness. And due to developments in renewable materials, the use of optical daylighting systems for active lighting control can be simple, reliable, and relatively inexpensive.

Over the last fifty years or so the development of a number of highly efficient reflective and refractive materials has made the redirection of daylight into areas of buildings remote from the façade a practical possibility. There are two main approaches. The first, "Beam daylighting" the redirection of sunlight by adding reflective or refracting elements to conventional facades essentially the enhancement of traditional devices such as louvers or light shelves using the new optical materials. The second method known as "Light guidance" captures daylight using collector devices and transports it into core areas of buildings using some form of linear guidance system.

The "Light guidance" systems known as "Light tubes" or "Light pipes" are used for transporting or distributing natural or artificial light. In applications for daylighting, they are also often called "Sun pipes", "Solar pipes", "Solar light pipes", "Daylight pipes" or "Solar tubes". All the devices are referred to as systems in this report. Optical daylighting systems rely primarily on the direct component of sunlight as a light source. The direct sunlight at a building envelope is collected and optically delivered by a series of mirrors or pipes. Theoretically, the transmission network may guide the collected light beams four to eight stories down with distribution at each floor and extending as much as 15 meters horizontally through the building fabric via reflective or optic devices. The transmitted light may be reflected initially into the occupied space, or the light may be guided through pipes for distribution at the task area with a lighting level of about 500 lux.

Typical optical daylighting systems can be divided into "Light pipe systems" and "Mirror systems". As shown in Figure1-1, a light pipe is also known as a ''Tubular skylight'', ''Sun scoop,'' or ''Tubular daylighting device.'' This device comprises a clear polycarbonate domed light collector that accepts sunlight and skylight from the whole sky, a light transport tube lined with highly reflective silvered or prismatic material, and a diffuser to distribute light in an interior. Compared to conventional skylights and windows, a Tubular skylight offers better heat insulation properties and more flexibility for use within buildings, but little visual contact with the external environment.

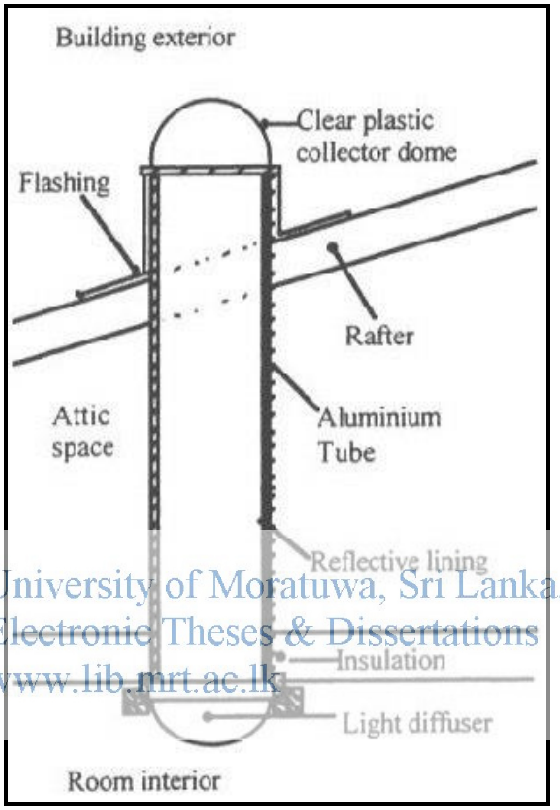


Figure 1-1: A typical Tubular day lighting device

1.2 Research Objectives

(i) Review of existing Tubular skylight designs.

(ii) Review of research studies carried out on Tubular skylights.

(iii) Studying the potential of integrating daylight with Tubular skylights in a Sri Lankan office building which mainly functions in day time.

1.3 Scope of Research

The scope of this research is to investigate the potential of integrating daylight in a Sri Lankan office building with Tubular skylights under following conditions

(i) Lighting the office rooms entirely with the Tubular skylights in the day time functional hours of the office.

(ii) Lighting the office rooms with Tubular skylights together with an artificial lighting system in the day time functional hours of the office.

2 LITERATURE REVIEW

2.1 Invention of the Tubular Sky Light

Tubular Sky light was patented in USA in March 31 of 1992 (Patent No. 5099622) by Steven M Sutton [2].

This device as illustrated in Figure 2-1 comprises a Tube (2) which has one hemi spherical end cap or upper bubble (3) and one dished or “Bowter” end cap or diffuser (4) attached thereto. The top end cap (3) is made of a clear Perspex or similar such material and the lower surface has a pattern impressed thereto forming a diffusing effect. The top end cap or upper bubble (3) has a reflector (5) affixed thereto on its inside surface. The reflector (5) reflects the light that would otherwise pass through the sides of the upper bubble (3) into the tube to adding to the light incident and transmitted through the tube (2). The material of the tube (2) is either metal, fibre or plastics and has a finish which is highly reflective polish or coating, as found on “1150 Alloy Aluminium”, electroplating, anodising or metallised plastic film. The coatings applied to all the internal surfaces thereof. The highly reflective nature of the internal surfaces of the tube (2) assists in transmitting and reflecting light through the diffuser (4). The combined light passes through the diffuser (4) and is redirected sideways and upwardly, which is then reflected off walls (16) and ceiling (8) and therefore creates indirect lighting for the room (20).

In the installation procedure, the position in the ceiling (8) is determined and a suitable hole (9) is cut out. The corresponding roof tiles (10) vertically above the hole (9) are also removed. It is noted at this point that some small portion of battens (13) may need to be removed depending on the positional requirements. The same applies to small and remediable portions of the roof structure. Once the above mentioned has been noted, the tube (2) is then moved into position between the battens (13), and rested on the ceiling (8) level (flush with the underside of) which is automatically determined by aligning a bolt (17) with bracket (18) where the bolt (17) is affixed. This is associated with the embodiment of Figure 2-2 whilst in the embodiment of Figure 2-3 a plurality of tabs (18) rest on the ceiling (8). Flashing (6) is then placed and dressed to the tube (2) and the roof tiles (10) are replaced. It should be noted that the flashing (6) is placed under the roof tile (10) surrounding the tube (2). A hose clamp (11) is then fixed over the tube (2) and the upturn of the flashing 6 and a suitable water resistant sealant is applied there between.

The upper bubble 3 is then affixed and is secured onto the tube (2) by a hose clamp (11). The reflector (5) has already been placed upon the top side of the tube (2) prior to installation. The lower bubble or diffuser (4) is then affixed to the lower end of the tube (2) prior to installation. The lower bubble or diffuser (4) is then affixed to the lower end of the tube (2) through the hole (9) provided in the ceiling (8). The diffuser (4) has a flange (12) or alternatively a dress trim.

After the skylight (1) has been installed, ambient, permeative, and direct sunlight from the sky enters the upper bubble (3), a large proportion of the light striking the reflector (5), the balance of the light that would normally pass through the clear material of the upper bubble (3) is reflected back into the tube (2) by means of the reflector (5) located at the elevation away from the sun of the upper bubble (3) which is fixed to the tube (2) between the external surface of the tube (2) and the internal surface of the upper bubble (3). This reflected light now enters the tube (2) at a corresponding and opposite angle to the light received through the upper bubble (3). The combination of the variability angled light strikes the diffuser (4) and the light is scattered throughout the room (20).

With regard to the thermal considerations it has found that greater amount of heat has been found under skylighted areas in the summer and conversely less with the lower temperatures in winter. This invention eliminates such problems due to the substantially sealed nature of the Skylight. The before mentioned close fit of all the components prevents excess air movement which creates a static column of air within the skylight. The column of air acts as an insulator combined with the insulating properties of plastics forming the upper bubble (3) and diffuser (4) which prevents heat from entering the room (20). The heat that builds up within the skylight is dissipated into the roof cavity via the conductive material of the tube (2).

Conversely in a winter situation, it is found that heat rises, therefore the roof cavity would not be as cool as the external temperature prevailing the outside of the building. The conductive material of the tube (2) would absorb some of the heat warming the air column within. As the air column is heated, it therefore follows that the skylight acts as an insulator and maintains a substantial amount of heat within the room (20).

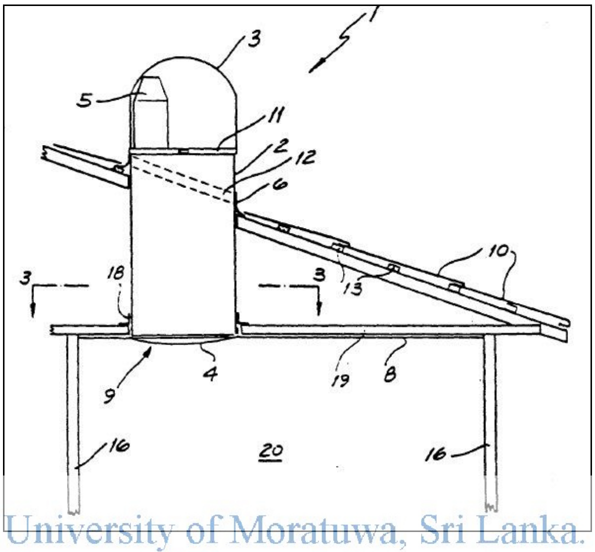


Figure 2-1: Sectional View of Apparatus

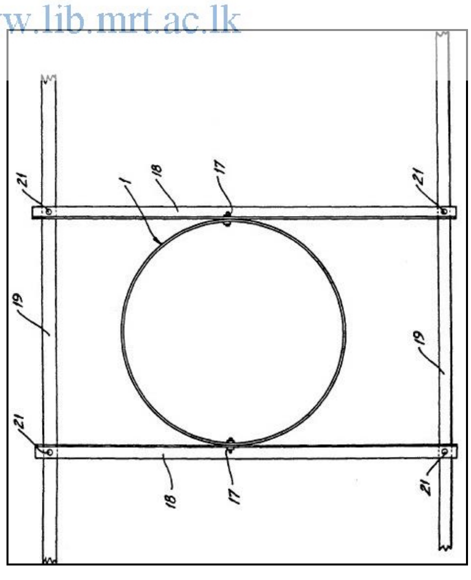


Figure 2-2: Tube fixed with bolts

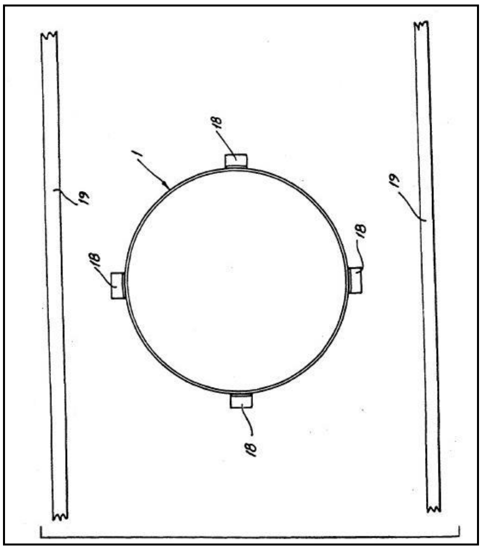


Figure 2-3: Tube fixed with tabs

2.2 Light Pipes in the Design Process

Light pipes, sometimes called waveguides, are optical elements that transfer, “pipe” or “guide” light from a source to a lighting task, primarily by the process of reflectance. It is found in all types of devices, in just about every industry.

While production is simple, designing a light pipe is a complex task. Although light pipes appear to have simple performance requirements, a false assumption is that they are simple devices to design. Consequently, light pipes are often neglected until late in the engineering process, when it is too late to produce a usable, cost-effective, manufacturable design [3].

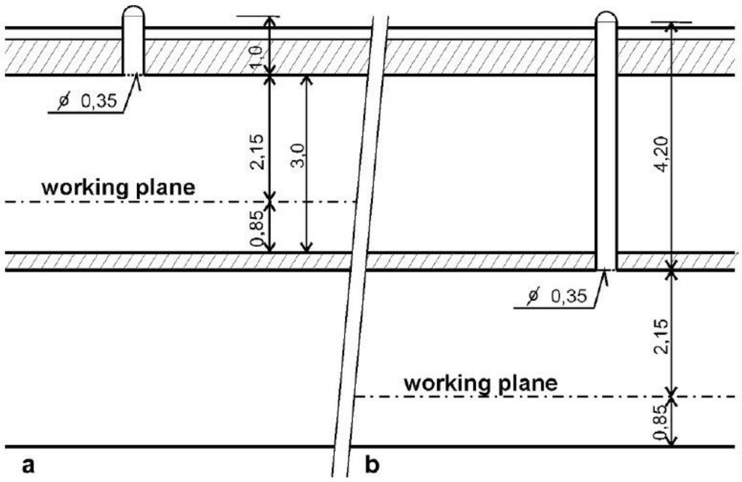
2.3 The Research Work That Has Been Carried Out

A strong preference for natural light and a view to the outdoors as well as a strong health consciousness have stimulated an interesting related research, as evidenced in the literature. One category of the studies is the development of a theoretical background and evaluation algorithms for optical daylighting design and assessment. Another category of research is to evaluate the economic benefits of using the daylight guidance systems. Following is a review of the literature on the research work done for analysing the daylight guidance systems.

2.3.1 Luminous effectiveness of tubular light-guides in tropics

Stanislav Darula, Richard Kittler and Miroslav Kocifaj [4] have analysed the Luminous effectiveness of tubular light-guides in tropics.

It has discussed about several daylight conditions in tropical interiors illuminated by tubular light-guides. They have analysed the complex illuminance patterns produced on the underside of the tube, i.e. on top of the glazed ceiling aperture that illuminates the interior space or its working plane due to the tube's diameter, length and multiple reflections. The HOLIGILM calculation program and the user-friendly tool HOLIGILM 4.2 have facilitated the analysis. The study has been done for two tube configurations of 1 m long tube and 4.20 m tube length (Figure 2-4).They have plotted the Isolux patterns on top of the ceiling interface glazing at the bottom of two tubes under four different exterior illuminance conditions using HOLIGILM 4.2.



Schematic section showing the two chosen tube configurations with dimensions in meters, on left – (a) for a 1 m long tube, on the right – (b) for a 4.20 m tube length.

Figure 2-4: Cross section of the space

They have concluded that the effective usefulness of tubular light-guides in the tropics stems from favourable daylight conditions under high solar altitudes and relatively long sunshine duration periods. High available sunlight luminous flux channelled onto the interior ceiling interface aperture and then onto the interior working plane or floor, enables the use of longer tubes with smaller diameters.

They have found that the isolux pattern at the bottom of the tube is the same whether a transparent or a diffuse glazing covers the ceiling aperture, but the glazing character does influence the distribution of illuminance on the interior working plane or floor. Specific hot spots are formed on top of this glazing by the sunbeams reflected within the tube but there are several possibilities for distributing the sunlight and skylight into the interior;

– by applying a transparent glazing at the tube bottom the specific hot spots are almost centrally projected onto the interior working plane or floor mainly directed towards the side walls of the room,

– by applying a diffuse glazing cover of the bottom of the tube the interior distribution is more evenly spread onto the working plane with the highest illuminance level directly under the tube,

–HOLIGILM 4.2 enables a designer to test a design and partially correct it, if needed, to achieve the optimal design of the tubular light-guide placement. Apart from the environmentally-friendly and stimulating effects of sunlight and skylight in windowless interiors, the daylight illumination of a building core can reduce the energy required for artificial illumination during daytime.

Another conclusion they have made is that the luminous effectiveness of tubular light-guides in tropics is higher due to prevailing high solar altitudes and long sunshine durations. In temperate climatic regions both these influences are relatively lower especially during winter seasons when the light-tube applications should be profitable.

2.3.2 Light-pipe prediction methods

David Jenkins and Tariq Muneer [5]have revised the Light pipe predictive methods.

They have summarised the operational uses of several methods used in light-pipe performance predictions. In their study they have described and discussed about Luxplot package (Jenkins–Muneer), Zhang–Muneer study, SkyVision software, Carter study and Tsangrassoulis study.

Luxplot package (Jenkins–Muneer)

This is part of an overall semi-empirical prediction method that first calculates the luminous flux from any size pipe with a ‘‘clear’’ diffuser (consisting of a curved, stippled clear plastic). Any number of bends of any angle can be used in the prediction. From the luminous-flux prediction, the model then estimates the light distribution at any distance below the ceiling diffuser: this is based on a quartic cosine illuminance relationship. The model is proposed as a design tool that is simple and straightforward to use.

Zhang and Muneer study

The predictive technique of Zhang and Muneer is for use with a light-pipe with an ‘‘opal’’ or cloudy diffuser. The predictions are largely based on illuminance /daylight factor measurements (taken over four months) of light pipes of diameter0.21, 0.33, 0.45 and 0.53 m, varying between 0.6 and 1.2 m in length. Extrapolation is then used for light pipes of other dimensions, although the most reliable predictions will be within the dimensions of the pipes used in the study. By measuring the effects of adding 30^0 elbow sections, pipe bends were also considered so as to produce two separate models (i.e., for straight and elbowed light-pipes).

SkyVision software

The SkyVision software package was formulated by the National Research Council of Canada as a predictive tool to describe the performance of daylighting methods. This includes sky wells and conventional skylights, as well as light pipes. It is a fairly detailed software-package in that it requires a large amount of data for a specific case to be able to formulate an illuminance /daylight factor prediction. While this can mean putting together a prediction may take some time, as a result it is quite versatile and able to cope with most examples where a room is being lit by a ceiling aperture. There is also a facility that can assess the additional electric lighting required for a room that has had skylights fitted (for a target illuminance).

Carter study

The method described by David Carter of University of Liverpool involves estimating or measuring the total amount of light emitted by the pipe (i.e., luminous flux) and then considering the distribution of this light (the intensity distribution).Again, measurements were taken to construct this design tool for pipes with diameters0.33, 0.45 and 0.53 m and for lengths of 0.6 and 1.2 m. The pipes involved had a similar opal diffuser to that considered in the investigation by Zhang and Muneer (but different from that of Jenkins and Muneer).

Tsangrassoulis study

A more theoretical approach was proposed by Aris Tsangrassoulis of the University of Athens, but using existing data for the transmittance of the pipe length, pipe collector and pipe diffuser/emitter. Such a method can therefore be used for arrangement of light pipes with different transmittance properties, providing the user knows this information.

They have Summarised advantages and disadvantages of different light-pipe design methods subjected to the study (Table 2-1).

Table 2-1: Summarised advantages and disadvantages of different light-pipe design methods

Method	**Advantages**	**Disadvantages**
Luxplot (Jenkins–Muneer)	• Requires only external illuminance and pipe/room dimensions as input • Self-contained calculation package with luminous flux and illuminance (lux plot) output • No limit on number of pipes or room area • Includes pipe elbows of any angle • Based on relatively large range of measurements	• Simplified approach does not include the subtle effects of solar altitude and sky clearness parameters • Current output specific to pipe of given type (although minor alterations could be made for other pipe reflectivities) • Does not explicitly state pipe collector and diffuser transmittances separately
Zhang–Muneer	• Includes estimated effects of solar altitude and sky clearness to allow season/time dependent predictions • Includes work on pipe elbows(in 30_ sections) • Fairly adaptable for pipes of other, e.g., reflectivities •Equations easily implemented into spreadsheet for large-scale Calculations	• Only two lengths used in the measurements for model formulation – may imply limit on length for predictions • Requires moderate knowledge of product/scenario to provide input • Model only applicable to diffuser/collector of one type (although study could be repeated for others)
SkyVision	• Self-contained, well-presented calculation package • Very adaptable to range of different products (including conventional skylights) • Database included to describe, e.g., glazing of collector • Range of sky models can be used (e.g., CIE overcast) • Graphical and tabular outputs offered	• . Large amount of knowledge on product necessary (takes time to produce prediction) • Maximum of nine pipes in prediction • Cannot input external illuminance explicitly (instead uses average for the time of day/year chosen) • Output is averaged over floor area, not position specific
Carter	• Proposes predictions for luminous flux as well as illuminance predictions • Not itself a ‘‘package’’ but one method applicable to existing illuminance packages (e.g., Lumen Micro) • Considers elbow losses	• Only two different lengths used in measurements for model formulation •Estimation/measurement of initialluminous flux output requires information perhaps not easily accessible to every user •No ‘‘stand-alone’’ expression for pipes with elbows
Tsangrassoulis	• Theoretical framework can be used with other studies • Applicable to any light-pipe configuration	•Requires detailed prior knowledge or modelling of pipe, collector and diffuser: therefore not a ‘‘stand-alone’’ model •Requires normal illuminance data

2.3.3 Tubular light guide evaluation

Jitka Mohelnikova[6] has evaluated the straight Tubular light guides.

It has investigated the straight tubular light guides. The theoretical description of light rays transport inside the tubular light guide and their distribution on the output from the light guide at the level of the ceiling has been presented. The theoretical model has been compared with light measurements. This study has been completed for the evaluation of the function of the tubular light guide system and determination of design requirements.

The study has been conducted as two parts as theoretical and experimental. In the theoretical part a model of the tubular light guide with a flat glass cover has been elaborated for boundary conditions of clear sky with direct solar radiation. The following input data has been used for the model:

- elevation angle of affecting light rays,

- number of incident levels of light rays entering into the lightguide (the number of levels influences accuracy of the calculation result),

- light pipe length and diameter,

- optical properties of the light pipe components as light transmittance of a roof transparent cover, light reflectance of the internal surface of the light guide tube.

Calculation results are values of relative light intensity on the output of the light guide tube.

The light pipe model has been programmed in Matlab programming language (Matlab– version 7.1.0.246/R14. Service pack 3). The example of the calculations has been completed for the light pipe of the following optical properties – reflectance of the pipe ρ= 0.95, roof dome transmittance T= 0.92. There is a comparison of results of the light pipe of the same optical properties calculated, diameter d =0.6 m and lengths *l*= 1.0, 2.5,5.0 and 15 m. Total number of incident levels j= 199 (u =

100) was selected for calculations, angle of incidence of light rays ϴ= 48° (Figure 2-5).

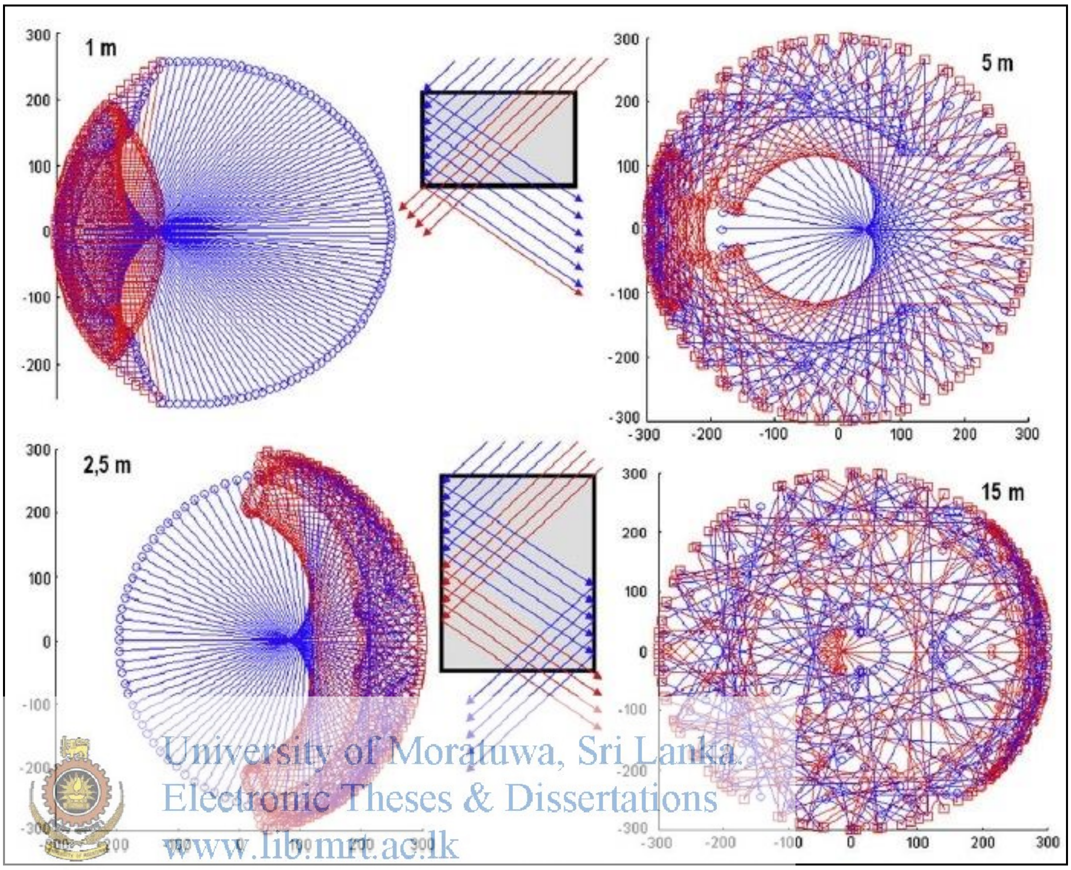


Figure 2-5: Light distribution on the output of the light guide.

(light guide of diameter 0.6 m and length 1, 2.5, 5 and 15 m for u = 100 levels and j = 199)

Luminance photographs of a ceiling diffuser of the tubular light guide of diameter 0.5 m and length 5 m has been carried out for the comparison of the result ofmodel with reality. They have been monitored by luminance camera LMK Vario 2000 (Techno Team, GmbH, Mobile LMK vario 2000. Ilmenau; 2002).The luminance photograph presented in Figure 2-6 a.

Relative intensity on the ceiling diffuser is I =0.29 – it is determined for the average luminance 1591 cdm^{-2} monitored for sky luminance 5428 cdm^{-2}. The average relative intensity of the model is I =0.24 Figure 2-6 b.

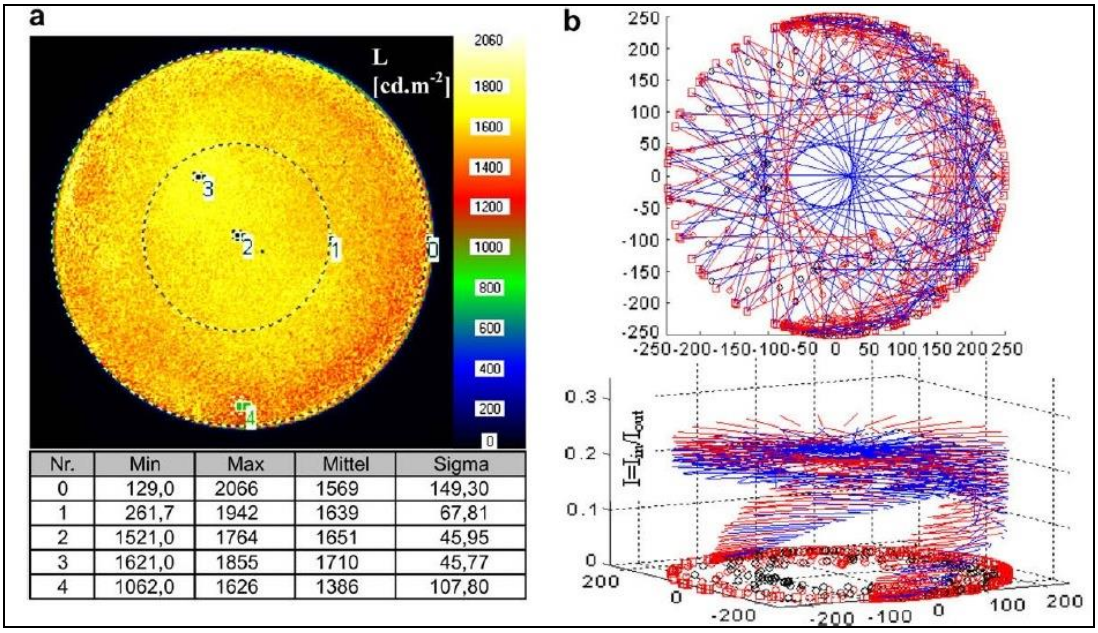


Figure 2-6: Luminous intensity plots

Comparison of light distribution on the ceiling diffuser of the light guide of diameter 0.5 m and length 5 m. a) luminance camera photograph of the light guide ceiling diffuser, b) model of the light guide.

In the experimental part, Illuminance availability has been evaluated for determined luminance of the ceiling diffuser of light guides of diameters 0.25, 0.5, 0.75 m and length 5 m. The following values of the ceiling diffusers has been determined:

- Ld= 1000 cdm_2 for overcast sky conditions,

- Ld= 4000 cdm_2 for partly cloudy sky conditions

- Ld= 12000 cdm_2 for clear sky conditions.

Interior illuminance at points of interest in the horizontal distance 0, 1, 2 and 3 m from the vertical axis of diffuser on the working plane of 2 m under the ceiling diffuser was investigated. The results are presented in Table 2-2.

Table 2-2: Indoor illuminance E [lx] on the working plane under the light guide in dependence of the luminance L [cdm^{-2}] of the ceiling diffuser.

	L [$cd\,m^{-2}$]	r = 0.25 m	r = 0.50 m	r = 0.75 m
Distance from vertical axis x = 0 m				
$\theta = 0°$	1000	12	49	110
	4000	49	196	442
	12000	148	589	1325
Distance from vertical axis x = 1 m				
$\theta = 26.6°$	1000	9	35	79
	4000	35	141	316
	12000	106	421	948
Distance from vertical axis x = 2 m				
$\theta = 45°$	1000	4	17	39
	4000	17	69	156
	12000	52	209	468
Distance from vertical axis x = 3 m				
$\theta = 56.3°$		r = 0.125	r = 0.25	r = 0.375
	1000	2	8	19
	4000	8	34	75
	12000	25	101	226

The control measurement of internal illuminance under the light guide of diameter 0.52 m and length 4.8 m has been carried out on the working plane of 2 m under the ceiling. The light guide system has been installed in a windowless corridor of a school building. It consists of a roof transparent dome, pipe with very high internal surface reflectance (r= 0.96), and ceiling transparent cover-diffuser. The diffuser scatters daylight from the light guide into the building interior.

The photograph of the corridor illuminated by the tubular light guide and vertical section of the building with the installed tubular light guide and illuminance distribution on the working horizontal plane of 2 m under the diffuser is shown in Figure 2-7.

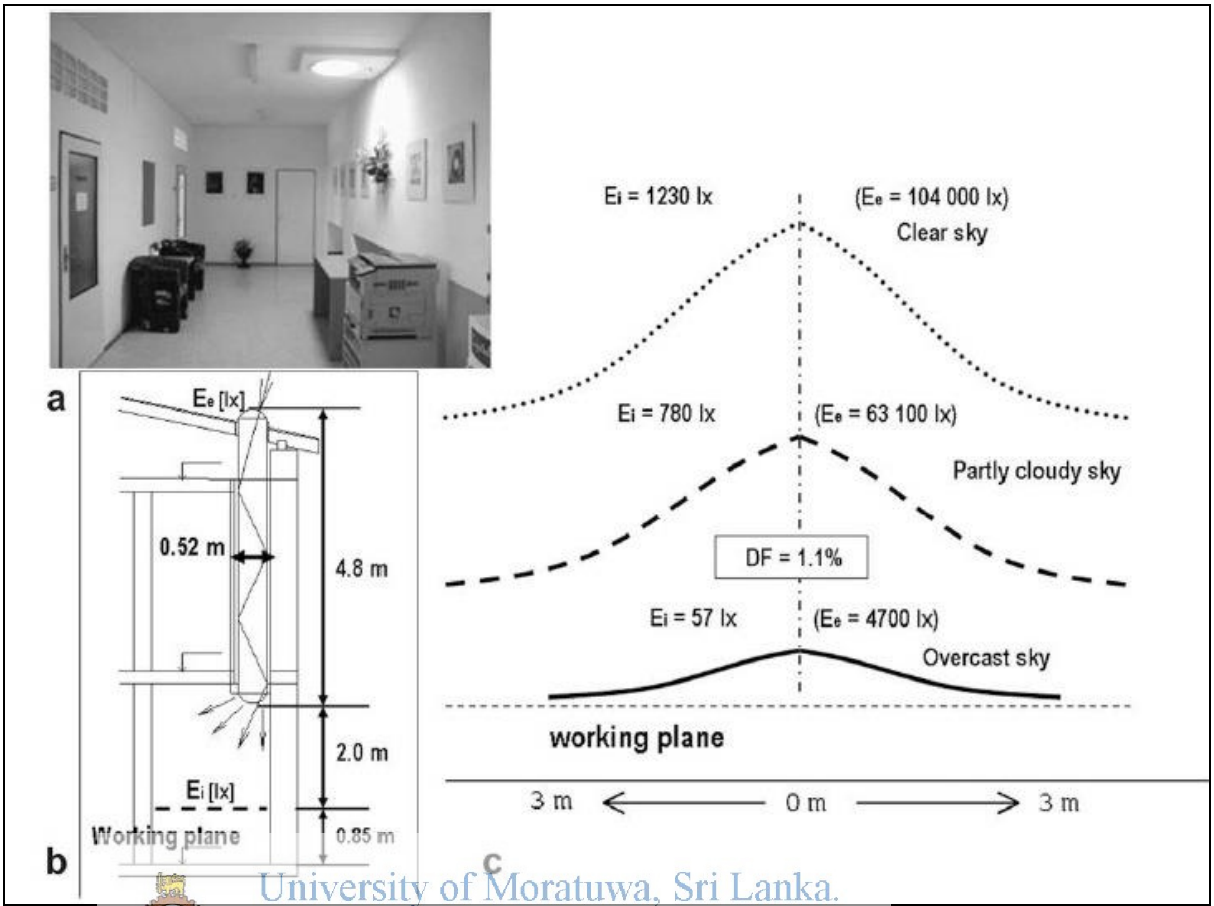


Figure 2-7: Details of the room and illuminance levels

Results of illuminance measurements in the windowless corridor in the school building. a) Photograph of the corridor illuminated by the tubular light guide, b) Vertical section of the building with the installed tubular light guide, c) Illuminance on the working horizontal plane 2 m under the light guide diffuser.

From the Calculation results and data from light measurements, they have given information for design requirements for tubular light guides as follows.

- high transmittance of the roof transparent cover; a dome is preferred to the flat glass cover, antireflective glass with very high light transmittance is recommended.

- surface of the transparent ceiling cover must have patterned surface for light scattering uniformly inside the room(patterned surface must face to the interior side because of smaller light losses compared to installation of the ceiling diffuser with the patterned surface inside the light guide).

- very high reflectance of internal surface of the light guide, specular surface is required, elimination of internal joints and uneven places.

- it is recommended to complete shorter light guides with additional shading elements for elimination of glare during sunny days.

- optimal geometry of the straight tubular light guides – the ratio diameter/length is recommended 1/10, maximal permitted is1/20, longer light guides have very low light transmittance.

- light guides of small diameters (less than 0.2 m) are not efficient because of material waste and high light losses inside light guide.

- tubular light guides are very efficient for direct solar radiation and they give low illuminance for conditions of overcast sky.

They have concluded that the presented results compared indicate that the light guide technology cannot properly substitute traditional windows but it could be used as the subsidiary daylight system in deeper rooms with needs of natural lighting or it could reduce artificial lighting energy consumption in the windowless parts in buildings. The main contribution of the tubular light guides lies in possibility of natural spectrum and dynamic variations of daylight and in improvement of visual comfort in difficult illuminated parts of buildings.

2.3.4 An analysis of light-pipe system via full-scale measurements

Danny H.W. Li, Ernest K.W. Tsang, K.L. Cheung, C.O. Tam [1] have conducted an analysis of light pipe system via full – scale measurements.

This research project has been initiated to evaluate the issues of lack of local data to indicate the visual performance, energy savings and design implications of light pipe systems in Hong Kong. The study includes field measurements of daylight illuminance in a corridor installed a number of light pipes. The results demonstrate that the light-pipe system can provide sufficient illuminance, improve the daylight uniformity and have a high potential to reduce the electric lighting energy consumption.

An air-conditioned non-residential block built in 2004 has been selected for the study. It has been composed of a 7-storey main building containing offices, vehicle workshops and computer data centres. In total, 10 straight light pipes have been installed on the roof of the building which is generally free of obstruction. Eight of them have been evenly distributed along a corridor which has been used for circulation to various offices and galleries with the dimensions of 10 m x 3.06 m x2.495 m (height). During daytimes, the electric light fittings insidethe corridor have been switched off and the internal illumination has been provided by the light pipes only. The length of each light pipe has been 2.8 m with a diameter of 250 mm and a reflectivity of 98%.The measurements of daylight illuminance for the light-pipe system have been made by a number of illuminance meters which have been manufactured and calibrated by Minolta (Japan). The measurements have been carried out by means of a multi-point illuminance measurement system with main body adapter (T-A20) and the required receptor head adapters (T-A21) connected serially. A Visual Basic program has been written for data capturing. The measured data has been displayed in real time for individual receptors and a measurement interval of 1-min has been set. All logged data has been sent to a notebook computer for storage. To precisely record the variations of the illuminance across the light pipe surface, the daylight illuminance direct under a typical light pipe has been measured by several sensors. Figure 2-8 depicts the layout. To record the global illuminance falling on the light pipes, another illuminance sensor has been placed horizontally on the rooftop of the building. Due to site restriction, the illuminance sensor has been installed about 10 m away from the light pipe where is generally free of external obstruction. The interior daylight illuminance has been measured by means of five illuminance sensors which have been spaced equally along the centreline of the corridor at0.8 m above the finished floor level. The corridor layout plan and the locations for the five measurement points are presented in Figure 2-9. The measurements have been made at daytime with all electric light fittings inside the corridor off.

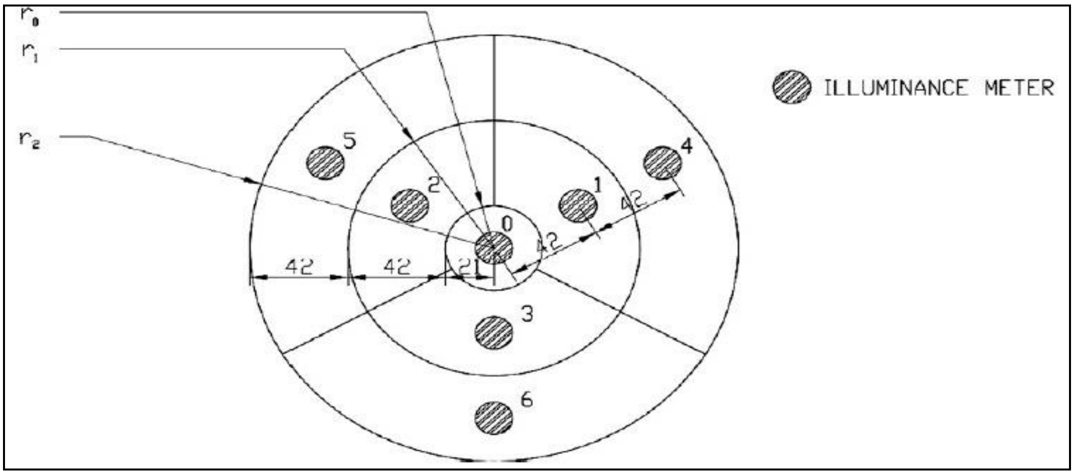


Figure 2-8: The seven-sensor layout for the light pipe measurement.

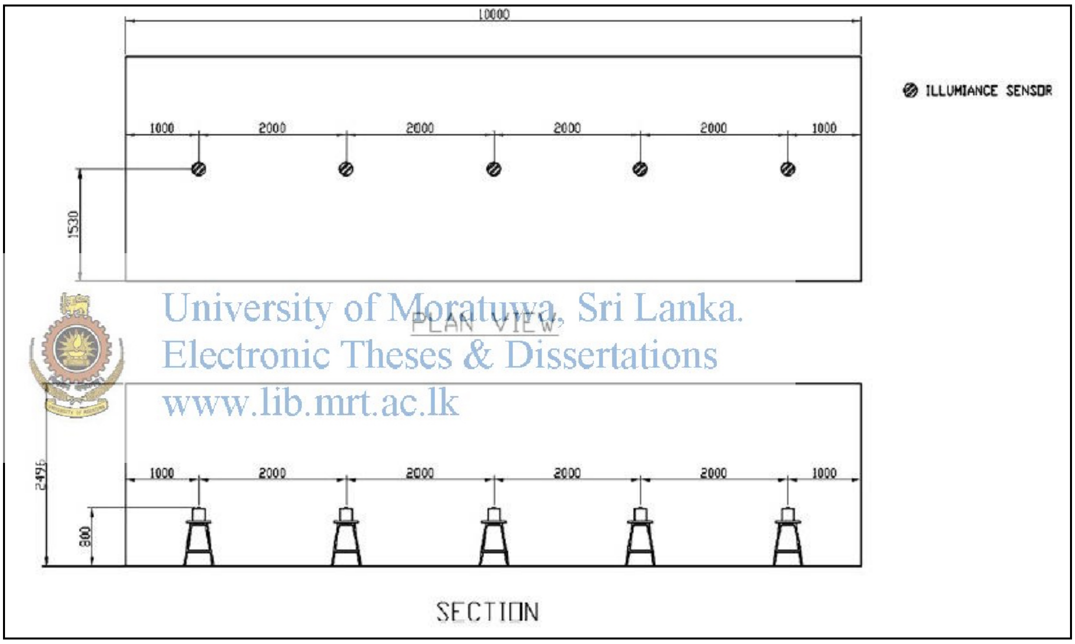


Figure 2-9: Plan view and section of the five measuring points in the corridor.

In total, more than 1100 sets of data has been recorded although there have been some short periods of missing readings. Data has been recorded and analysed for Interior Illuminance and Sky conditions.

The light pipe model has been analysed using three model types named as Zhang and Muneer model, Jenkins et al. model, CIE model.

Accordingly, the predicted illuminance results for the five reference points using the three models has been computed and evaluated against measured data.

The daylight illuminance falling on and transmitted via the light-pipe system and the illuminance levels in the corridor has been recorded and compared.

It has found that the mean transmittance (s) has been 0.21 with a standard deviation of 0.03. The daylight illuminance in the corridor has been measured by means of five illuminance meters. For overcast sky conditions with the clearness index (Kt) below 0.18, the measured illuminancehas been between 8 and 55 lx. Under clear skies which are dominated by direct component, the Kt has been over 0.7 and the interior illuminance more than 200 lx. When the skies have been in partly cloudy conditions, the measured illuminance ranged from 15 to250 lx. The determined uniformity has been very good with the minimum value of around 0.8 for all sky conditions. To predict the illuminance output of a given light-pipe system, three prediction models have been analysed. Due to its universal nature, simplicity of use and good predictive ability, the CIE model has been presently selected to determine the long-term internal illuminance (Ein) produced by the light-pipe system. Based on the measured outdoor illuminance, the Ein and hence the lighting energy expenditures for various lighting controls have been calculated. It has found that the light-pipe system integrated with proper lighting controls can substantially reduce the lighting energy use.

2.3.5 Tubular guidance systems for daylight: Achieved and predicted installation performances

Mohammed Al-Marwaee, David Carter [7] have presented the results of several surveys of daylight guidance systems in 13 working buildings in UK. They have revised the various prediction methods that have been promulgated and describes and identifies those that are both capable of acknowledging design criteria and are suitable for routine design use. The methods have been tested against the data from the results of the surveys of installations.

Surveys have been carried out in 13 buildings in UK. The installations have been mainly in commercial, healthcare or academic buildings, in which clerical or similar work has been undertaken. Five of the installations have been in new buildings, but most have been retrofitted to existing accommodation. All buildings have been equipped with electric lighting in addition to guided daylight. The electric lighting has been almost exclusively mirrored louvered down lighters with tubular or compact fluorescent lamps. Eight of the installations have been windowless, the others having vertical windows. The guide output devices have been circular domed or flat opal diffusers, or 600 mm x 600 mm square lensed panels, all located in suspended ceilings. Two installations have had daylight linked continuously to variable electric-lighting. A further site has had an individual luminaire control, but the majority of the sites have had no additional control of electric lighting.

In their survey they have found some facility management issues. Only two installations have had any form of daylight linking installed, but on their visits, this system has been disabled. The effect of this was that the lighting levels in all installations varied upwards from the electric-lighting design illuminance. There has been no evidence of systematic maintenance in any installation despite evident problems of condensation and dirt accumulation inside some guides. The mode of usage of the systems has been that of an electric system with conventional on–off switching. In no installations had staff received information on system use, and anecdotal evidence has suggested that knowledge of the guidance systems amongst users was sparse.

They have measured the achieved lighting levels. Analysis of the data shows the illuminance for installations with windows not to be statistically significantly different from those without. Only 7% of the total occupants have been working below the SLL recommended values for offices (300–500 lux), but some 75% have been working in illuminance values above this range.

Only 20% of the measured daylight levels would on their own satisfy SLL illuminance requirements for offices. In general, the daylight contribution represents between 25% and50% of total illuminance. A major reason for this is that the number of luminaires exceeds the number of daylight output devices in all installations, in some cases greatly so. Also there is a big difference between the light outputs of the luminaires and the daylight output devices.

The most common type of luminaire used – 600 mm x 600 mm downlight with four PL lamps has a typical light output of 4800 lumens. The daylight output of the devices in some installations , for example, ranges from approximately 950 lumens in prevailing temperate overcast conditions to 8500 lumens under a midsummer clear-sky with sunlight.

2.3.6 Efficient tubular light guide with two-component glazing with Lambertian diffuser and clear glass

M. Kocifaj[8] has analyzed the performance as well as the illuminating abilities of a tubular light guide system furnished by two component glazing on its base. The glazing has consisted of two optical elements: a Lambertian diffuser and clear glass where the inner parts of circular glazing behave like Lambertian diffuser while the edges of the glazing are built of clear glass. The illuminance distributions on the two-component glazing and the work plane situated below the light guide has been calculated simultaneously.

The efficiency of light guide systems with two-component optical interface has been analyzed from the performance point of view. The two-component optical element composed of circular Lambertian diffuser situated in its inner part and fully transparent glass at its edges has been modelled. It has found several advantages of the optical component with such concentric rings as:

(a) It utilizes the electromagnetic energy much better than traditional Lambertian diffusers

(b) The direct sunbeams are appropriately redirected to the work plane and thus interior lighting conditions are improved significantly (especially in the morning and evening times, when the elevation of the Sun is quite low)

(c) The light excesses typically presented below fully transparent glazing are efficiently eliminated if the inner part of the glazing is replaced by Lambertian diffuser.

It has concluded that two component optical element seems to be convenient solution for moderately long light tubes in which the multiply reflected sunbeams play an important role.

2.3.7 The costs and benefits of using daylight guidance to light office buildings

M.S. Mayhoub and D.J. Carter [9] have analysed the costs and benefits of using the two main classes,

- Tubular Daylight Guidance Systems (TDGS) used in combination with Electric Lighting Systems
- Hybrid Daylight/Electric Systems (HLS) of daylight guidance to light offices as an alternative to conventional electric lighting.

They have analysed costs and benefits of using Daylight Guidance Systems (DGS) to light offices as an alternative to Electric Lighting Systems (ELS). The study has used firstly, conventional quantifiable measures of cost and benefit and secondly, additional benefits including cooling loads savings, carbon emission savings, and user productivity improvements.

It has found that out of the two main guidance types tubular daylight guidance systems, although commercially successful, have been used to light only a limited number of working buildings, mainly offices, worldwide. The newer hybrid daylight/electric systems, although on the market, have to date been used for only a handful of actual installations. The work has concerned whole life cycle economic analysis of daylight guidance. Current practice for application of this method to lighting systems is to include only capital cost items, and running costs such as electricity and maintenance.

The associated 'Level 1'benefits are mainly savings in electricity by daylight substitution, and maintenance. The work has used whole life cycle methods for interiors lit using daylight guidance and electric systems but extends the analysis to include a range of 'Level 2' costs and benefits. The latter may include the cost of accommodating guidance systems in a building, and the range of possible benefits include reductions in heating/cooling loads, reduction in carbon taxes and improvement in well-being and productivity of occupants due to daylight. This breakdown of costs and benefits are tabulated in Table 2-4.

Table 2-3: Breakdown of costs and benefits

	Costs	Benefits
Level 1 "Tangible Benefits"	Initial Capital Cost Running Cost	Electricity Savings Electric lighting system capital and maintenance saving
Level 2 "Intangible Items"	Opportunity cost of floor/roof space	Building heating/cooling savings Carbon tax savings Effect of daylight on human well-being Enhanced corporate prestige Residual value

They have observed that the Daylight Guidance Systems (DGS) require a substantially greater capital investment than Electric Lighting Systems (ELS). Some such as Tubular Daylight Guidance Systems (TDGS) have been shown to be economic over the long term if they are solely regarded as devices to enable daylight to be substituted for electric lighting - the 'tangible benefits'. This work has attempted to quantify the 'intangible' benefits of the delivery of guided daylight to an interior. These are by their nature more difficult to quantify and a number of assumptions, each of which may be questioned, are necessary to make this possible. The results suggest that the benefits of Heat Replacement Effect (HRE) and carbon taxes pale into insignificance in comparison with those of productivity improvements.

The latter suggests that investment paybacks could be reduced by up to 75% of those calculated using only Level 1 assumptions. However it is evident that DGS which are fundamentally uneconomic using Level 1 cost/benefits struggle to achieve satisfactory paybacks even taking productivity into account. However in the case of those systems that are only marginally uneconomic the inclusion of productivity does give a more favourable balance of cost and benefit. This work has established that the economic performance of daylight guidance systems has several dimensions. System payback periods are mainly determined by levels of capital cost, energy costs, external illuminance level (which in turn is influenced by geographical location) and, potentially, considerations of the influence of productivity gains due to daylight in working areas. This study, although based on current technology and costs and a limited number geographic locations, has set out the principles of economic analysis of guidance systems.

3 PRODUCT REVIEW ON TUBULAR DAYLIGHTING SYSTEMS

Currently, various light pipe systems are commercially available and each system has its own characteristics and effectiveness. The light pipe systems manufactured by Solatube International Inc. (USA), Monodraught Ltd (UK), Velux (Denmark), and Solarspot International (Italy) were selected in this investigation to show their characteristics and applications.

3.1 Systems Produced by Solatube International Inc. (USA)

The product from Solatube International Inc. (USA) is called as "Solatube".

3.1.1 Technical Details of "Solatube"

The manufacturer highlights following key features in their products.

- Raybender 3000 Technology
- Patented daylight-capturing dome lens
- Redirects low-angle sunlight
- Rejects overpowering summer midday sunlight
- Consistent lighting throughout the day

"Raybender 3000 Technology" is a patented component of "Solatube" products that intercepts low angle light and redirects it down the tube. The light is actually reflected down the tubing at a steeper angle, in order to minimize the amount of times the light must reflect (which reduces light output). The technology allows the "Solatube" Daylighting System to capture much more early morning light and early evening light. With this technology, "Solatube" products can enjoy natural daylight for longer periods of time.

"LightTracke Reflector" is a patented in – dome reflector installed in Solatube which redirects low-angle sunlight. It increases light input for increased light output.

The reflective tube which is called "Spectralight Infinity Tubing" gives 99.7% spectral reflectivity for "Solatube" and a pure color rendition. This can transfer sunlight up to a length of 50ft/15m according to the manufacturers.

Engineered Light Diffusion of "Solatube" blocks UV transmission and the optical lenses deliver a maximum amount of diffusion for visual comfort.

The accessories of the "Solatube" system are having characteristics as described below according to the manufacturer.

Dome

"Solatube" domes are injection molded from impact-resistant acrylic. This special formula includes UV screening up to 380 nanometers to prevent fading and cancer causing solar radiation. The unique dome geometry maximizes light collection while staving off airborne particulates. Natural moisture, nighttime dew and rain help maintain dome clarity.

Flashing

"Solatube" has designed a circular flashing that doubles as a built-in water diverter. The one-piece flashings have no seams that could open from thermal expansion and contraction, setting the industry standard for leak-proof flashing systems.

Angle Adaptors

Standard on all "Solatube" Daylighting Systems, angle adaptors make navigating around attic obstructions a breeze. Extension tubes are available for four angles 0^0, 30^0 ,$60^0$and 90^0.

Moisture Control System

"Solatube" Daylighting System is constructed with factory-installed seals for minimum air infiltration and a Moisture Control System that draws moisture into a special channel below the dome and out through specially-designed exit holes.

Tubular Skylights manufactured by Solatube International Inc. are available in two categories as **Brighten Up** Series and **Solar Master** Series.

Brighten Up Series

The "Solatube 160 DS" and "Solatube 290 DS" Daylighting Systems of the Brighten Up series feature the patented "Raybender 3000" Technology and "Light Tracker" Reflector to deliver an Effective Daylight Capture Surface (EDCS). EDCS (Effective Daylight Capture Surface) represents the surface area of the dome that collects and redirects sunlight. For comparison, a clear dome with no lens on a typical 10 inch tube system has an EDCS of 78.5 square inches. Figure 3-1 shows a Brighten Up series product installed on a pitched roof. Table 3-1 shows the characteristics of the Brighten Up series models.

Figure 3-1: Installation on a pitched roof

Table 3-1: Brighten Up series models

Model	Tube Size (Diameter)	EDCS	Light Coverage Area	Potential Tube Length
Solatube 160 DS	≈10 inch (250 mm)	160 in^2 (1032 cm^2)	150 - 200 ft^2 (14 - 19 m^2)	20 ft+ (6 m+)
Solatube 290 DS	≈14 inch (350 mm)	290 in^2 (1871 cm^2)	250 - 300 ft^2 (23 - 28 m^2)	30 ft+ (9 m+)

Typical applications of above mentioned products are Bathrooms, Hallways/ Corridors, Utility Rooms, Dens/Home Offices, Kitchens, Dining Rooms and Closets.

Brighten Up Series Accessories

The key features of the accessories are described as below.

Flashings

These are available for most of the roof types and pitches. The flashings provide complete protection and create an attractive appearance on the roof. They're fabricated as a single, seamless piece to ensure leak-proof performance. Pitched flashings provide the optimal position for the tube to capture daylight on sloped roofs (Figure 3-2).

No Pitch	Pitched	Universal Tile	Curb Mounted
			

Figure 3-2: Flashing types of “Brighten up series”

Turret Extensions

These are used to raise the height of the “Solatube” dome on a roof to avoid snow, water, or shading from roof obstructions (Figure 3-3). These are Available in 2 in/50 mm,4 in/100 mm, 12 in/300 mm,24 in/600 mm, 36 in/900 mmand 48 in/1200 mm sizes.

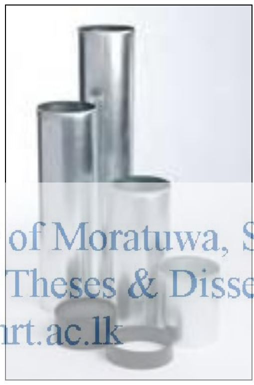


Figure 3-3: Turret extensions

Extension Tubes

Extension tubes (Figure 3-4) can be added in increments of 16 in/400 mm or 24 in/600 mm for long runs without sacrificing performance. The secret is the unrivalled reflectivity of Spectralight® Infinity tubing, making it possible to create up to 90 degree angles and long tube runs up to 3ft/9m.

Figure 3-4: Extension Tubes

Daylight Dimmer

Because we don't need 100% of the light 100% of the time, the Daylight Dimmer easily controls the amount of daylight entering a room with the convenience of a switch. The proprietary variable butterfly baffle controls the light output (Figure 3-5)

• Applicable for bedrooms, media rooms and offices.

• Wall mounted switch provides convenient low voltage control.

Figure 3-5: Dimmer

Flashing Insulator

This insulating material helps to reduce flashing condensation in cold climates when the flashing is exposed to a humid interior space. The insulator is affixed to the flashing base and the top tubes lips through the opening, which provides a seal between the interior and metal flashing (Figure 3-6)

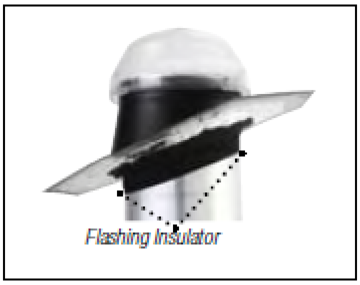


Figure 3-6: Flashing insulator

Light Add-On Kit

When equipped with a Light Add-On Kit, the Solatube Daylighting System provides the convenience of a switched light for night time use (Figure 3-7).

Figure 3-7: Light add on kit

SolaMaster Series

SolaMaster Series of "Solatube" has been designed for expansive spaces require extraordinary amounts of natural light. With the highest Effective Daylight Capture Surface (EDCS) available, these Daylighting Systems feature the largest aperture tubing and patented LightTracker™ Reflector for effective daylight harvesting. With the Spectralight® Infinity tubing, these systems make it possible to bring natural light deep into buildings where natural light has rarely been an option. These are available in two types as **Solatube 21-C daylighting system** and **Solatube 21-O daylighting system .**

Solatube 21-C

The Solatube 21-C features a patented transition box that seamlessly converts the round tubing to a square diffuser. This transition box easily fits into standard commercial ceiling grids. The Solatube modular design offers the ability to be reconfigured when spaces need to change. For hard ceilings, the transition box has a sleek, integrated, self-trim feature, eliminating the need for finishing trim work. These are available of 21 in/ 530mm in tube diameter (Figure 3-8).

These are specially designed for retail, stairwells, schools, lobbies, offices, family rooms, medical rooms etc.

Figure 3-8: Solatube 21-C

Solatube 21-O

The Solatube 21-O brings high-performance daylighting to spaces without a finished ceiling. The Solatube 21-O uses Spectralight Infinity tubing to bypass light-absorbing structural members and deliver highly diffused natural light with a less obtrusive roof opening than required with traditional skylights. Additionally, this system is excellent for retrofits because it can be installed from the roof, eliminating the need for interior scaffolding or lift systems. These are available of 21 in/ 530mm in tube diameter (Figure 3-9).

These are specially designed for warehouses, manufacturing plants, gymnasiums, lofts and for unique architectural effects.

Figure 3-9: Solatube 21-O

SolaMaster Series accessories

There are various additional accessories available for Sola Master series as Daylight Dimmer, Flashing Insulator, Security Bar, Open Ceiling Trim Ring, Shock Dome, Wire Suspension Kit, Spectralight Infinity Extension Tubes and Dome Security Kit. The key features of the accessories are described as below.

Flashings

Table 3-2 Shows the available flashing types for Solar Master Series.

Table 3-2: Flashings

	Self-Mounted	**Curb Mounted**
Built-up		
	Self-Mounted	**Curb Mounted**
Membrane		

Turret Extensions

These are used to raise the height of the Solatube dome on a roof to avoid snow, water or shading from roof obstructions. These are available in 12 in/300 mm, 24 in/600 mm, 36 in/900 mm and 48 in/1200 mm sizes.

Figure 3-10: Turret Extensions

Shock Dome

High Velocity Wind Zone areas require the Solatube Shock Dome. This optional highly impact resistant polycarbonate dome can be installed for extra protection from extreme environmental forces (Figure 3-11).

Figure 3-11: Shock dome

Security Bar

This stainless steel bar inserts into the flashing turret across the diameter of the opening. The bar is fastened using rivets and prohibits entry through the dome (Figure 3-12).

Figure 3-12: Security bar

3.1.2 Price of Solatube

Some of the Solatube prices of the "Brighten Up Series" as those were available by April 2012 are included in Table 3-3.

Table 3-3: Solatube Price list

Product	Price
160DS: Cement Poly Single Tile for 1.52m max install distance	$341.55 + VAT
160DS: Cement Poly Single Tile for 2.64m max install distance	$442.75 + VAT
160DS: Cement Poly Single Tile for 3.76m max install distance	$543.95 + VAT
160DS: Cement Poly Single Tile for 4.88m max install distance	$645.15 + VAT
160DS: Slate and PlainTile Polypropylene/Angled Upstand for 1.52m max install distance	$354.20 + VAT
160DS: Slate and PlainTile Polypropylene/Angled Upstand for 2.64m max install distance	$455.40 + VAT
160DS: Slate and PlainTile Polypropylene/Angled Upstand for 3.76m max install distance	$556.60 + VAT
160DS: Slate and PlainTile Polypropylene/Angled Upstand for 4.88m max install distance	$657.80 + VAT
160DS: Angled Metal Upstand for 1.52m max install distance	$354.20 + VAT
160DS: Angled Metal Upstand for 2.64m max install distance	$455.40 + VAT
160DS: Angled Metal Upstand for 3.76m max install distance	$556.60 + VAT
160DS: Angled Metal Upstand for 4.88m max install distance	$657.80 + VAT
160DS: Universal Angled Upstand Interlocking Tile for 1.52m max install distance	$376.20 + VAT
160DS: Universal Angled Upstand Interlocking Tile for 2.64m max install distance	$477.40 + VAT
160DS: Universal Angled Upstand Interlocking Tile for 3.76m max install distance	$578.60 + VAT
160DS: Universal Angled Upstand Interlocking Tile for 4.88m max install distance	$679.80 + VAT
290DS: Slate and Plain Flat Tile/ABS/Angled Upstand for 1.52m max install distance	$434.50 + VAT
290DS: Slate and Plain Flat Tile/ABS/Angled Upstand for 2.64m max install distance	$555.50 + VAT
290DS: Slate and Plain Flat Tile/ABS/Angled Upstand for 3.76m max install distance	$676.50 + VAT
290DS: Slate and Plain Flat Tile/ABS/Angled Upstand for 4.88m max install distance	$797.50 + VAT
290DS: Angled Metal Upstand for 1.52m max install distance	$434.50 + VAT
290DS: Angled Metal Upstand for 2.64m max install distance	$555.50 + VAT
290DS: Angled Metal Upstand for 3.76m max install distance	$676.50 + VAT
290DS: Angled Metal Upstand for 4.88m max install distance	$797.50 + VAT
290DS: Universal Angled Interlocking Tile for 1.52m max install distance	$464.20 + VAT
290DS: Universal Angled Interlocking Tile for 2.64m max install distance	$585.20 + VAT
290DS: Universal Angled Interlocking Tile for 3.76m max install distance	$706.20 + VAT
290DS: Universal Angled Interlocking Tile for 4.88m max install distance	$827.20 + VAT

3.2 Systems Produced by Monodraught Ltd

Monodraught Ltd Uk. Produces light guidance systems called “**SunPipe”**, “**SunCatcher”** and “**SolaVent”.**

3.2.1 Technical details

SunPipe

The Monodraught SunPipe (Figure 3-13) natural daylight system directs sunlight into a roomfrom roof level. Here, the “SunPipe” collects daylight using a patented Diamond dome, then ituses a silverised mirror-finished aluminium tube with 98% reflectance to transfer the light to a room, and finally aceiling diffuser evenly distributes the light around the room. The horizontal “SunPipe” system (Figure 3-14) has been designed for applications where a south facing wall is used for termination up to 4 meters.

The Diamond dome and diffuser also seal the “SunPipe” from the ingress of rain, dust, and insects. The “SunPipe” is effective in sunny, overcast, and rainy conditions, requires no maintenance, and is compatible with many building designs. For example, multi-floor solutions are possible and common, but some loss of transmittance will occur.

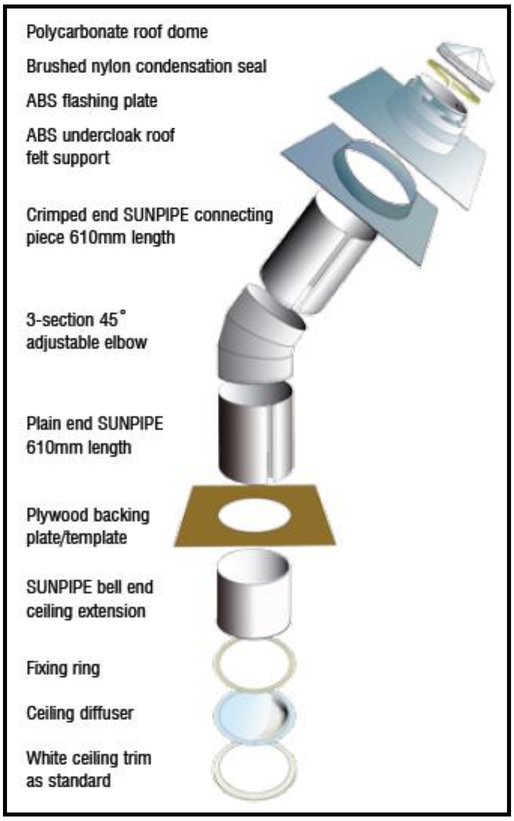


Figure 3-13: SunPipe System

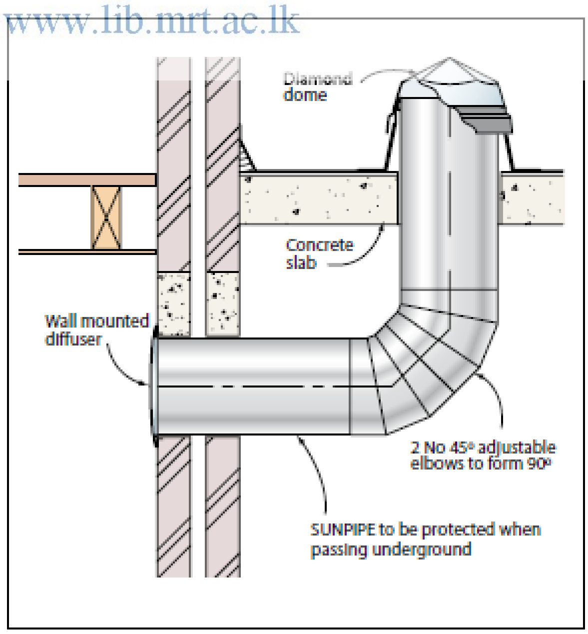


Figure 3-14: Horizontal SunPipe

“SunPipe” is available in various models as Pitched Roof Sunpipe, Flat Roof Sunpipe Kits, Gallery Sunpipe Kits and Square Sunpipe Kits. Using the adjustable sections it can be applied in three different angles 0^0, 30^0 and 45^0. This is available in four different diameters of 230mm (9”), 300mm (12”), 450mm (18”), 530mm (21”). Table 3-4 shows manufacturer recommendation for “Sunpipe” size selection. Table 3-5 shows manufacturer recommendation for extension pipe selection.

Table 3-4: Manufacturer Recommendation for size selection

Area to be lit (to a normal daylight condition)	**Sunpipe Size**
approx 7.5m^2 (80 sq. ft.)	230mm (9” dia)
approx 14m^2 (150 sq. ft.)	300mm (12” dia)
approx 22m^2 (230 sq. ft.)	450mm (18” dia)
approx 40m^2 (430 sq. ft.)	530mm (21” dia)

Table 3-5: Manufacturer Recommendation for Extension Pipe usage

Overall length ('X')	**No. of Extension Sunpipes**
up to 1200mm (4ft)	none
1200mm(4ft) to 1800mm (6ft)	one
1200mm (6ft) to 2400mm (8ft)	two
2400mm (8ft) to 3000mm (10ft)	three
3000mm (10ft) to 3660mm (12ft)	four
over 3660mm (12ft) add one length per extra 610mm (2ft)	

Sunpipe Accesories

Flashings

Figure 3-15 shows different flashing types available for "Sunpipe".

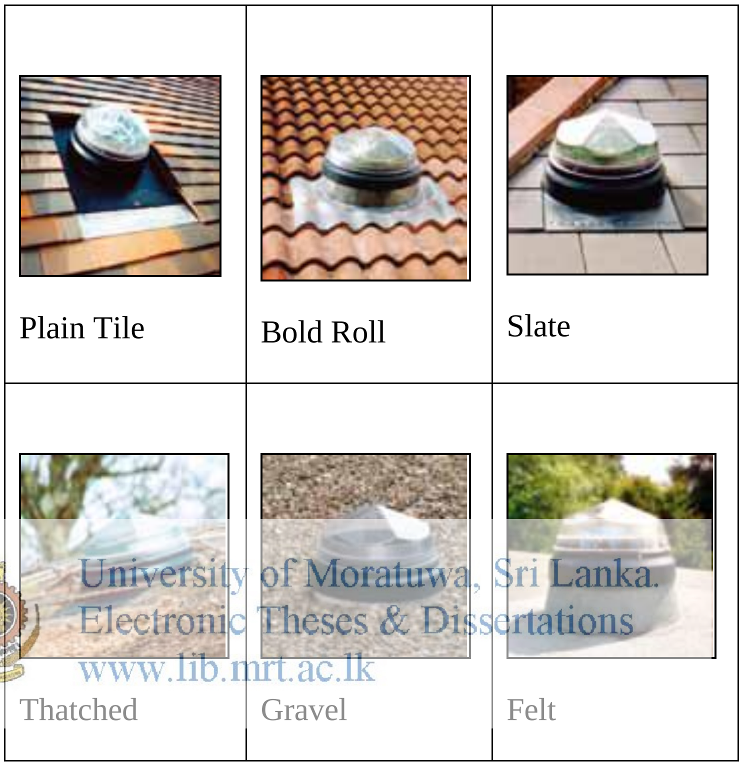


Figure 3-15: Sunpipe Flashing Types

Applications of SunPipe

The applications of "Sunpipe" are presented in Table 3-6.

Table 3-6: Applications of Sun Pipe

Domestic	**230mm (9" diameter)**	**300mm (12" diameter)**	**450mm (18" diameter)**	
	Shower rooms, toilets up to 7.5 m^2	Stairs and landings, kitchens, study and living rooms up to 14 m^2	For larger areas up to 22 m^2	
Schools	**300mm (12" diameter)**	**450mm (18" diameter)**	**530mm (21" diameter)**	**750mm, 1000mm (30",40" diameter)**
	Corridors at 3m centres, store rooms, toilet areas and changing rooms up to 14 m^2	Wider corridors 4m centres and small class rooms up to 22 m^2	Deep plan class rooms	Sports halls and similar areas where floor to ceiling height exeeds 5m
Hospitals	**300mm (12" diameter)**	**450mm (18" diameter)**	**530mm (21" diameter)**	
	Internal corridors and store rooms	Consulting rooms, waiting areas, larger offices	For areas with floor to ceiling heights up to 5m	
Offices	**300mm (12" diameter)**	**450mm (18" diameter)**	**530mm (21" diameter)**	
	Small separate offices up to 14m^2	Open plan offices with a ceiling height grid of 4m	To suit a ceiling grid of 5 to 6m	
Industrial and leisure	**450mm (18" diameter)**	**530mm (21" diameter)**	**750mm (30" diameter)**	**1000mm (40" diameter)**
	For where ceilings are 4m above floor	For where ceilings are 5m above floor	sports halls, retail stores etc.	Warehouses

SunCatcher

SunCatcher is a system produced as an integration of natural ventilation system called WindCatcher with the "SunPipe" system (Figure 3-16)

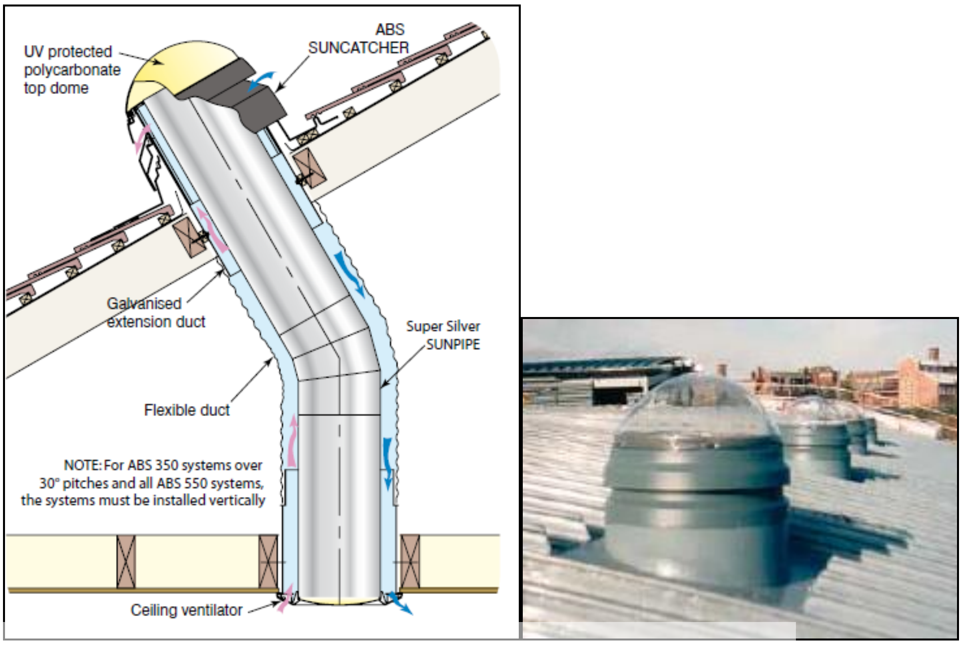


Figure 3-16: SunPipe system

The system provides controlled natural ventilation as well as providing all the benefits of natural daylight. Any prevailing wind pressure carries a continuous fresh air supply through weather protected louvers on the windward side of the system at the roof level. The wind movement is encapsulated by internal quadrants which turns the wind through 90 degrees forcing air down through internal ducts into the room below. Warm stale air is expelled from the room by passive stack ventilation principle of differential temperatures and the natural buoyancy of air movement. Manual or motors at the base of the system control the rate of ventilation. The central "SunPipe" natural daylight system is integrated into the system and conveys natural daylight where needed.

SolaVent

This is an integration of the “SunPipe” system with a solar powered extract ventilation system designed for bathroom lighting and ventilation. This consist of a “SunPipe” , two compact florescent halogen downlighters and a solar powered extract fan (Figure 3-17).

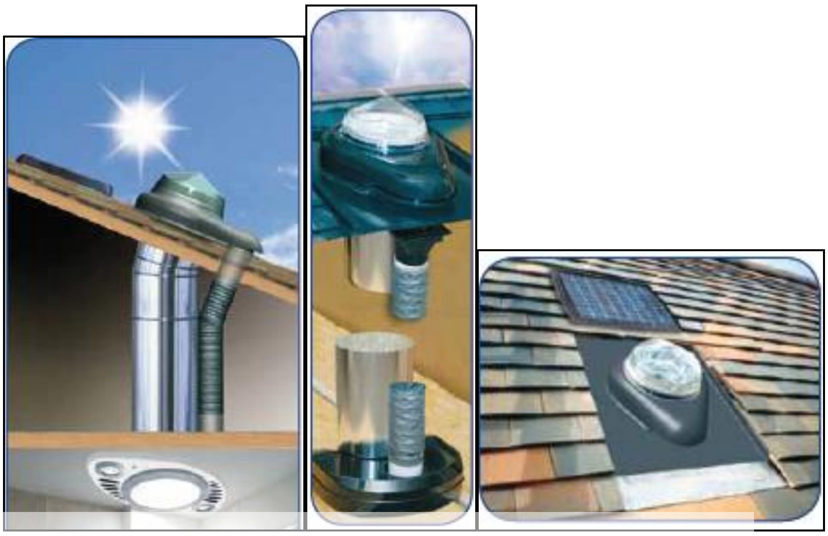


Figure 3-17: Solavent with SunPipe

3.2.2 Price of Sunpipe

Table 3-7 shows some of the "SunPipe" prices as those were available by April 2012.

Table 3-7: SunPipe prices as those were available by April 2012

PITCHED Roof SUNPIPE **Kits (up to 45˚)**	**230mm dia** **(9")** **$**	**300mm dia** **(12")** **$**	**450mm dia** **(18")** **$**	**530mm dia** **(21")** **$**
Slate Roof Kit (ABS flashing plate)	222.20	284.90	416.90	511.50
Plain Tiled Roof Kit (ABS flashing plate with weathering skirt)	247.50	308.00	446.60	540.10
Bold Rolled Tiled Kit (Code 4 lead flashing)	349.80	397.10	630.30	752.40
Metal Roof Kit (excluding flashing & elbow)	134.20	167.20	237.60	316.80
Standard extension 24" (610mm) Pipe	30.80	42.90	55.00	64.90
3-section adjustable 45˚ elbow	35.20	45.10	92.40	111.10
2-section adjustable 30˚ elbow	29.7	40.70	70.40	83.60

3.3 Systems Produced by Solarspot International

Solarspot International produces the devices called “Solarspot”. Solarspot lighting system (Figure 3-18) catches the sunlight in any sky condition (clear or overcast) coming by every direction. It consists of its specific components: the transparent dome in anti-shock acrylic, protected against UV rays, the optical intercepting device RIR® - a light funnel - that redirects all light beams coming from North and even the lowest on the horizon, inside the transfer cylindrical duct, made of internal and super-reflective surfaces of “Vegalux” with a reflectivity of 99.5% according to the manufacturers. Bouncing on the specular surface of the duct, the light beams reach and cross the translucent diffuser (available with many finishings) by creating a highly lighting surface (circular or quadrangular) on the ceiling, capable of lighting even the darkest areas.

“Solarspot” blocks UV rays and doesn't heat the areas with direct heating, usually produced by glass windows and traditional skylights.

“SolarSpot” day lighting devices are manufactured as various models called “Solar-Wall” , “Solar-Attic”, “Solar-Work”.

The “Solar Wall” systems (Figure 3-19) are designed for the areas where can be reached only from ground and wall. Here “Solarspot” is used to convey light horizontally and uphill using angle adapters and reflective tubes.

Figure 3-18: Solarspot System

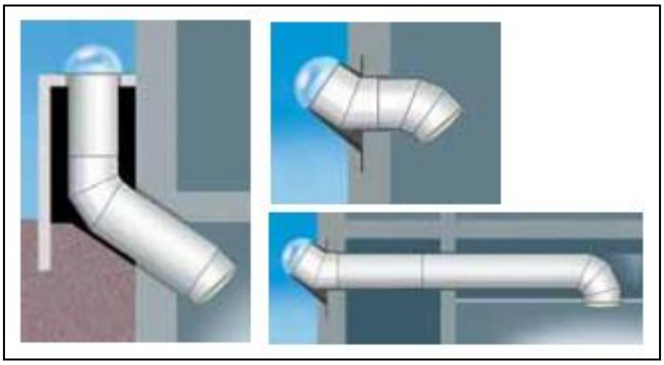


Figure 3-19: Solar Wall Systems

3.3.1 Technical Details

“SolarSpot” Device is available in 250mm, 375mm, 530mm, 650mm, 900mm in Diameter sizes.

Angle adapters are available in 30^0, 60^0 and 90^0angles whereas the extension tubes are available in 0.3 m – 1.2 m size range.

Flashings are available as universal flashing for any diameter, tile and sloping roof. Also there exists number of other flashing types as Round and flat aluminized flashing with brim, Round and flat aluminized flashing, Square and flat copper flashing 625mm*625mm available forD.250-375 with bent brims according to standard measures.

Metal transition boxes are available for the circular to square shape transformation. Darkening systems are available as electrical and manual.

“Vegalux” - super-reflective duct produced with the multi-layer VMF film on rolled aluminium alloys hardened, to assure the maximum elasticity and solidity to the duct, which will have the interior walls with a specular reflectance in the visible range (440-780 nm) of almost 99,5%.

According to the manufacturers this product does not reflect the infrared long waves and minimizes the heat transfer, even due to solar heat gains, for the best true colors rendering (100%). Various diffuser types are available to apply with different sizes of tubes and to achieve different visual performance.

3.4 Systems Produced by VELUX Canada Inc

VELUX produces the systems called "Sun tunnels". The "Sun tunnels" are manufactured as "Rigid Sun tunnels" and "Flexible Sun tunnels". "Rigid Sun tunnels" are available as "TMR", "TLR" and "TGR" models. Flexible Sun tunnels are available as "TMF", "TGF" models. They manufacture a Sun tunnel for commercial applications under the model name "TCR".

The VELUX "Flexible Sun tunnels" (Figure 3-20) and "Rigid Sun tunnels" (Figure 3-21) are designed to provide natural light into areas of the house such as corridors, stairwells, bathrooms, cupboards, etc.

Rigid and Flexible "Sun tunnels" Can be installed in sloped roofs with roof pitch is in a range of 14°-60°.

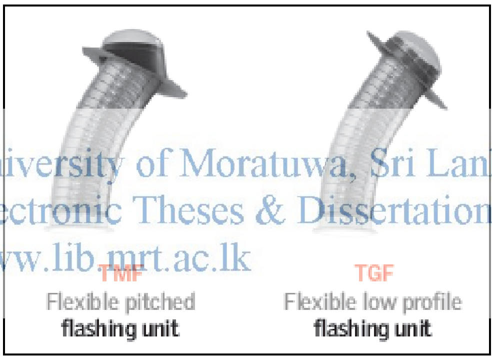


Figure 3-20: Flexible Sun tunnels

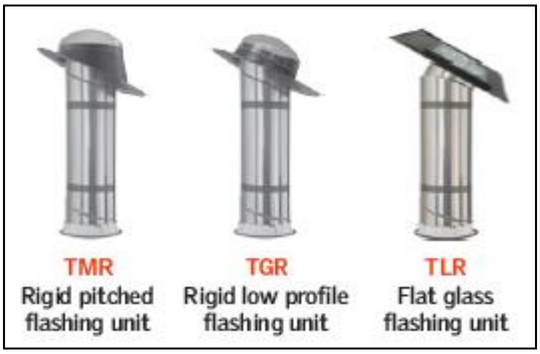


Figure 3-21: Rigid Sun tunnels

The commercial Sun tunnel model "**TCR"** is available in a 14" or 22" diameter. Run length calculated based on vertical drop .Run length accounts for standard 2" overlap between components. Effective lighting area is up to 400 square feet (22" model) or up to 325 square feet (14" model). These can be applied on the pitched roofs with the angle in a range of 0^0- 30^0.

3.4.1 Guide lines given by the manufacturer for choosing Sun tunnels

1. Choose Flashing by Roof Orientation

• Pitched model (North, South, East, West exposure).

• Low profile model (South exposure only).

2. Choose Tunnel Type

• Rigid - For straight runs and moderate bends. Maximum light output.

• Flexible - Easily bends around attic obstructions.

3. Choose Sun Tunnel Size and Quantity

• 10", 14" or 21".

• Consider truss/rafter spacing.

• Consider room size and light requirements

Table 3-8 shows the light coverage capacity of "Sun tunnels" according to the manufacturer.

Table 3-8: Light coverage of Sun tunnels

Pitched Flashing N, S, E, W exposures	10”	14”	21”
	Light Coverage	**Light Coverage**	**Light Coverage**
Rigid Tunnel	Up to 200 sq. ft. Model TMR 10	200 to 325 sq. ft. Model TMR 14	N/A
Flexible Tunnel	N/A	Up to 200 sq. ft. Model TMF 14	See TGF 21 option
Low Profile Flashing (South exposures only)			
Rigid Tunnel	Up to 200 sq. ft. Model TGR 10	200 to 325 sq. ft. Model TGR 14	N/A
Flexible Tunnel	N/A	Up to 150 sq. ft. Model TGF 14	150 to 325 sq. ft. Model TGF 21

3.4.2 Price of Sun tunnel

The maximum recommended installation lengths and the prices for the packages including dome, shingle roof flashing, tunnel, two adjustable elbows, ceiling ring and diffuser of the Rigid Sun tunnels as in Table 3-9. The price is as that was available by March 2012.

Table 3-9: Rigid Sun tunnel Prices

Model	**TMR**		**TGR**		**TLR**
Rough opening diameter	10”	14”	10”	14”	14”
Max. Recommended installation length	14’	18’	14’	18’	18’
Price ($)	289	409	279	399	479

The maximum recommended installation lengths and the prices for the packages including dome, shingle roof flashing, flexible tunnel, ceiling ring and diffuser of the Flexible Sun tunnels as in Table 3-10. The price is as that was available by March 2012.

Table 3-10: Flexible Sun tunnel Prices

Model	**TMF**	**TGF**	
Rough opening diameter	14”	14”	21”
Max. Recommended installation length	8’	8’	12’
Price ($)	409	399	529

4 RESEARCH METHODOLOGY

A case study is carried out for two office rooms in the 2nd floor of "The Proposed Irrigation Department of Sri lanka office building at Galgamuwa" which is a project undertaken by Central Engineering Consultancy Bureau, 415, Bauddhaloka Mawatha, Colombo 07, Sri lanka.

Three Tubular daylight guidance systems which are of 250mm, 350mm and 525mm in diameter are analysed for their lumen outputs with DIAlux 4.11 software [15].

DIAlux 4.11 software [15] is used to carry out modelling and light simulation of the lighting systems in the existing design.

DIAlux 4.11 software [15] is used to plan and analyse the performance and lumen outputs of the Tubular daylight guidance systems for the following cases and the results are compared.

(i) Light up the rooms entirely with the Tubular daylight guidance systems in the day time functional hours of the office to maintain the currently planned illuminance levels.

(ii) Light up the rooms entirely with the Tubular daylight guidance systems in the day time functional hours of the office to maintain the standard average illuminance levels.

(iii) Light up the rooms by Tubular daylight guidance systems together with the artificial lighting systems in the day time functional hours of the office to maintain the currently planned illuminance levels.

(iv) Light up the rooms by Tubular daylight guidance systems together with the artificial lighting systems in the day time functional hours of the office to maintain the standard average illuminance levels.

An economic life cycle cost analysis for 10 years period is carried out for the lighting systems integrated with Tubular daylight guidance systems.

The results are analyzed to find out the most feasible solution to integrate day light with Tubular day light guidance systems in the office rooms subjected to study.

5 ANALYTICAL FRAMEWORK

This research is carried out to find out the feasibility of integrating day light in the office buildings of Sri Lanka with Tubular skylights.

Three models of Tubular skylights which are designed for lighting offices subjected to study in the research are as in Table 5-1.

Table 5-1: Tubular Skylight models

Tubular Skylight	**Pipe Diameter (mm)**
TS1	250
TS2	350
TS3	525

Luminaire data files of the Tubular skylights developed for Sri lanka to be used in lighting simulation software were obtained from the Tubular skylight manufacture called Solatube®corporation USA [11] via the local agents. Since the lumen output of a Tubular skylight varies with the Altitude angle of the sun (Figure 5-1), the manufacturer provided luminaire data files developed for 10°,20°,30°,40°,50°,60°,70°,80°,90° altitude angles of the sun.

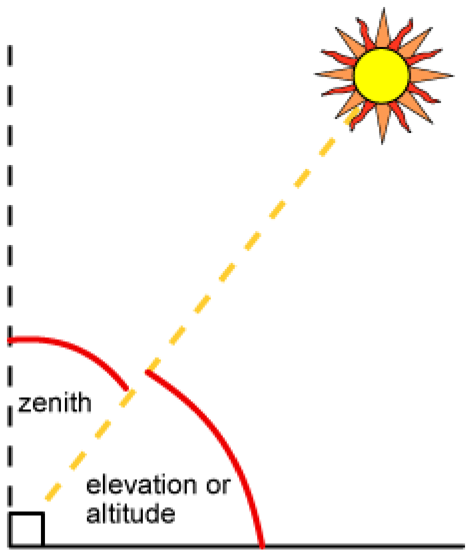


Figure 5-1: Altitude angle of the sun

Since the lumen output of the Tubular skylights vary with the sky condition, the manufacturer provided luminaire data files developed for the Clear sky conditions and Cloudy sky conditions (Table 5-2).

Table 5-2: Lumen outputs of Tubular skylight Models

Tubular Skylight	**Sun Altitude Angle(°)**	**Average Lumen Output (lm) for Clear sky in Sri Lanka**	**Average Lumen Output (lm) for Overcast sky in Sri Lanka**
TS1	10	351	58
	20	904	148
	30	1093	179
	40	1521	249
	50	1826	300
	60	1860	305
	70	2028	333
	80	2378	390
	90	2362	387
TS2	10	881	149
	20	1714	290
	30	2531	428
	40	2920	493
	50	3502	592
	60	3560	602
	70	3873	655
	80	4462	754
	90	4538	767
TS3	10	962	192
	20	2539	508
	30	4990	998
	40	7670	1534
	50	10229	2117
	60	13460	2692
	70	15401	3080
	80	17156	3431
	90	18193	3639

In the research the average lumen outputs of the Tubular skylights are referred to as lumen outputs.

The lumen outputs of the Tubular skylight models are plotted against Sun altitude angles as (Figure 5-2, Figure 5-3, Figure 5-4).

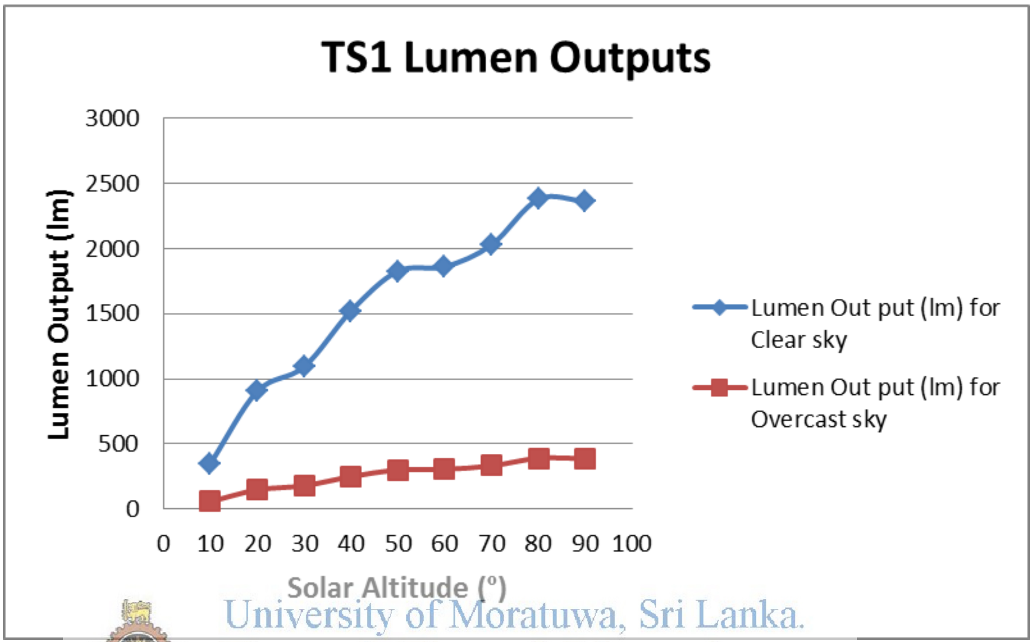


Figure 5-2: Lumen output Vs Solar Altitude angle for TS1

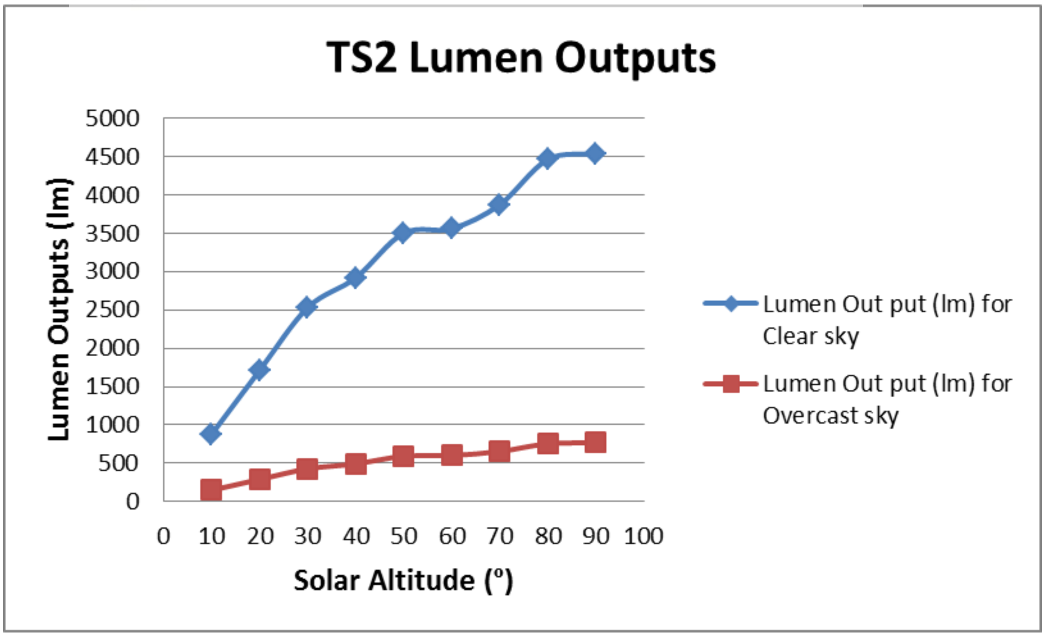


Figure 5-3: Lumen output Vs Solar Altitude angle for TS2

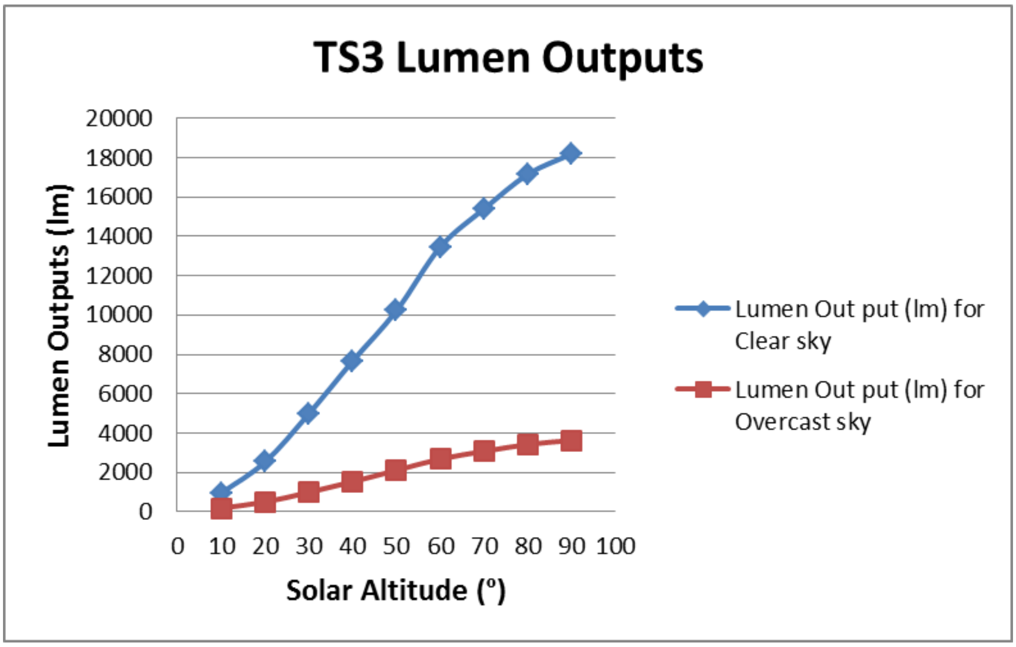


Figure 5-4: Lumen output Vs Solar Altitude angle for TS3

The tubular skylight models have been developed to analyze the illuminance levels in different altitude angles of the sun in the modeled spaces with the lighting simulation software. Therefore when a certain Tubular skylight model of a specific Sun altitude angle is inserted into a modeled space in DIAlux 4.11 [15] software, it can calculate the illuminance level on a desired workplane. But it would be possible to analyze the illuminance levels only at the given set of Sun altitude angles varied from 10º to 90º in 10º increments.

Therefore, to analyze the Tubular skylight performance for a certain case a method had to be formed with certain assumptions and approximations.

5.1 Method Formation

5.1.1 Method to perform Light simulation and analysis

The lumen output variation of Tubular skylights with the time

The altitude angle of the sun varies with the time of the day from sun rise to sun set from 0° to 180°. The sun rise and sun set times in Sri lanka slightly varies with the day of the year (Table 5-3)

Table 5-3: Sun rise - Sunset times in Sri Lanka of the year 2015

Sun Rise and Sun Set 2015

2015	January		February		March		April		May		June		July		August		September		October		November		December	
Day	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set
01	0622	1806	0629	1819	0623	1823	0609	1820	0557	1819	0553	1823	0559	1830	0604	1829	0603	1818	0559	1802	0558	1750	0607	1752
02	0622	1806	0629	1819	0623	1823	0609	1820	0557	1819	0554	1823	0559	1830	0604	1829	0603	1818	0558	1802	0558	1750	0607	1752
03	0623	1807	0629	1820	0623	1823	0608	1820	0556	1819	0554	1824	0559	1830	0604	1829	0603	1817	0558	1801	0558	1750	0608	1753
04	0623	1807	0629	1820	0622	1823	0608	1820	0556	1819	0554	1824	0559	1830	0605	1829	0603	1816	0558	1801	0558	1750	0608	1753
05	0624	1808	0629	1820	0622	1822	0607	1820	0556	1819	0554	1824	0600	1830	0605	1828	0603	1816	0558	1800	0558	1750	0609	1753
06	0624	1808	0629	1820	0621	1822	0607	1820	0556	1819	0554	1824	0600	1830	0605	1828	0603	1815	0558	1800	0558	1750	0609	1754
07	0624	1809	0629	1821	0621	1822	0606	1819	0555	1819	0554	1825	0600	1831	0605	1828	0602	1815	0558	1759	0559	1750	0610	1754
08	0625	1809	0629	1821	0621	1822	0606	1819	0555	1819	0554	1825	0600	1831	0605	1828	0602	1814	0558	1759	0559	1750	0610	1754
09	0625	1810	0629	1821	0620	1822	0605	1819	0555	1819	0554	1825	0601	1831	0605	1827	0602	1814	0558	1758	0559	1749	0610	1755
10	0625	1810	0628	1821	0620	1822	0605	1819	0555	1819	0554	1825	0601	1831	0605	1827	0602	1813	0557	1758	0559	1749	0611	1755
11	0626	1811	0628	1821	0619	1822	0604	1819	0555	1819	0555	1826	0601	1831	0605	1827	0602	1813	0557	1757	0600	1749	0611	1756
12	0626	1811	0628	1821	0619	1822	0604	1819	0554	1819	0555	1826	0601	1831	0605	1826	0602	1812	0557	1757	0600	1749	0612	1756
13	0626	1812	0628	1822	0618	1822	0604	1819	0554	1820	0555	1826	0601	1831	0605	1826	0601	1812	0557	1756	0600	1749	0613	1756
14	0627	1812	0628	1822	0618	1822	0603	1819	0554	1820	0555	1826	0602	1831	0605	1826	0601	1811	0557	1756	0600	1749	0613	1757
15	0627	1813	0628	1822	0617	1822	0603	1819	0554	1820	0555	1827	0602	1831	0605	1825	0601	1811	0557	1756	0601	1749	0614	1757
16	0627	1813	0627	1822	0617	1822	0602	1819	0554	1820	0555	1827	0602	1831	0605	1825	0601	1810	0557	1755	0601	1749	0614	1758
17	0627	1814	0627	1822	0616	1822	0602	1819	0554	1820	0556	1827	0602	1831	0605	1825	0601	1810	0557	1755	0601	1749	0615	1758
18	0628	1814	0627	1822	0616	1822	0601	1819	0554	1820	0556	1827	0602	1831	0605	1824	0601	1809	0557	1754	0602	1750	0615	1759
19	0628	1814	0627	1822	0616	1821	0601	1819	0554	1820	0556	1827	0603	1831	0605	1824	0600	1808	0557	1754	0602	1750	0616	1759
20	0628	1815	0626	1822	0615	1821	0601	1819	0553	1821	0556	1828	0603	1831	0604	1824	0600	1808	0557	1754	0602	1750	0616	1800
21	0628	1815	0626	1822	0615	1821	0600	1819	0553	1821	0556	1828	0603	1831	0604	1823	0600	1807	0557	1753	0603	1750	0617	1800
22	0628	1816	0626	1822	0614	1821	0600	1819	0553	1821	0557	1828	0603	1831	0604	1823	0600	1807	0557	1753	0603	1750	0617	1801
23	0628	1816	0625	1822	0614	1821	0559	1818	0553	1821	0557	1828	0603	1831	0604	1822	0600	1806	0557	1753	0603	1750	0618	1801
24	0629	1816	0625	1823	0613	1821	0559	1818	0553	1821	0557	1829	0603	1831	0604	1822	0600	1806	0557	1752	0604	1750	0618	1802
25	0629	1817	0625	1823	0613	1821	0559	1818	0553	1822	0557	1829	0604	1831	0604	1821	0559	1805	0557	1752	0604	1751	0619	1802
26	0629	1817	0624	1823	0612	1821	0558	1818	0553	1822	0558	1829	0604	1830	0604	1821	0559	1805	0557	1752	0605	1751	0619	1803
27	0629	1817	0624	1823	0612	1821	0558	1818	0553	1822	0558	1829	0604	1830	0604	1820	0559	1804	0557	1752	0605	1751	0619	1803
28	0629	1818	0624	1823	0611	1820	0558	1818	0553	1822	0558	1829	0604	1830	0604	1820	0559	1804	0557	1751	0605	1751	0620	1804
29	0629	1818			0611	1820	0557	1819	0553	1822	0558	1829	0604	1830	0604	1819	0559	1803	0557	1751	0606	1751	0620	1804
30	0629	1818			0610	1820	0557	1819	0553	1823	0559	1830	0604	1830	0604	1819	0559	1803	0557	1751	0606	1752	0621	1805
31	0629	1819			0610	1820			0553	1823			0604	1830	0603	1819			0558	1751			0621	1805

For the simplicity of the analysis it was taken the sun rise time as 06.20 in a typical day and the sun set time as 18.20.

The 12 hrs from sun rise to sun set is divided into 18 slots and taken the approximate interval of the sun's altitude angle's variation by 10° for a typical day which gives the result as 40mins.

The sunrise time, sunset time and the time of the sun to arrive a specific altitude varies with the Sun path variation throughout the year. But this variation is not considered in the analysis.

According to the manufacturer's recommendation it was assumed the lumen output variation of the "Solatube" for the sun's altitude angles from 90° to 180° are the mirrored outputs from 0º to 90°. Therefore based on the above mentioned assumptions and considerations the lumen outputs of the Tubular skylights from sun rise to sun set are tabulated as follows. (Table 5-4.)

Table 5-4: Tubular skylight lumen outputs from sunrise to sunset on a typical day

Time	Sun Altitude Angle(°)	TS1		TS2		TS3	
		Lumen Output (lm)		Lumen Output (lm)		Lumen Output (lm)	
		for Clear sky	for Overcast sky	for Clear sky	for Overcast sky	for Clear sky	for Overcast sky
06.20	0	-	-	-	-	-	-
07.00	10	351	58	881	149	962	192
07.40	20	904	148	1714	290	2539	508
08.20	30	1093	179	2531	428	4990	998
09.00	40	1521	249	2920	493	7670	1534
09.40	50	1826	300	3502	592	10229	2117
10.20	60	1860	305	3560	602	13460	2692
11.00	70	2028	333	3873	655	15401	3080
11.40	80	2378	390	4462	754	17156	3431
12.20	90	2362	387	4538	767	18193	3639
13.00	100	2378	390	4462	754	17156	3431
13.40	110	2028	333	3873	655	15401	3080
14.20	120	1860	305	3560	602	13460	2692
15.00	130	1826	300	3502	592	10229	2046
15.40	140	1521	249	2920	493	7670	2117
16.20	150	1093	179	2531	428	4990	998
17.00	160	904	148	1714	290	2539	508
17.40	170	351	58	881	149	962	192
18.20	180	-	-	-	-	-	-

The lumen outputs of the Tubular skylight models are plotted against Time as (Figure 5-5, Figure 5-6, Figure 5-7).

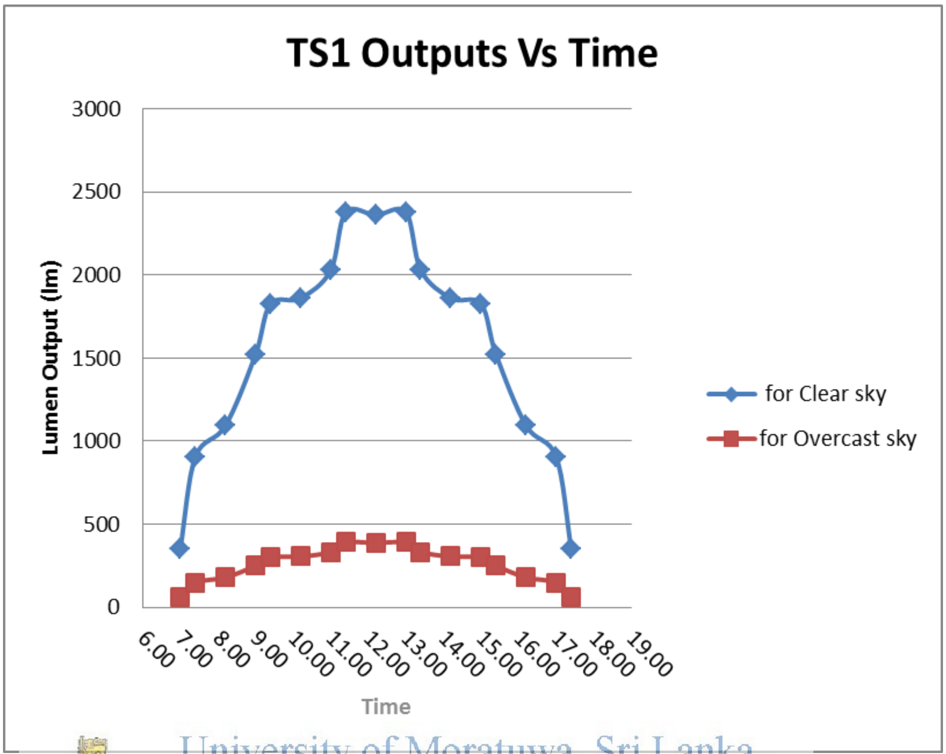


Figure 5-5: Lumen output Vs Time for TS1

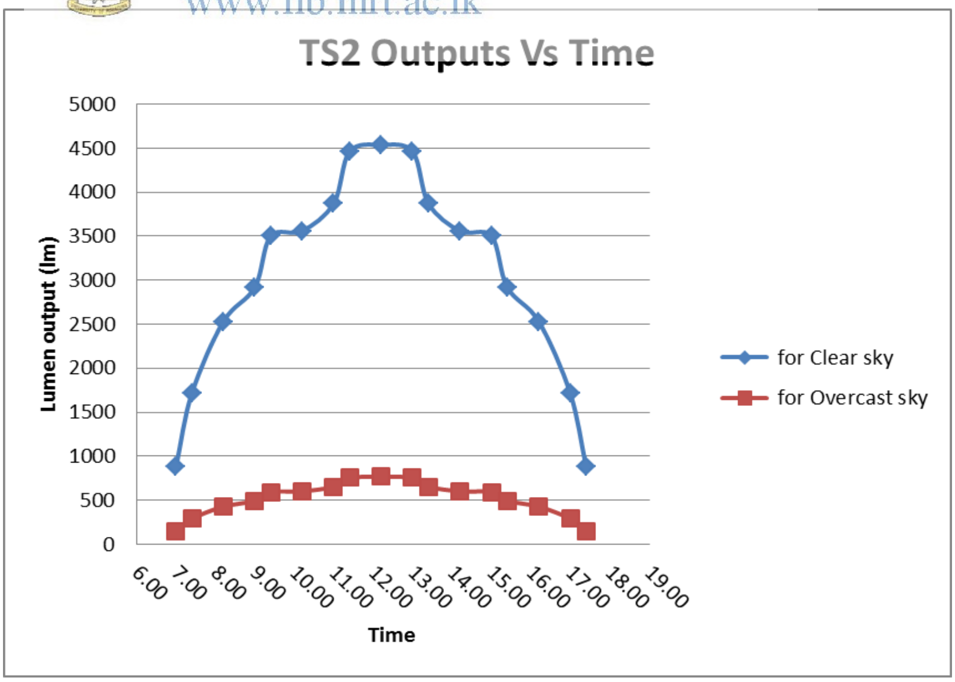


Figure 5-6: Lumen output Vs Time for TS2

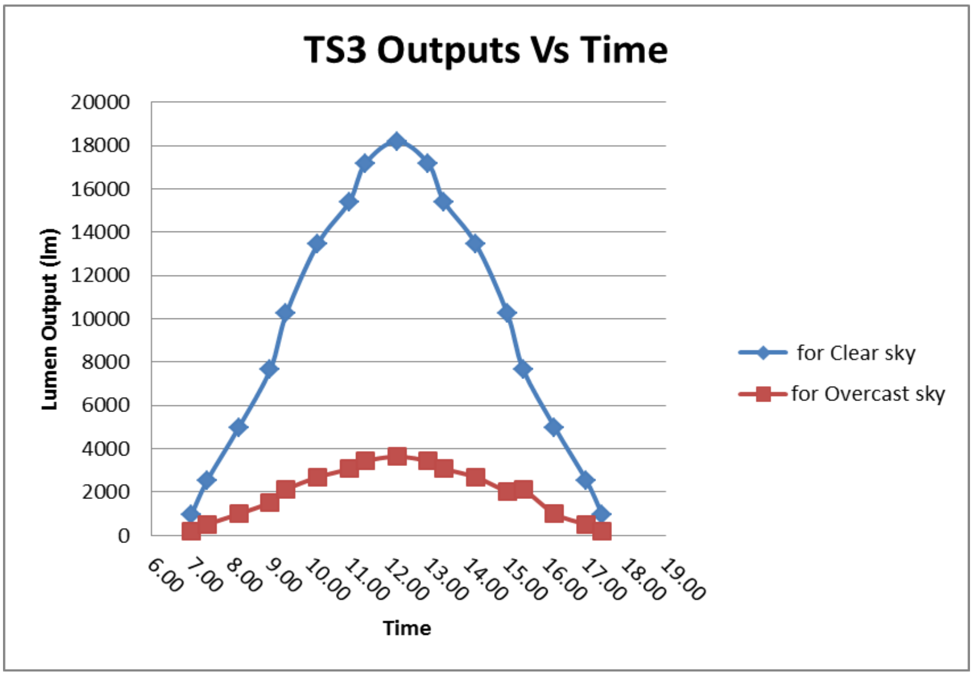


Figure 5-7: Lumen output Vs Time for TS3

Although it is observed a gradual variation of lumen output of Tubular skylights it is assumed the lumen output to be constant within a 40min time period to simplify the analysis. The simplified lumen outputs of the Tubular skylight models are plotted against Time as (Figure 5-8, Figure 5-9, and Figure 5-10).

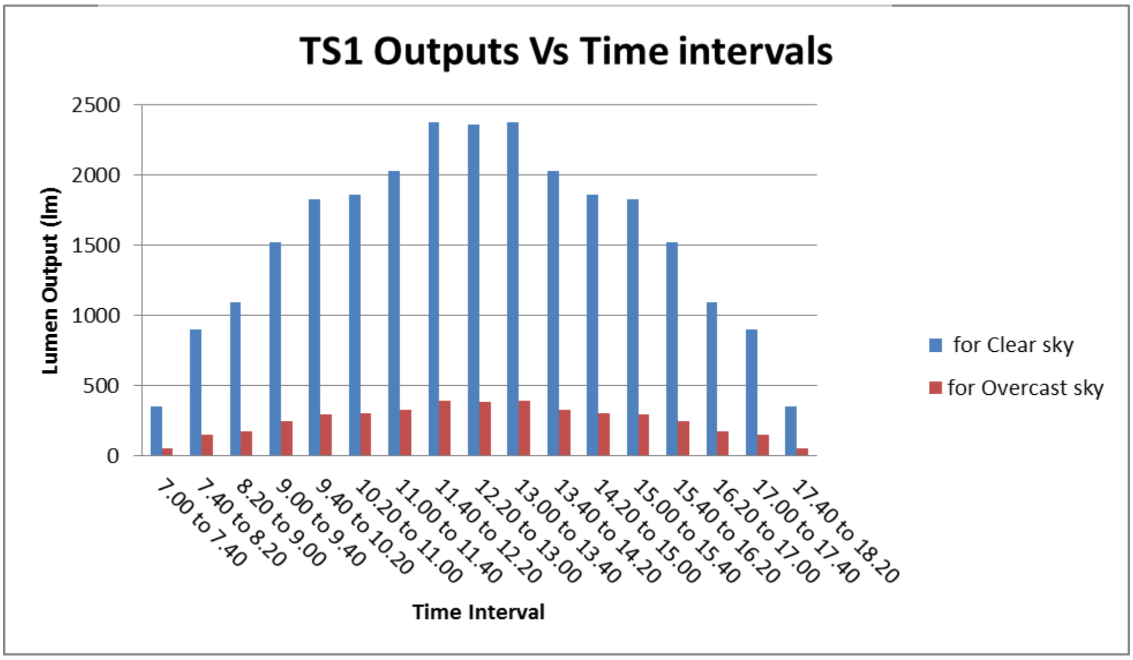


Figure 5-8: TS1 Outputs Vs Time intervals

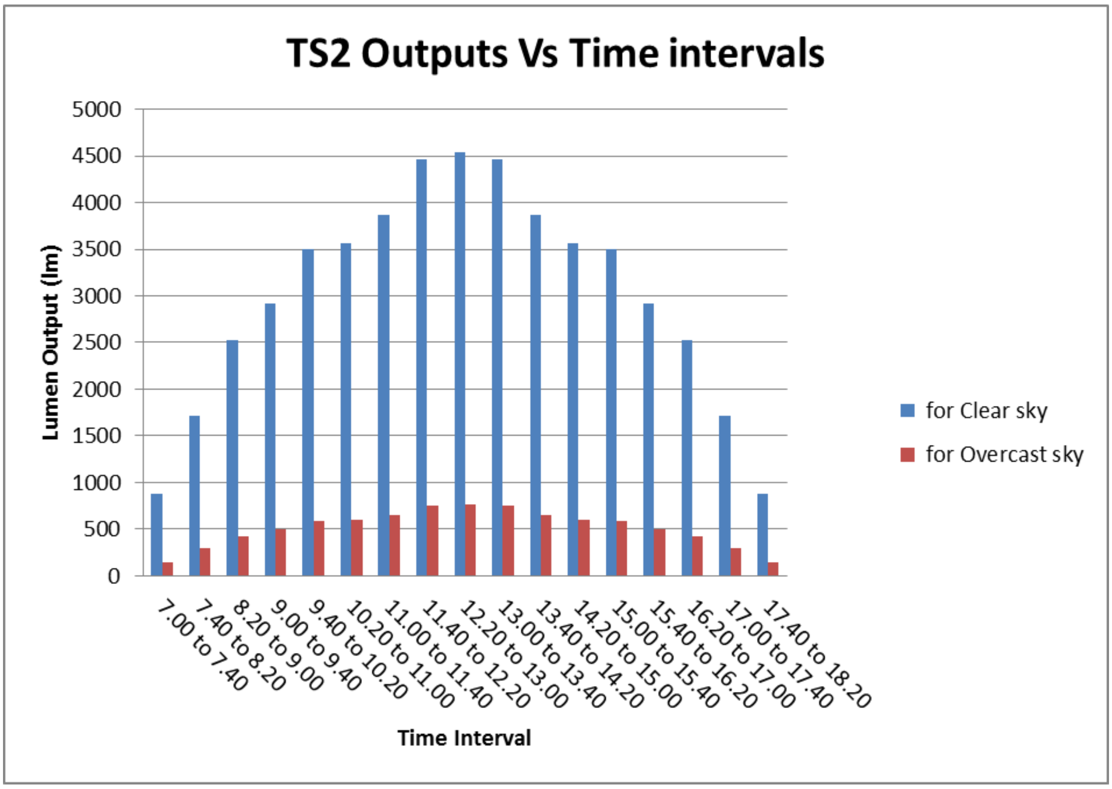


Figure 5-9: TS2 Outputs Vs Time intervals

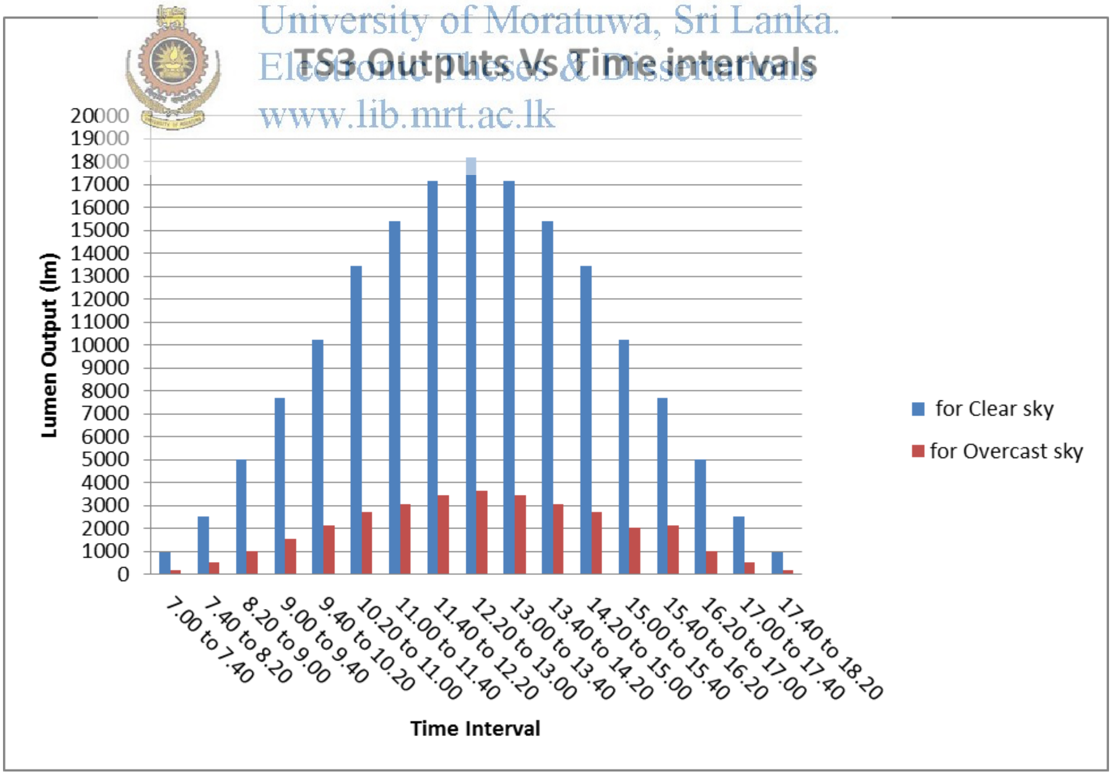


Figure 5-10: TS3 Outputs Vs Time intervals

Lumen outputs of TS1, TS2 and TS3 tubular skylight models from 07.00 to 18.20 in 40 min time intervals are considered to be as in Table 5-5.

Table 5-5: Lumen outputs for Tubular skylights in 40 min time intervals

Time Interval	**TS1**		**TS2**		**TS3**	
	Lumen Output (lm)		**Lumen Output (lm)**		**Lumen Output (lm)**	
	for Clear sky	**for Overcast sky**	**for Clear sky**	**for Overcast sky**	**for Clear sky**	**for Overcast sky**
07.00 to 07.40	351	58	881	149	962	192
07.40 to 08.20	904	148	1714	290	2539	508
08.20 to 09.00	1093	179	2531	428	4990	998
09.00 to 09.40	1521	249	2920	493	7670	1534
09.40 to 10.20	1826	300	3502	592	10229	2117
10.20 to 11.00	1860	305	3560	602	13460	2692
11.00 to 11.40	2028	333	3873	655	15401	3080
11.40 to 12.20	2378	390	4462	754	17156	3431
12.20 to 13.00	2362	387	4538	767	18193	3639
13.00 to 13.40	2378	390	4462	754	17156	3431
13.40 to 14.20	2028	333	3873	655	15401	3080
14.20 to 15.00	1860	305	3560	602	13460	2692
15.00 to 15.40	1826	300	3502	592	10229	2046
15.40 to 16.20	1521	249	2920	493	7670	2117
16.20 to 17.00	1093	179	2531	428	4990	998
17.00 to 17.40	904	148	1714	290	2539	508
17.40 to 18.20	351	58	881	149	962	192

The light output of the Tubular skylight luminaire is varying with the Sun's altitude angle so with the time. In other words the Tubular skylight is a variable light source. But when providing a lighting solution for a space with Tubular skylights to maintain a specific illuminance level on a specific workspace it has to decide the lumen output of an individual luminaire in the arrangement. In other words it has to consider a lumen output in a specific time interval which has been figured out based on the relationship between the Tubular skylight output and the Sun's altitude angle.

In the research it has compared the outputs of the tubular skylight arrangements planned based on the individual tubular skylight luminaire outputs of the three time slots 7.00 to 7.40, 12.20 to 13.00 and 9.40 to 10.20 which are the time slots the sun altitude angle is considered to arrive to 10º, 50º and 90º. Also these are the time slots that the individual tubular skylight giving its least, medium and maximum output.

The space was modeled in DIAlux 4.11 [15] software and the Tubular skylight luminaires for each diameter and each Sun altitude angle were imported. Firstly this was done assuming clear sky conditions.

For example when considering TS1 model; nine luminaire versions of TS1 for Sun's altitudes 10º,20º,30º,40º,50º,60º,70º,80º,90º were imported into the space modeled in DIAlux 4.11 [15].

Then the light arrangements were planned to achieve the target illuminance on the work plane and the results were recorded. For example when the plan was done with TS1 luminaire; firstly the light plan was done by using the luminaire TS1 of sun's altitude 10º as a field arrangement. Then the individual luminaires in the field arrangement were replaced with the other TS1 luminaires of 20º, 30º, 40º, 50º, 60º, 70º, 80º, 90º while recording the resultant illuminance levels. So it could observe the variation of the resultant illuminance level on the work plane with the time. The results were tabulated. This process was repeated by planning the lighting arrangement using luminaires of TS1 for 50º and 90º then and the results were tabulated. Same method of light simulation and analysis was carried out for TS2 and TS3 Tubular skylight luminaires and the results on the achieved illuminance levels were recorded.

5.1.2 Method to perform Energy evaluation

The existing tools and method in the DIAlux 4.11 [15] software for energy evaluation are suitable for a case of performing and energy analysis in a space which is integrated with daylight coming from a daylight source such as a window, roof light etc. So it can estimate how much of energy it can be saved in a room by dimming the lights when the day light is integrated. DIAlux 4.11 [15] uses either

EN 15193 standard [16] or DIN 18599 standard for energy evaluation. Unfortunately DIAlux 4.11 [15] does not identify the Tubular skylight luminaires from Solatube® corporation USA [11] as day light sources.

Therefore a new method is formed to perform energy evaluation using DIAlux 4.11 [15] software and a Spreadsheet. The number of artificial luminaires to be switched on or off is found to maintain a targeted illuminance level on the desired work plane. The evaluation is done at 40 min intervals throughout the defined time period in a day. The energy required for the artificial lighting is computed and the total energy requirement is calculated.

When considering the luminaire field arrangements planned with DIAlux 4.11 [15] using TS1,TS2,TS3 luminaires when the arrangement was based on the sun's altitude angle 10º ; there is no artificial light requirement trough out the day under clear sky conditions. But when the arrangement is planned using 50º or 90º altitude angles to be based with, there is a period in the day which needs backup lighting to maintain a constant target illuminance level due to the lumen output variation of the luminaires.

It is assumed that the backup lighting is done by the artificial lights which need electrical energy. In the case study it was evaluated how many artificial lights of the present artificial lighting plan needs to be turned on to supply backup lighting in each time slot during the period of analysis throughout a day. Also the energy requirement was evaluated and recorded.

5.1.3 Method to perform Economic analysis

According to the procedure used in the study described so far it can find a number of options when planning the lighting arrangement with Tubular skylights. It needs to find the most feasible solution out of the number of options.

The luminaire arrangements planned with TS1, TS2, TS3 Tubular sky light luminaires based with different Solar altitudes are evaluated to find out the most economical solution to be used in the application. A life cycle payback period calculation is done based on the Initial cost, Operation and maintenance cost for the lighting arrangements planned with the three Tubular sky light models and the Artificial luminaires subjected to study.

The lifecycle cost evaluation was done for 10 years period in the case study because it is the normal product warranty period of the tubular skylights in the market at present.

The life cycle cost for the present lighting plan in the case study was carried out using the initial supply and installation cost, re lamping cost as the maintenance cost, energy cost as the operational cost.

In the tubular skylight arrangements with artificial lights used as backup lighting the initial cost is taken as the supply and installation of tubular skylights, maintenance cost is evaluated by evaluating the re lamping cost of backup lighting and the operational cost is evaluated by evaluating the energy cost for backup lighting.

The methodology used in the study can be depicted as an algorithm as in Figure 5-11.

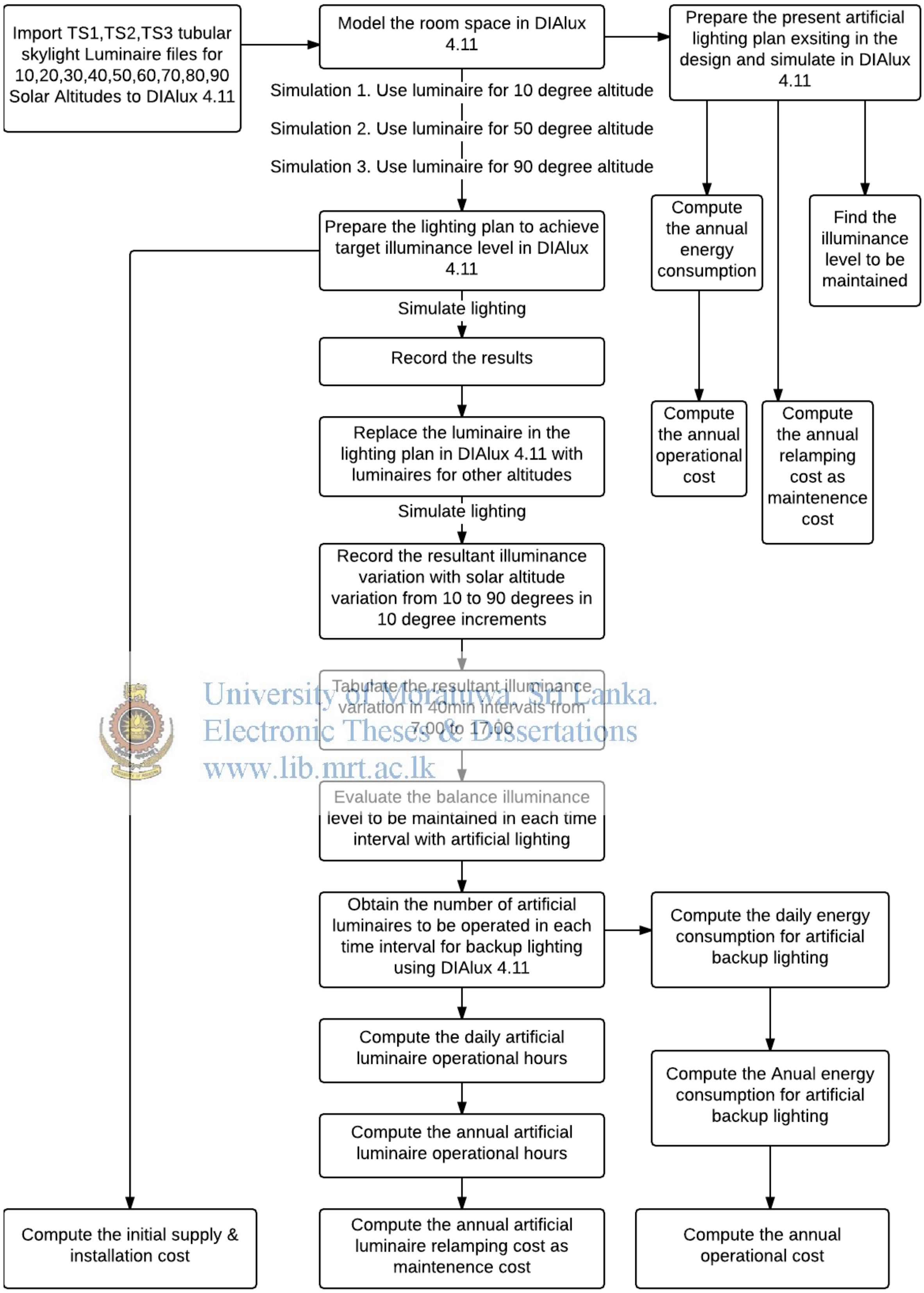


Figure 5-11: Methodology used in the analysis as an algorithm

6 CASE STUDY AND COMPUTER SIMULATIONS

The building which is subjected to study is an office building with three floors as Ground, First and Second. The building expected to be functioned mainly in day time.

The study is carried out for the following rooms in the building (Appendix 5 – Drawing C1069-D1, D2).

(1) Library room located in the Grid D-C,2-3
(2) Staff room located in the Grid D-C, 3-4

The present lighting plan is shown in (Appendix 5 –Drawing C1069-D3).

6.1 Building data

6.1.1 Library room

Room Dimensions

Inside length – 5.83m

Inside width – 5.83m

Ceiling height – 3.9m

Table 6-1: Room surface properties of library room

Room surface	Material	Reflection factor %	Transparency %	Roughness %
Walls	-	50	0	0
Floor	Tile	67	0	10
Ceiling	Metal	70	0	50

Work plane height – 0.8m

Light loss factor – 0.8

North alignment – 0.0º

Luminaires used in the present lighting plan –4xTL5-14W

Lumen output of 1 luminaire – 5000 lm

Number of luminaires installed – 9

6.1.2 Staff room

Room Dimensions

Inside length – 5.83m

Inside width – 3.43m

Ceiling height – 3.9m

Table 6-2: Room surface properties of staff room

Room surface	Material	Reflection factor %	Transparency %	Roughness %
Walls	-	50	0	0
Floor	Tile	67	0	10
Ceiling	Metal	70	0	50

Work plane height – 0.8m

Light loss factor – 0.8

North alignment – 0.0°

Luminaires used in the present lighting plan – 4xTL5-14W

Lumen output of 1 luminaire – 5000 lm

Number of luminaires installed - 3

6.2 Case 1 – Library room

6.2.1 Lighting simulation

Room was modeled in DIAlux 4.11 software [15] with the current lighting plan. The average illuminance level maintained on the work plane Eav[lx] was found.

Average illuminance level maintained on the work plane by the current lighting Eav – 557 lx

The DIAlux 4.11 [15] output is annexed in **Appendix 1**.

Lighting arrangements with TS1, TS2, TS3 Tubular skylights were planned using the currently maintained average illuminance level as the target illuminance level and based on the Sun altitude angles 10º, 50º, and 90º with clear sky conditions. It was assumed that the room will be illuminated only with the Tubular sky lights at the particular Sun altitude angle.

The DIAlux 4.11 [15] simulation results of different tubular skylight arrangements at different sun altitudes are annexed in **Appendix 1**.

The summarized result is displayed in Table 6-3.

Table 6-3: Summery of lighting simulation for current lighting plan for Library room

Lighting Arrangement	Luminaires used	Number of luminaires in the field arragement	Target Illuminance	Resultant Average Illuminance
		(nr)	[lx]	Eav [lx]
Existing lighting plan	4xTL5-14W/ 5000lm	9	-	557
Tubular skylights planned for 10º Altitude angle	TS1	132	550	672
	TS2	48	550	627
	TS3	42	550	626
Tubular skylights planned for 50º Altitude angle	TS1	24	550	729
	TS2	12	550	693
	TS3	4	550	679
Tubular skylights planned for 90º Altitude angle	TS1	15	550	660
	TS2	8	550	698
	TS3	2	550	781

The variation of the resultant illuminance level on the work plane with the variation of the sun's altitude angle is observed in the simulations done with DIAlux 4.11 [15].

As an example the average resultant illuminace level (Eav) variation of TS2 tubular skylight system based with 50º altitude of the sun for a number of sun altitudes throughout a day is depicted in Figure 6-1 and Figure 6-2.

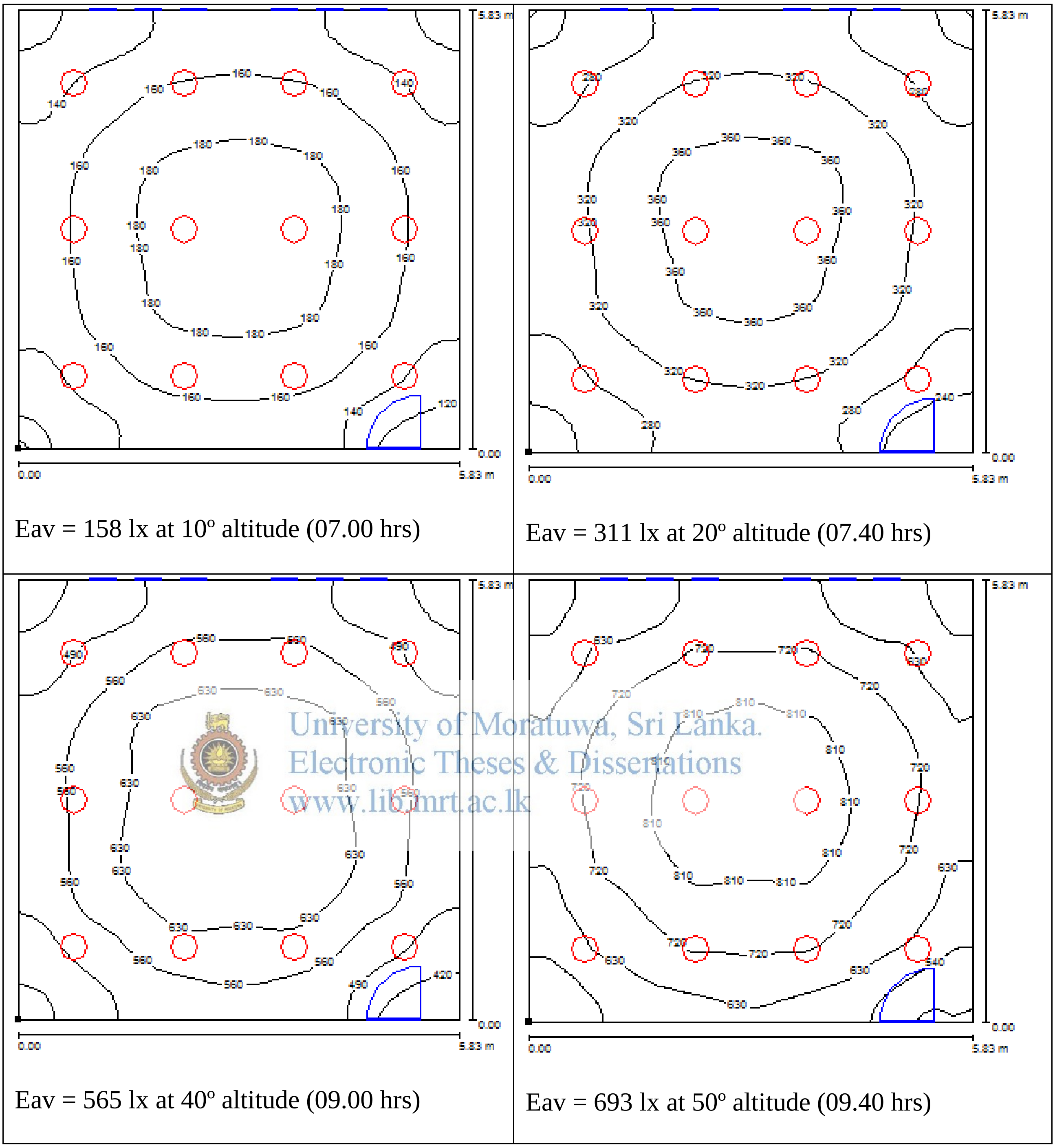
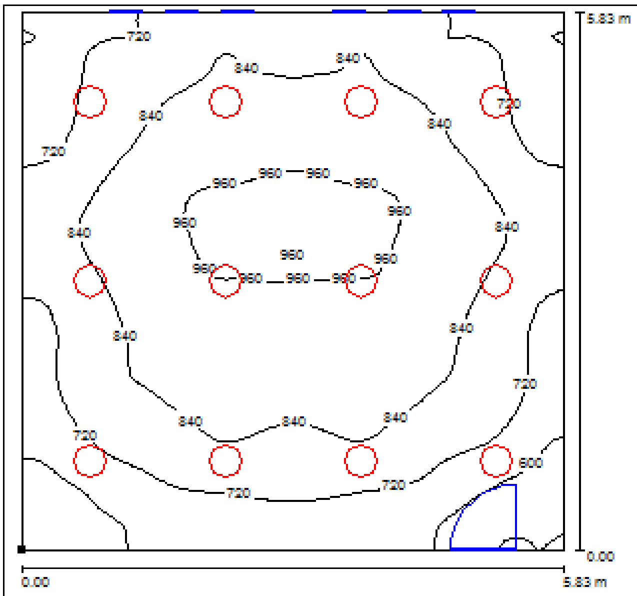
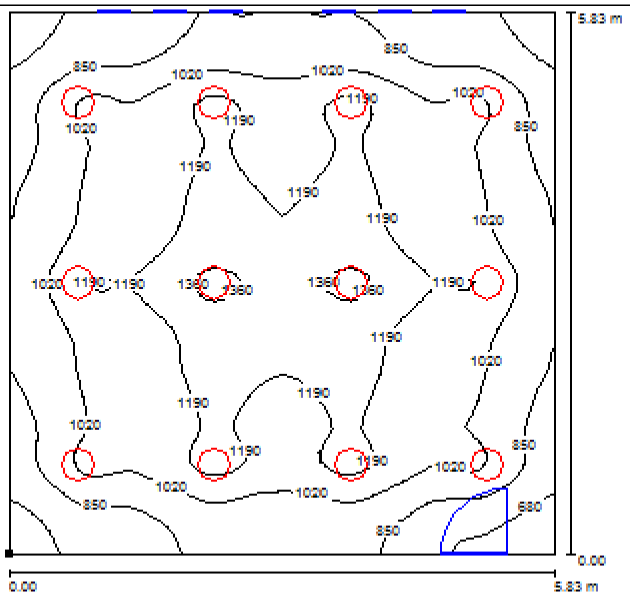


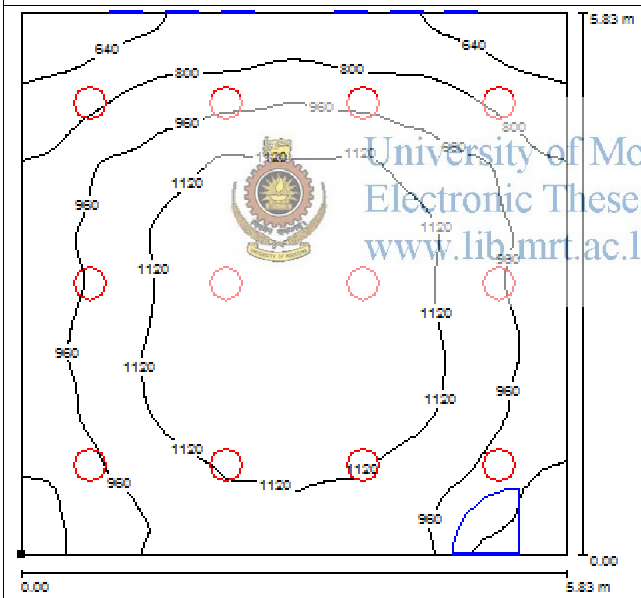
Figure 6-1: Average illuminance level variation at 10º,20º,40º, 50º altitudes



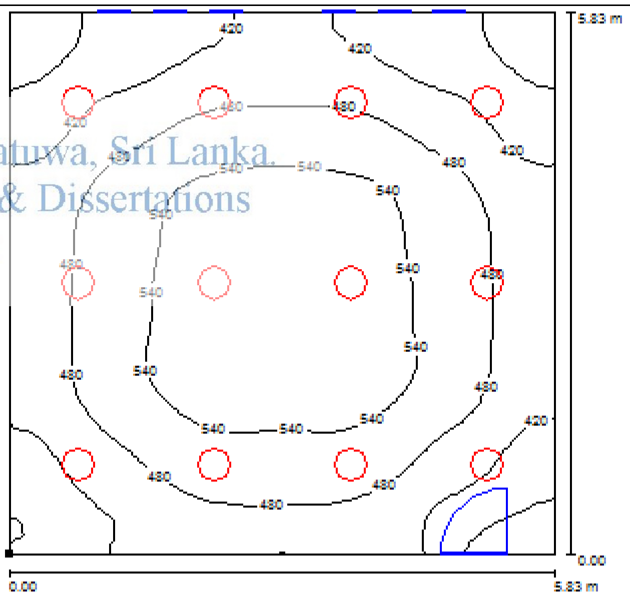
Eav = 799 lx at 70º altitude (11.00 hrs)



Eav = 1025 lx at 90º altitude (12.20 hrs)



Eav = 985 lx at 100º altitude (13.00 hrs)



Eav = 477 lx at 150º altitude (16.20 hrs)

Figure 6-2: Average illuminance level variation at 70º,90º,100º, 150º altitudes

6.2.2 Energy evaluation

Following assumptions are made

- Office Opening time – 07.00 hrs.
- Office Closing time – 17.00 hrs.
- Working days per week – 5
- Working days per month – 20
- Working days per year – 240
- Sky condition – Clear sky
- Library is operated with windows covered with blinds
- Library room is operated full time and the currently planned illuminance level (557lx) needs to be maintained always.

Energy consumption in the Library room with the current lighting plan for artificial lighting is displayed in Appendix 2 -Table 1.

When the Tubular skylight installation is done for daylight integration it is assumed that the currently designed artificial lighting system will be installed to be used as the backup when the light outputs of Tubular skylights are reduced with the Sun altitude angle.

Energy consumption in the Library room with the TS1 Tubular skylights planned for 10º Sun altitude angle with clear sky conditions is displayed in Appendix 2 -Table 2.

Energy consumption in the Library room with the TS1 Tubular skylights planned for 50º Sun altitude angle with clear sky conditions is displayed in Appendix 2 - Table 3.

Energy consumption in the Library room with the TS1 Tubular skylights planned for 90º Sun altitude angle with clear sky conditions is displayed in Appendix 2- Table 4.

Energy consumption in the Library room with the TS2 Tubular skylights planned for 10º Sun altitude angle with clear sky conditions is displayed in Appendix 2 -Table 5.

Energy consumption in the Library room with the TS2 Tubular skylights planned for 50º Sun altitude angle with clear sky conditions is displayed in Appendix 2 - Table 6.

Energy consumption in the Library room with the TS2 Tubular skylights planned for 90º Sun altitude angle with clear sky conditions is displayed in Appendix 2- Table 7.

Energy consumption in the Library room with the TS3 Tubular skylights planned for 10º Sun altitude angle with clear sky conditions is displayed in Appendix 2 -Table 8.

Energy consumption in the Library room with the TS3 Tubular skylights planned for 50º Sun altitude angle with clear sky conditions is displayed in Appendix 2 - Table 9.

Energy consumption in the Library room with the TS3 Tubular skylights planned for 90º Sun altitude angle with clear sky conditions is displayed in Appendix 2- Table 10.

Table 6-4 displays the summery of the energy consumption per day for backup lighting in different lighting arrangements of the Library room.

Table 6-4 Summery of the energy consumption per day

Lighting Arrangement	**Energy Consumption per day (kWh)**
4xTL5-14W/ 5000lm system	5.040
TS1 system planned for 10º Sun altitude angle, clear sky	0.000
TS1 system planned for 50º Sun altitude angle, clear sky	0.747
TS1 system planned for 90º Sun altitude angle, clear sky	1.755
TS2 system planned for 10º Sun altitude angle, clear sky	0.000
TS2 system planned for 50º Sun altitude angle, clear sky	0.672
TS2 system planned for 90º Sun altitude angle, clear sky	1.680
TS3 system planned for 10º Sun altitude angle, clear sky	0.000
TS3 system planned for 50º Sun altitude angle, clear sky	1.157
TS3 system planned for 90º Sun altitude angle, clear sky	2.165

6.2.3 Economic Evaluation

Cost Estimation

Following assumptions are made

- Office Opening time – 07.00 hrs.
- Office Closing time – 17.00 hrs.
- Working days per week – 5
- Working days per month – 20
- Working days per year – 240
- Sky condition – Clear sky
- Library is operated with windows covered with blinds
- Library room is operated full time and the currently planned illuminance level (557lx) needs to be maintained always.

CEB Tarrif considered for energy cost – G2 customer category/ LKR 22/kWh

Exchange rate – 130 LKR =1 $

The cost estimation calculation for the current artificial lighting system is displayed in Appendix 3, Table 1

Cost estimation for the TS1 tubular skylight system planned for 10° Sun altitude angle with clear sky conditions is displayed in Appendix 3, Table 2

Cost estimation for the TS1 tubular skylight system planned for 50° Sun altitude angle with clear sky conditions is displayed in Appendix 3, Table 3

Cost estimation for the TS1 tubular skylight system planned for 90° Sun altitude angle with clear sky conditions is displayed in Appendix 3, Table 4

Summarized cost estimation is displayed in Table 6-5.

Table 6-5 Summarized Cost estimations for Library

System	Number of luminaires installed	Initial Cost ($)	Annual Maintenance cost ($)	Annual Operational cost ($)	Annual Total Operational & Maintenance cost ($)
4xTL5-14W/ 5000lm	9.00	1,176.92	69.23	205.63	274.86
TS1,planned for 10°,Clear sky	132.00	53,031.69	0.00	0.00	0.00
TS1,planned for 50°,Clear sky	24.00	9,614.31	7.69	30.48	38.17
TS1,planned for 90°,Clear sky	9.00	3,643.62	23.08	71.60	94.68
TS2,planned for 10°,Clear sky	48.00	24,775.38	0.00	0.00	0.00
TS2,planned for 50°,Clear sky	12.00	6,242.31	7.69	27.42	35.11
TS2,planned for 90°,Clear sky	8.00	4,161.54	23.08	68.54	91.62
TS3,planned for 10°,Clear sky	42.00	23,307.63	0.00	0.00	0.00
TS3,planned for 50°,Clear sky	4.00	2,236.92	15.38	47.21	62.59
TS3,planned for 90°,Clear sky	2.00	1,118.46	30.77	88.33	119.10

6.2.4 Life cycle payback evaluation

The life cycle payback calculation was performed for 10 years using a spreadsheet method for different Tubular sky light arrangement using the currently planned artificial lighting system as the base case.

It was checked the payback period of different Tubular skylight arrangements for the Case 1 assuming an annual interest rate of 10%

It was assumed that the Tubular skylights will be installed without reducing or eliminating currently planned artificial lights.

Pay back calculation was performed to find out the number of years taken to recover the Initial costs of the Tubular Skylight arrangements

The results of life cycle payback calculations are displayed in Appendix 4.

Summary of the 10 year life cycle payback analysis is displayed in Table 6-6.

Table 6-6 Summary of the 10 year life cycle payback analysis

System	Initial cost ($)	Cumulative saving at the end of 10th year ($)	Percentage saving at the end of 10th year	Rank
TS1,10°,clear sky	53,031.69	1237.29	2.33%	9
TS1,50°,clear sky	9,614.31	1065.47	11.08%	6
TS1,90°,clear sky	3,643.62	811.09	22.26%	3
TS2,10°,clear sky	24,775.38	1237.29	4.99%	8
TS2,50°,clear sky	6,242.31	1079.24	17.29%	5
TS2,90°,clear sky	4,161.54	824.86	19.82%	4
TS3,10°,clear sky	23,307.63	1237.29	5.31%	7
TS3,50°,clear sky	2,236.92	955.54	42.72%	2
TS3,90°,clear sky	1,118.46	701.16	62.69%	1

The results shows that none of the Tubular arrangements are getting fully paid back within 10 years with the current assumptions, and when trying to install Tubular skylights without eliminating or reducing the artificial lighting.

The capability of reducing or eliminating artificial lighting was assessed for each Tubular skylight arrangement.

Previously it has assumed that the office start time as 7.00 hrs. and office close time as 17.00 hrs. But normally general office work in a typical Sri Lankan office starts around 08.30 hrs. to 09.00 hrs. Normally the time before or after general office work time is used for activities like cleaning. Hence following assumptions will be added for the analysis.

- General office work start time 09.00 hrs.
- General office work finish time 17.00 hrs.
- The lighting requirement in the room before or after the general office work time is assumed to be around 50% of the general requirement. Hence the target illuminance level to be maintained inside the room before or after the general office work time becomes
  (550 lx) x 50/100 = 275 lx

Each of the arrangement is evaluated for life cycle cost.

TS1, 10° altitude, clear sky conditions

The requirement for artificial lighting with this arrangement under the said conditions is zero.

Therefore the initial cost for supply and installation of artificial lighting system is saved.

The initial cost saving attained by eliminating artificial lighting

= **$ 1,176.92**

Hence the targeted cost to be recovered within 10 years period

= $ 53,031.69 - $ 1,176.92

= $ 51,854.77

The operational and maintenance cost for the currently planned artificial lighting system with the new assumptions stated above

= $ 261.15

Annual saving of operational and maintenance cost relative to the currently planned artificial lighting system

= $ 261.15

The initial cost will not be paid back within 10 years (Appendix 4 – Table 10)

TS1, 50° altitude, clear sky conditions

The maximum number of artificial luminaires to be operated during 9.00 hrs. – 17.00 hrs = 3 (Appendix 2 – Table 3)

The maximum number of artificial luminaires to be operated before 9.00 hrs. = 3 (during 07.00 hrs – 07.40 hrs)

Therefore initial cost saving to be attained by eliminating 6 artificial luminaires

= $ (107.69 + 23.08) x 6

= $ 784.62

Hence the targeted cost to be recovered within 10 years period = $ (9614.31 -784.62)

= $ 8829.69

Annual operational and maintenance cost

= $ 9.14

Annual operational and maintenance cost saving = $ (261.15 – 9.14)

=$ 252.01

The initial cost will not be paid back within 10 years (Appendix 4 – Table 11)

TS1, 90° altitude, clear sky conditions

The maximum number of artificial luminaires to be operated during 9.00 hrs. – 17.00 hrs = 6 (Appendix 2 – Table 4)

The maximum number of artificial luminaires to be operated before 9.00 hrs. = 4 (during 07.00 hrs – 07.40 hrs)

Therefore initial cost saving to be attained by eliminating 3 artificial luminaires

= $ (107.69 + 23.08) x 3

= **$ 392.31**

Hence the targeted cost to be recovered within 10 years period = $ (3643.62 -392.31)

= **$ 3251.31**

Annual operational and maintenance cost

= **$ 62.59**

Annual operational and maintenance cost saving = $ (261.15 – 62.59)

=**$ 198.56**

The initial cost will not be paid back within 10 years (Appendix 4 – Table 12)

TS2, 10° altitude, clear sky conditions

The requirement for artificial lighting with this arrangement under the said conditions is zero.

Therefore the initial cost for supply and installation of artificial lighting system is saved.

The initial cost saving attained by eliminating artificial lighting

= **$ 1,176.92**

Hence the targeted cost to be recovered within 10 years period

= **$ 24,775.38 - $ 1,176.92**

= **$ 23,598.46**

The operational and maintenance cost for the currently planned artificial lighting system with the new assumptions stated above

= **$ 261.15**

Annual saving of operational and maintenance cost relative to the currently planned artificial lighting system

= **$ 261.15**

The initial cost will not be paid back within 10 years

TS2, 50° altitude, clear sky conditions

The maximum number of artificial luminaires to be operated during 9.00 hrs. – 17.00 hrs = 2 (Appendix 2 – Table 6)

The maximum number of artificial luminaires to be operated before 9.00 hrs. = 2 (during 07.00 hrs – 07.40 hrs)

Therefore initial cost saving to be attained by eliminating 7 artificial luminaires

= $ (107.69 + 23.08) x 7

= **$ 915.39**

Hence the targeted cost to be recovered within 10 years period = $ (6242.31 -915.39)

= **$ 5326.92**

Annual operational and maintenance cost

= **$ 6.08**

Annual operational and maintenance cost saving

= $ (261.15 – 6.08)

=**$ 255.07**

The initial cost will not be paid back within 10 years

TS2, 90° altitude, clear sky conditions

The maximum number of artificial luminaires to be operated during 9.00 hrs. – 17.00 hrs = 6 (Appendix 2 – Table 7)

The maximum number of artificial luminaires to be operated before 9.00 hrs. = 3 (during 07.00 hrs – 07.40 hrs)

Therefore initial cost saving to be attained by eliminating 3 artificial luminaires

= $ (107.69 + 23.08) x 3

= **$ 392.31**

Hence the targeted cost to be recovered within 10 years period = $ (4161.54 - 392.31)

= **$ 3769.23**

Annual operational and maintenance cost

= **$ 56.51**

Annual operational and maintenance cost saving

= $ (261.15 – 56.51)

=**$ 204.64**

The initial cost will not be paid back within 10 years.

TS3, 10° altitude, clear sky conditions

The requirement for artificial lighting with this arrangement under the said conditions is zero.

Therefore the initial cost for supply and installation of artificial lighting system is saved.

The initial cost saving attained by eliminating artificial lighting

= $ 1,176.92

Hence the targeted cost to be recovered within 10 years period

= $ 23,307.63 - $ 1,176.92

= $ 22,130.71

The operational and maintenance cost for the currently planned artificial lighting system with the new assumptions stated above

= $ 261.15

Annual saving of operational and maintenance cost relative to the currently planned artificial lighting system

= $ 261.15

The initial cost will not be paid back within 10 years

TS3, 50° altitude, clear sky conditions

The maximum number of artificial luminaires to be operated during 9.00 hrs. – 17.00 hrs = 6 (Appendix 2 – Table 9)

The maximum number of artificial luminaires to be operated before 9.00 hrs. = 4 (during 07.00 hrs – 07.40 hrs)

Therefore initial cost saving to be attained by eliminating 3 artificial luminaires

= $ (107.69 + 23.08) x 3

= $ 392.31

Hence the targeted cost to be recovered within 10 years period = $ (2236.92 -392.31)

= $ 1844.61

Annual operational and maintenance cost

= $ 29.03

Annual operational and maintenance cost saving

= $ (261.15 – 29.03)

=$ 232.12

The initial cost will not be paid back within 10 years (Appendix 4 – Table 13)

TS3, 90° altitude, clear sky conditions

The maximum number of artificial luminaires to be operated during 9.00 hrs. – 17.00 hrs = 8 (Appendix 2 – Table 9)

The maximum number of artificial luminaires to be operated before 9.00 hrs. = 6 (during 07.00 hrs – 07.40 hrs)

Therefore initial cost saving to be attained by eliminating 1 artificial luminaires

= $ (107.69 + 23.08)

= $ 130.77

Hence the targeted cost to be recovered within 10 years period = $ (1118.46 -130.77) **= $ 987.69**

Annual operational and maintenance cost

= $ 90.11

Annual operational and maintenance cost saving = $ (261.15 – 90.11)

= **$ 171.04**

The initial cost will not be paid back within 10 years (Appendix 4 – Table 14)

The summary of the results of 10 year life cycle cost evaluation under the assumptions stated earlier is depicted in Table 6-7.

Table 6-7: Summary of the results of 10 year life cycle cost evaluation under the modified assumptions

Tubular Skylight Arrangement	Initial Cost to be recovered ($)	Cost recovered at the end of 10th year ($)	Percentage cost recovery at the end of 10th year	Rank
TS1,10°,clear sky	51,854.77	1175.58	2.27%	9
TS1,50°,clear sky	8829.69	1134.43	12.85%	6
TS1,90°,clear sky	3251.31	893.83	27.49%	3
TS2,10°,clear sky	23,598.46	1175.58	4.98%	8
TS2,50°,clear sky	5326.92	1148.21	21.55%	5
TS2,90°,clear sky	3769.23	921.19	24.44%	4
TS3,10°,clear sky	22,130.71	1175.58	5.31%	7
TS3,50°,clear sky	1844.61	1044.90	56.65%	2
TS3,90°,clear sky	987.69	769.94	77.95%	1

Even when the tubular skylights were planned with reduced artificial lighting; the results show that none of the options having an initial cost which will be recovered within 10 years.

Out of the three tubular skylight models evaluated the TS3 model which is having a tube diameter of 525mm appears to be the most economical model. Also it can observe that when planning tubular skylight systems planning based on the highest altitude angle 90° has given the most economical arrangement always.

6.2.5 Lighting up the room to achieve the standard minimum illuminance level

According to the “CIBSE – Code for lighting (Year 2002)” [17], the minimum average illuminance levels to be kept for a library are as follows.

Reading area – 500lx

Shelves – 200lx

Currently it has planned to maintain 550lx average illuminance level and even when tested the arrangements to achieve 500lx average illuminance level there was no significant changes observed in the arrangements. Hence for the case of the library room analyzed the results cannot be expected to deviate further.

6.2.6 Estimating the Energy consumption for artificial backup lighting under overcast sky conditions

The energy consumption for artificial backup lighting in the case study has been carried out mainly assuming the clear sky conditions. When overcast conditions are considered the annual energy use for artificial backup lighting may arise further.

However, it has to do the evaluations considering the overcast conditions to achieve most realistic results. The annual data on the overcast conditions at the building’s location needs to be used in the evaluation.

Following procedure needs to be followed in order to do the evaluation.

1. The hourly data of the location of the building shall be collected for a long period (ten or more years).

2. Direct normal illuminance irradiance (DNI) data which reflects the availability of direct radiation or any overcast conditions shall be derived from the data.

3. The variation of the DNI in each hour within the considered period of the day (07.00hr to 16.00hr in the case study) throughout the year shall be followed and noted (ignoring any seasonal variation from the change of sun position).

4. A design DNI, at which the required illumination is realized shall be defined, which will result in the use of a dimming devise (to cut down excess light) or an artificial back up light (to supplement lower than design lighting level)

5. Total number of hours below the design DNI (which indicate an overcast condition) shall be found for each hour within the considered period of the day (07.00hr to 16.00hr in the case study), along with the deficient amount of lighting

6. Illuminance levels maintained in each overcast time period shall be found with DIAlux 4.11 [15] software.

7. Number of artificial luminaires to be operated in each overcast time period shall be found with DIAlux 4.11 [15] software.

8. Annual Energy consumption for artificial backup lighting shall be estimated.

Comprehensive solar radiation data file for the location Anuradhapura, Sri Lanka which is the building location in the case study was obtained from Sri Lanka Sustainable Energy Authority for the period from year 1982 to year 2002.

The DNI which is the main factor influencing the light output of the tubular skylight is studied. Average amount of solar radiation in Wh/m^2 received within a 5.7° field of view centered on the sun, during the 60 minutes preceding the hour is indicated in the data sheet.

The variation of DNI throughout the Year 1990 of Anuradhapura, Sri Lanka is tabulated in Table 6-8.

Table 6-8: Annual data on DNI over Anuradhapura, Sri Lanka

Hour	Hourly average amount of DNI (Wh/m^2)		
	Annual Minimum	Annual Maximum	Annual Average
07.00	0	122	11.8
08.00	0	525	164.3
09.00	0	739	303.4
10.00	2	808	381.8
11.00	4	876	426.4
12.00	2	896	426.7
13.00	1	892	451.4
14.00	2	887	427.9
15.00	1	882	402.5
16.00	0	846	366.0

The distribution (solar duration curve) of DNI for 10.00 hr over Anuradhapura, Sri Lanka in year 1990 is displayed in Figure 6-3 as an example.

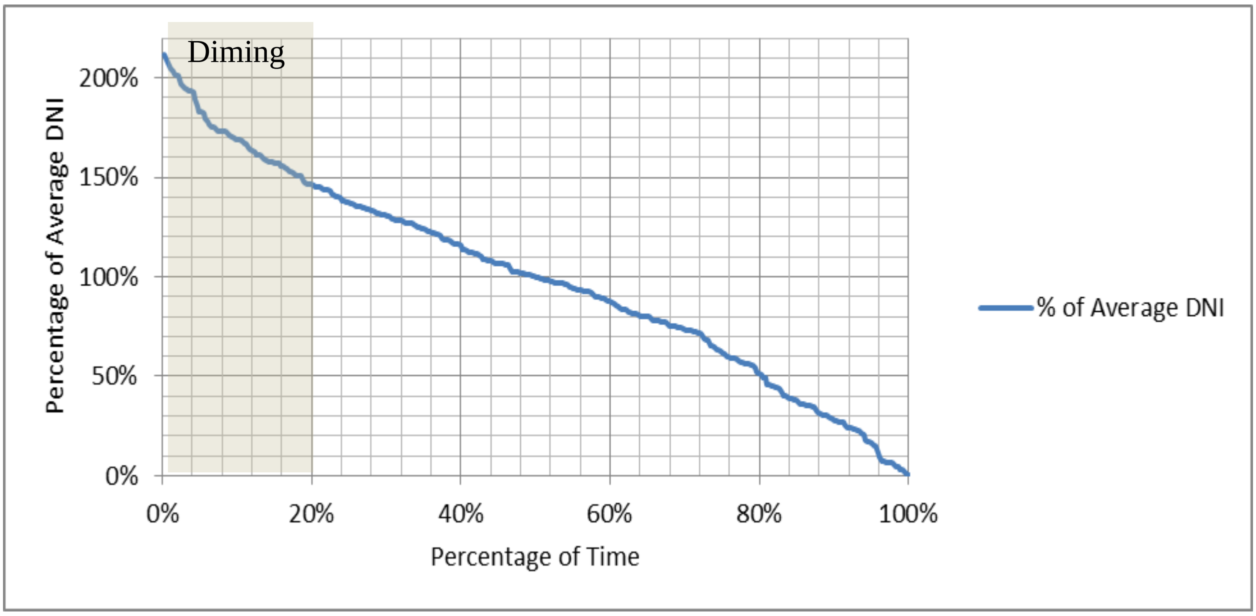


Figure 6-3: DNI distribution for 10.00 hr over Anuradhapura, Sri Lanka in year 1990

If the design DNI was taken to be the DNI which result in an illumination of 150% of the required illumination, the above curve indicates that 18.63% of the time, a dimming devise may be required to reduce the solar lighting level. The curve also indicates that 40% of the time, there will be a need of 23% artificial lighting demand. The likely demand for artificial lighting during the 10.00 hr. at various DNI levels are given in the table 27 below.

Table 6-9: The likely demand for artificial lighting during the 10.00 hr. at various DNI levels

Availability % time	DNI % of average for year xxxx	Sufficiency of solar lighting %	Supplement of artificial lighting %
18.63	150.0 (Design Value)	100	0
20	146.4	97.6	2.4
40	115.5	77.0	23.0
60	87.7	58.5	41.5
80	51.1	34.1	65.9
100	0.52	0.3	99.7

From the above, the likely demand for artificial lighting due to overcast conditions can be derived as shown in Table 6-10 below.

Table 6-10: The likely demand for artificial lighting due to overcast conditions

Availability % time	Demand for artificial lighting % of design level	Prevalence % for year 1990	Average demand % of design level	Likely energy impact %
18.63	-	18.63	-	-
20.00	2.4	1.37	1.2	0.02
40.00	12.0	20.00	7.2	1.44
60.00	41.5	20.00	26.8	5.35
80.00	65.9	20.00	53.7	10.74
100.00	99.7	20.00	82.8	16.56
			Total	34.11

From the above, it is clear that the demand for artificial lighting due to overcast conditions for year 1990 at 10.00 is 34.11%. Similar calculations can be performed for each sun hour for all the years for which data is available. Such an analysis will improve the accuracy of the lighting evaluation and further impact the feasibility of light tubes as a source of lighting energy.

7 DISCUSSION AND CONCLUSIONS

This research has been carried out based on a number of basic assumptions and currently available data. Simulation of the light out puts of Tubular skylights has been carried out with the luminaire data files collected from manufacturers who possess such tools. The computer simulation outputs are depending on the accuracy of the luminaire data files and the accuracy of DIAlux 4.11 Software [15].

DIAlux 4.11 Software [15] has been used in the simulation as a reliable and a user friendly tool for the researcher. Due to the limitations in the software the researcher has manipulated the software and taken the outputs to collect the data with the luminaire data files gathered from manufactures. Due to the limitations in the software the researcher has used spreadsheet methods to perform energy evaluation and life cycle cost analysis based on logics formed which are specific to the case.

The cost estimations are based on the market prices collected from the local suppliers. The Supply and Installation costs are quite time variant and varied with parity rates etc and the trends. Due to the scarcity of the suppliers of the product subjected to study, observed in the Sri Lankan market still the initial costs of the products are sold at relatively higher prices. The economic evaluation outputs are highly depending not only on the market prices of the product but also on the average installation costs collected from suppliers. It is observed that the installation cost component is relatively higher when compared with the nature of the product and the methods of installation observed. The life cycle cost analysis has been carried out for 10 years period which is the normal product warranty period of the manufacturers and suppliers.

The economic comparison has been carried out between the Tubular sky lights and one particular artificial luminaire applied in the Case subjected to study. The results may vary with the products which are compared with.

Based on the observations during the research it has found a clue such that replacing an artificial lighting arrangement completely with a luminaire arrangement with tubular skylights would not give significant economic benefit.

Based on the results of the research and the case study it can state that the tubular skylights will be more economical for the buildings functions mainly in the daytime and situated in locations which are having a higher amount of sunshine hours during a year. In overcast conditions the energy cost may arise due to the increment in artificial light usage. Therefore the payback periods will be more in a location which is getting less annual sunshine hours and having more overcast conditions throughout the year. It has assumed closed window conditions and avoided day light contribution by the windows in the model to find out the exact requirement of artificial lighting when the light outputs of the tubular sky lights drop.

The light outputs are depending on the surface properties which are kept constant during the study but needs to be varied and tested the outputs to address the worst case scenarios.

It was observed that the initial cost of Tubular skylight systems increases while the requirement of artificial lighting is kept zero under clear sky conditions when arrangement is planned for lower altitude angles of the sun. Although this appears to be a good energy saving option this tends to make the room over illuminated at the high altitude angles of the sun. Then necessary arrangements such as dimming systems would be needed for the reduction of light. In the other hand when the arrangement is planned based on the high altitude angles of the sun the requirement of artificial lighting increases at the lower altitude angles of the sun.

It has assumed that the lumen output of the Tubular skylights are constant within relatively shorter intervals like 40 min mainly for the convenience of the estimation of artificial light requirement when the light output drops to keep a constant illuminance level . This has done using a switching method. Hence an approximate value of energy for artificial lighting has been computed.

But in the real scenario the constant illuminance should be obtained with a dimming system of artificial lighting due to the gradual variation of the Tubular sky light output.

When the Tubular skylight arrangement is planned for a medium angle of the sun altitude , a dimming type artificial lighting arrangement and a dimmer systems for the Tubular skylights would be needed to maintain constant illuminance level.

It appears that for the places where constant illuminance is not demanded the tubular skylights can be applicable with no backup lighting or dimming systems arranged.

Since the case study has been carried out with closed window conditions it gives the idea about what happens when Tubular skylights are installed at the places where normal daylighting is not existing.

In deep room with windows three of the systems 1.Windows 2.Tubular skylights and 3. Artificial lighting can be installed. The room can be divided into two zones along its depth. Then One zone can be day lit with windows and the other zone can be day lit with Tubular skylights. The artificial lighting systems will act as a backup lighting system in both of the zones.

A more accurate analysis can be done while considering overcast and clear sky conditions specific to a location with the use of a comprehensive solar radiation data file. The DNI (Direct Normal Irradiance) factor which is the main contributor influencing the output of tubular skylights shall be analyzed hourly for about 10 to 20 years. The most economical DNI level to be based in the design specific to the location shall be identified. Then the annual energy demand for artificial backup lighting under both clear overcast sky conditions and dimming requirements shall be more accurately derived.

Mainly the research has made a platform and an analytical framework for the feasibility analysis of the Tubular skylight luminaire which is having a highly time variant dynamic output observed. The methods and logic formed during the research can be developed with future research work and the current research outputs may set examples and clues for other researchers.

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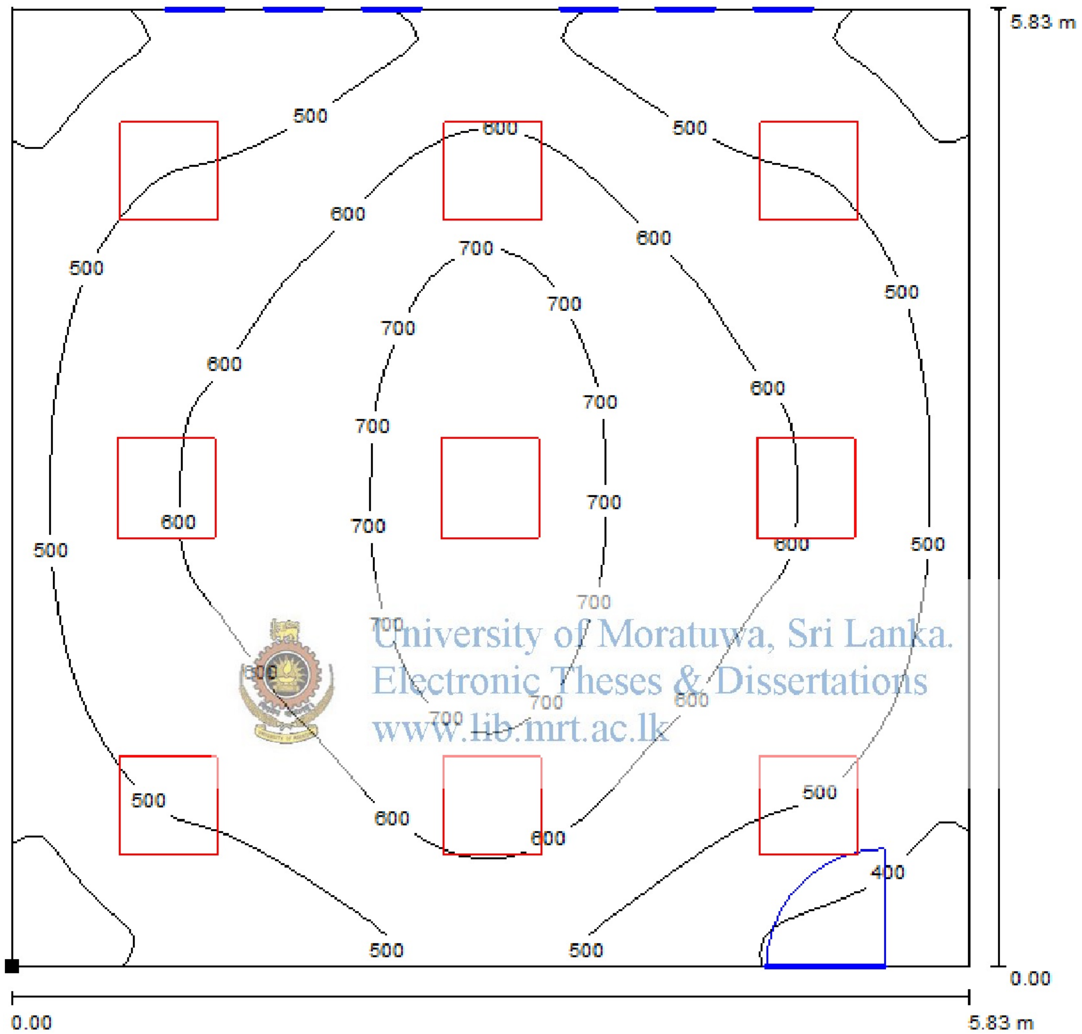
Operator
Telephone
Fax
e-Mail

Library / Workplane / Isolines (E)



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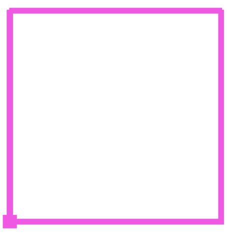


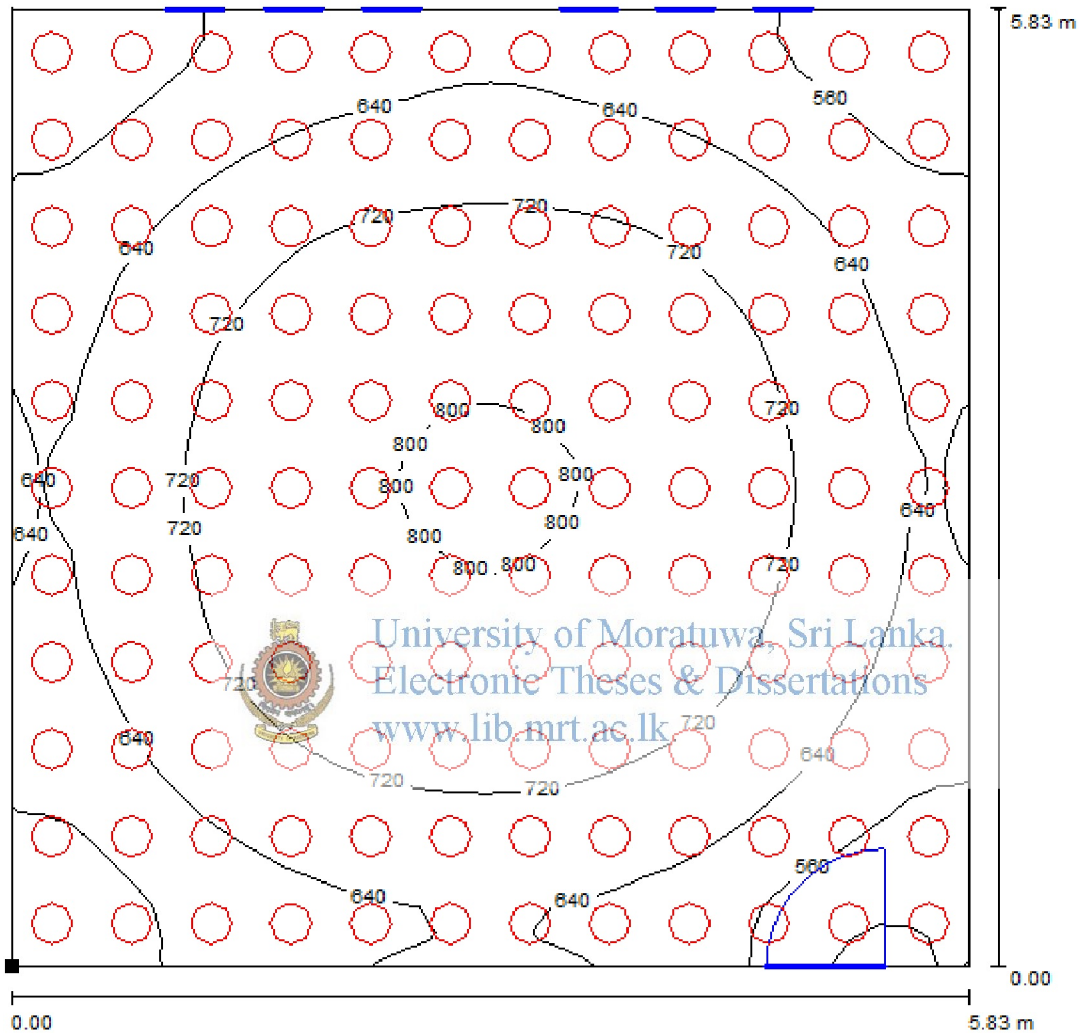
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
557	314	770	0.564	0.407

Existing lighting plan
Luminaire type - 4xTL5-14W/5000lm

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



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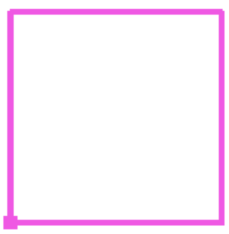


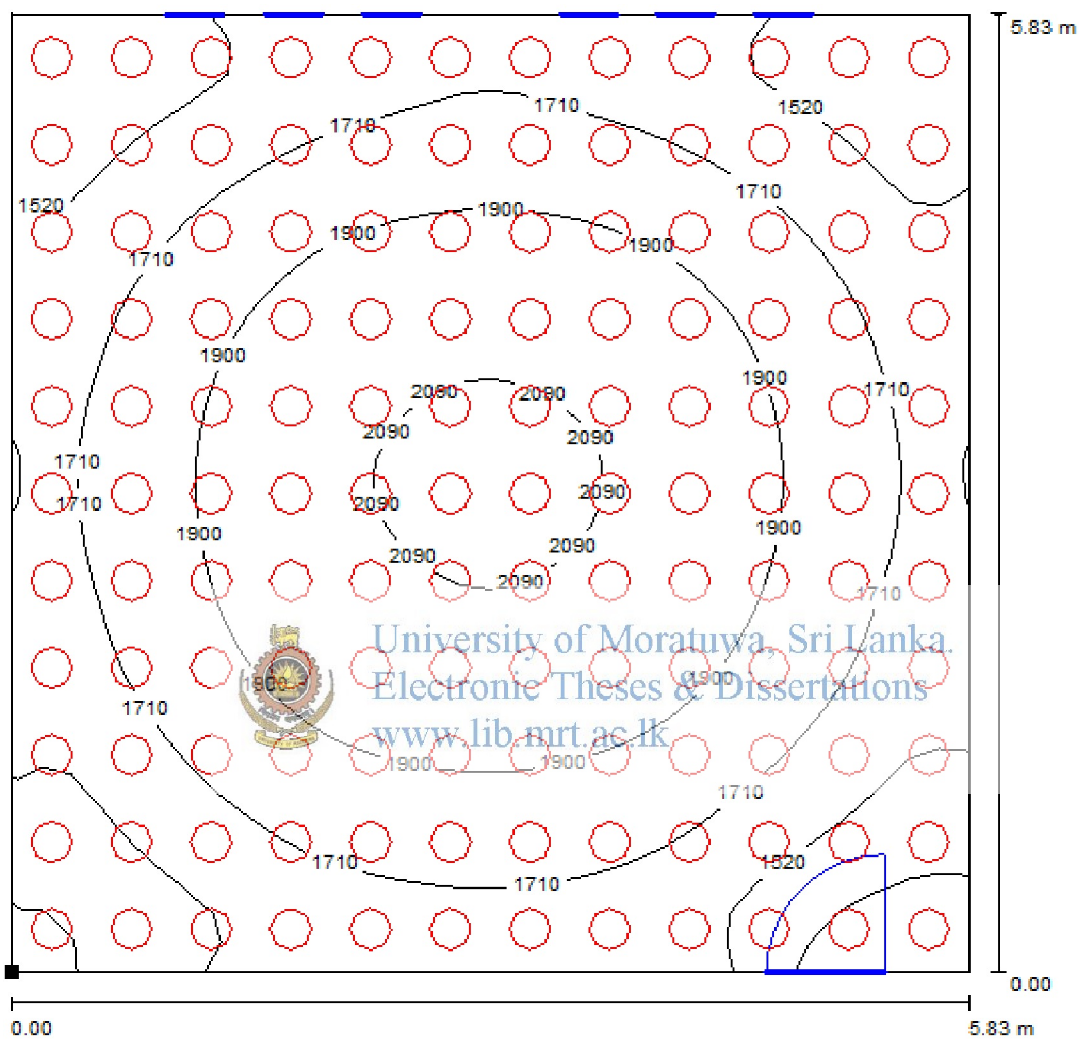
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
672	455	807	0.677	0.563

Luminaire type - Solatube/250mm
Sun Altutude based in lighting plan - 10°
Time of output - 07.00 hrs

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



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Position of surface in room:
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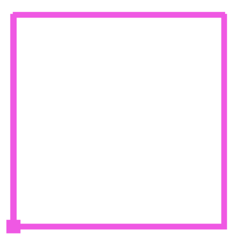


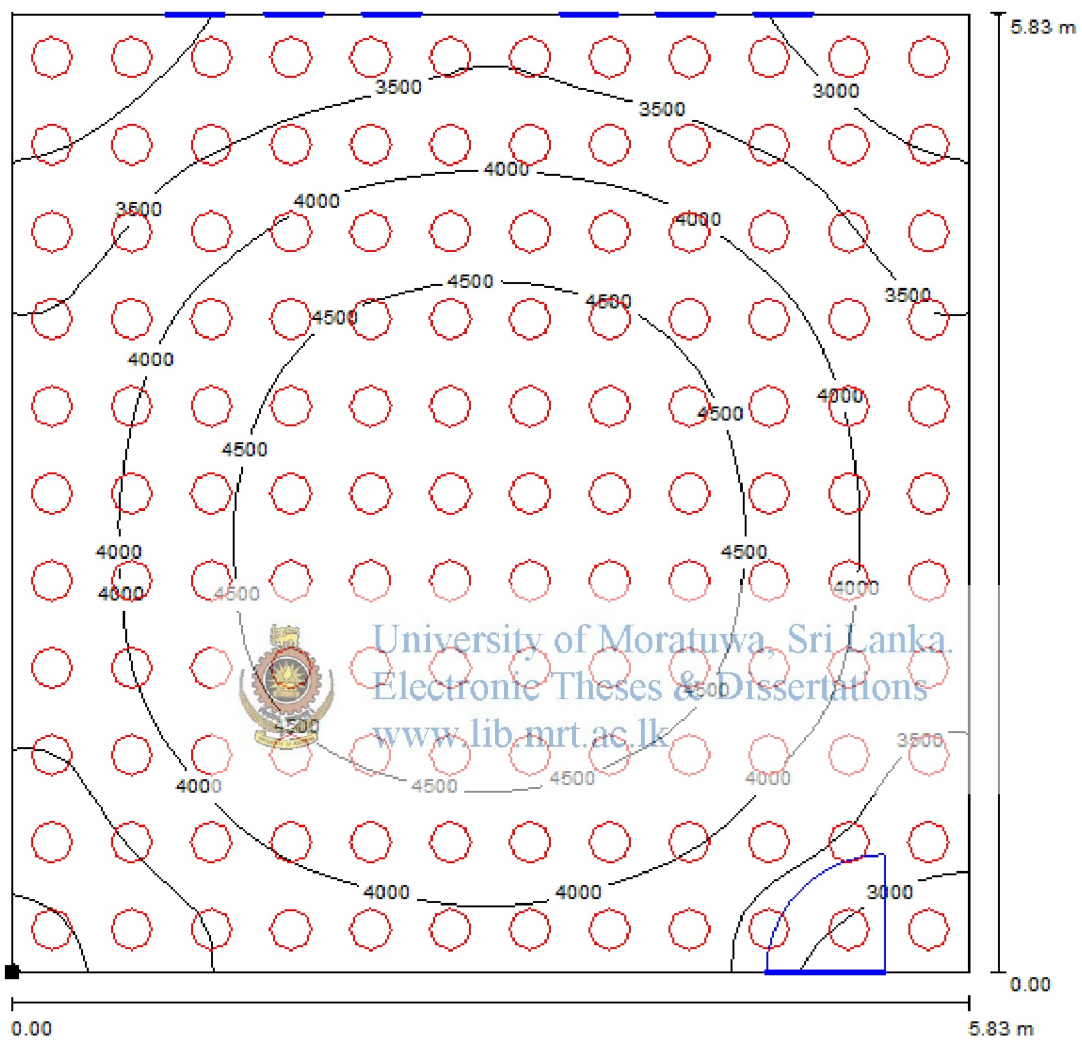
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
1761	1187	2126	0.674	0.558

Luminaire type - □□□□□□□□□□0□□
□□□□□□□□d□□□□□d□□□□□□□□□□□□□10□
□□□□□□□□□□□□0□40 hrs□□

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
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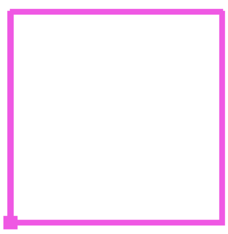
(-13.661 m, 3.056 m, 0.800 m)



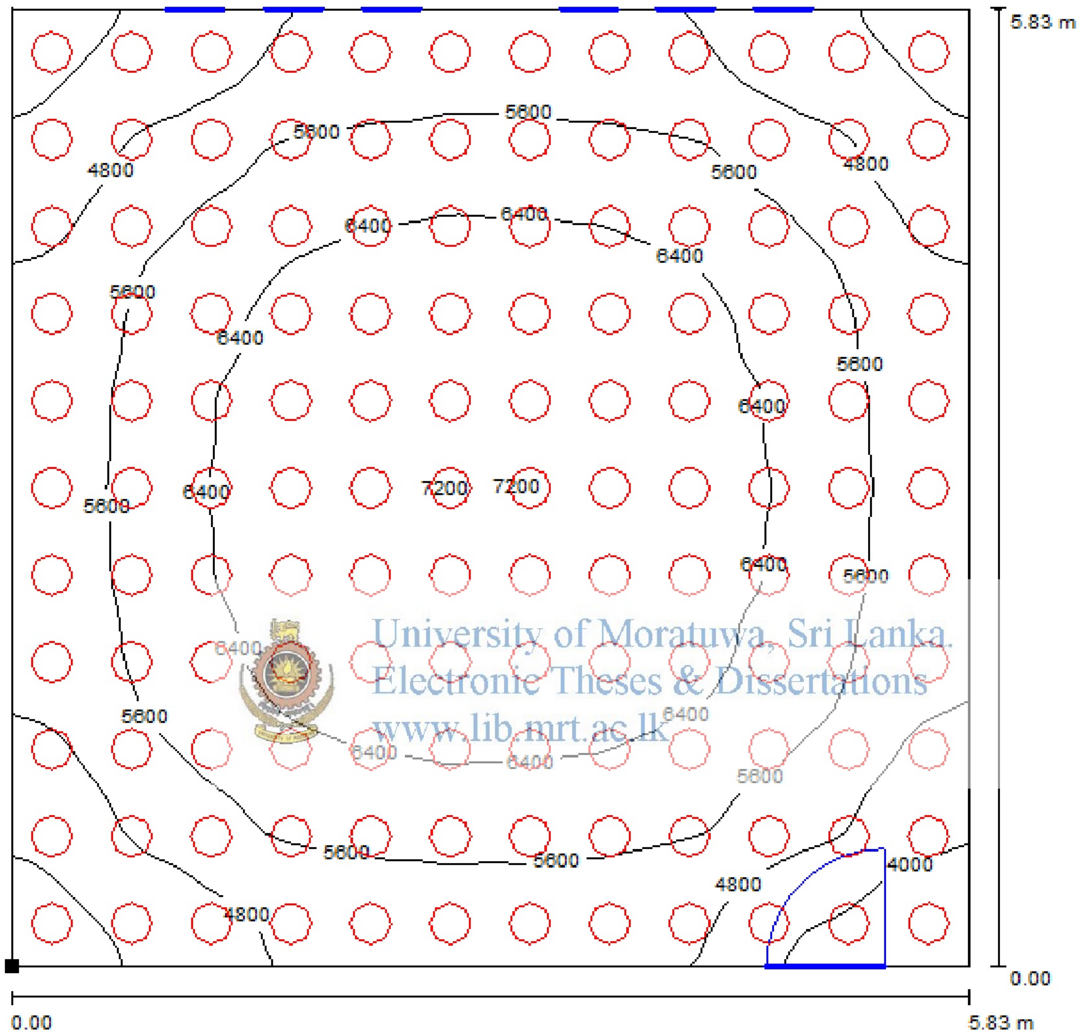
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
3976	2606	4961	0.655	0.525

Luminaire type - 0
d d 10
09 40 hrs

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



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Position of surface in room:
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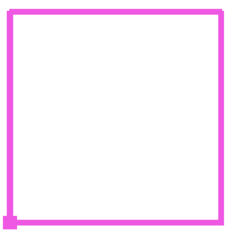


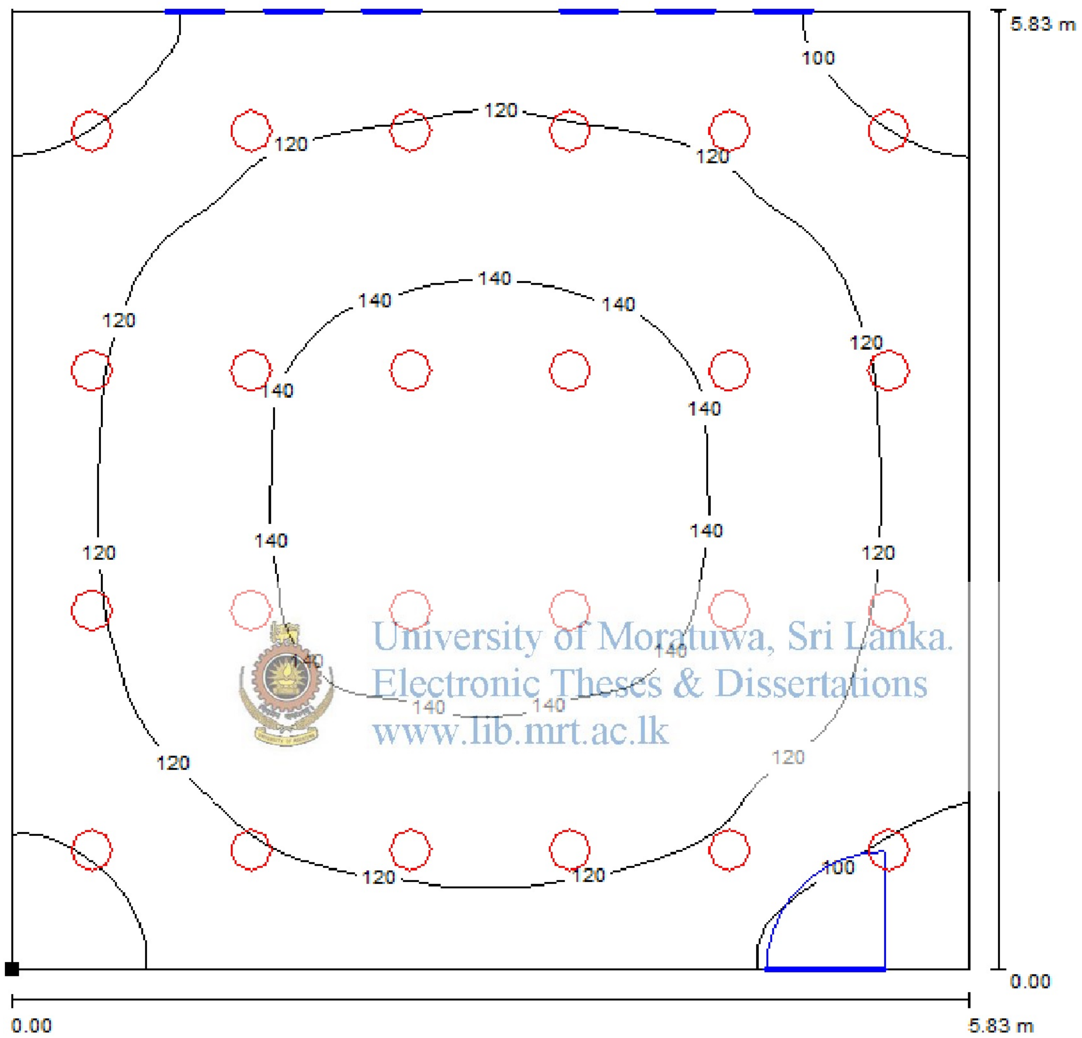
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
5712	3410	7224	0.597	0.472

Luminaire type -
d s d h
12.20 hrs

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
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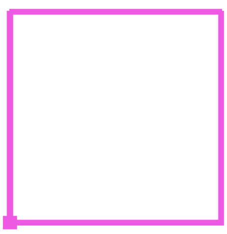


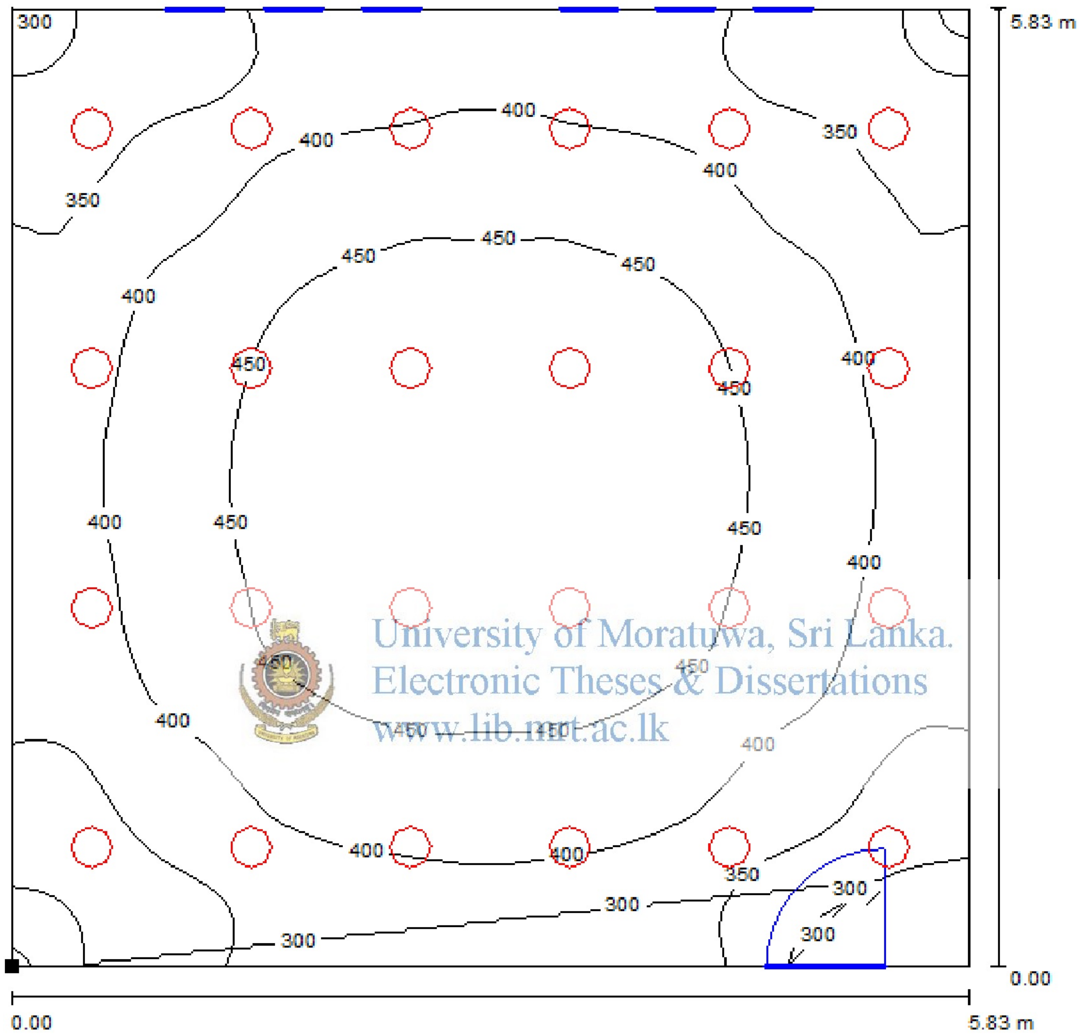
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
123	82	148	0.665	0.553

Luminaire type - □□□□□□□□□□□□ □
□□□□□□□□d□□□s□d□□□□h□□□□□□□□□5□□
□□ □□□□□□□□□07□0□hrs□□

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



Values in Lux, Scale 1 : 46

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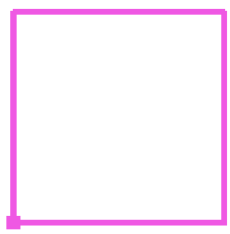


Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
404	268	492	0.664	0.546

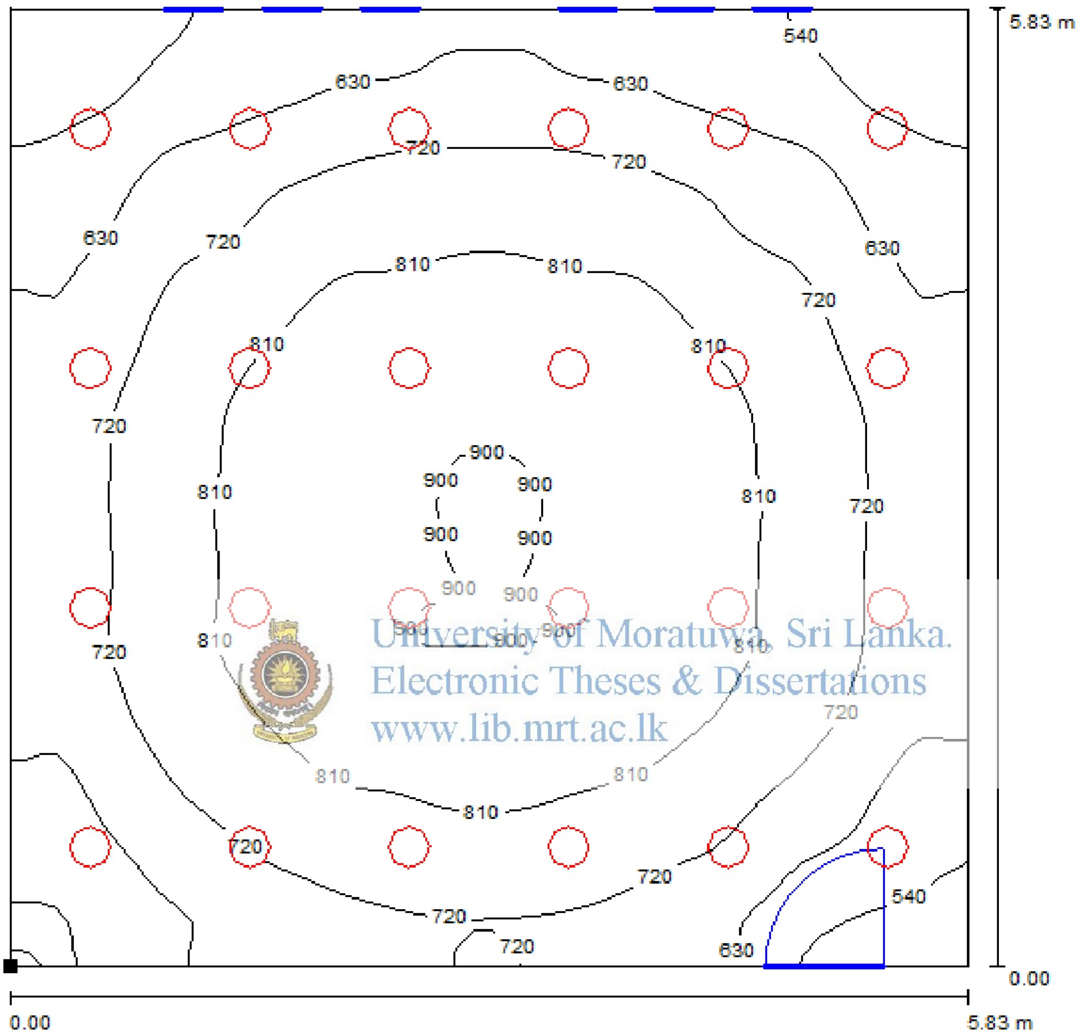
Luminaire type -

d s d h 5

08.20 hrs

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



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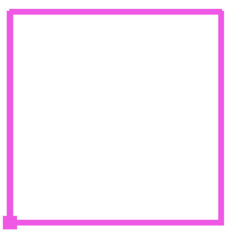


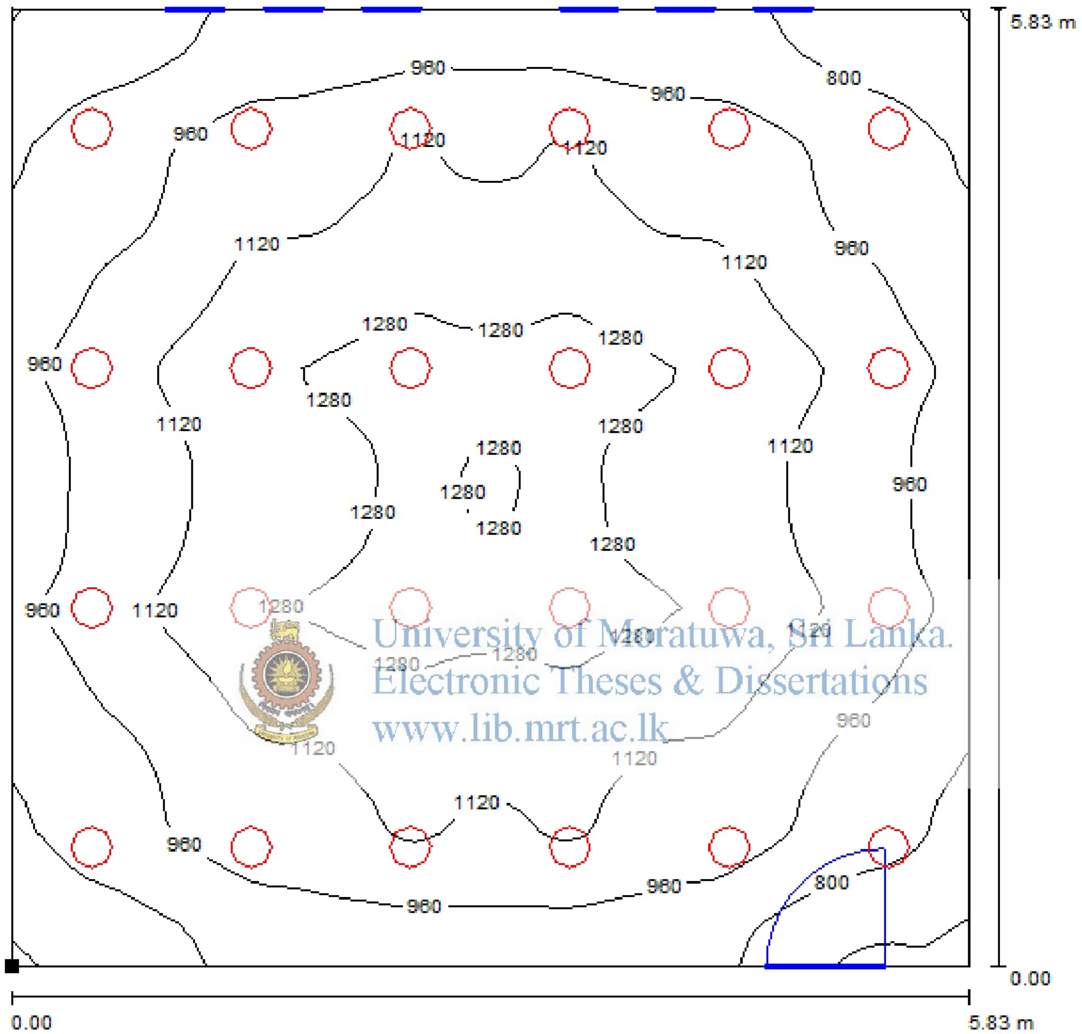
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
729	465	911	0.639	0.511

Luminaire type - □□□□□□□□□□□ □
□□□□□□□□d□□□s□d□□□□h□□□□□□□□□5□□
□□ □□□□□□□□□09□4□hrs□□

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
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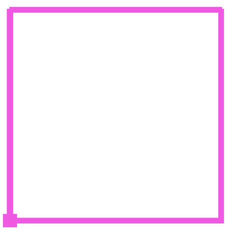


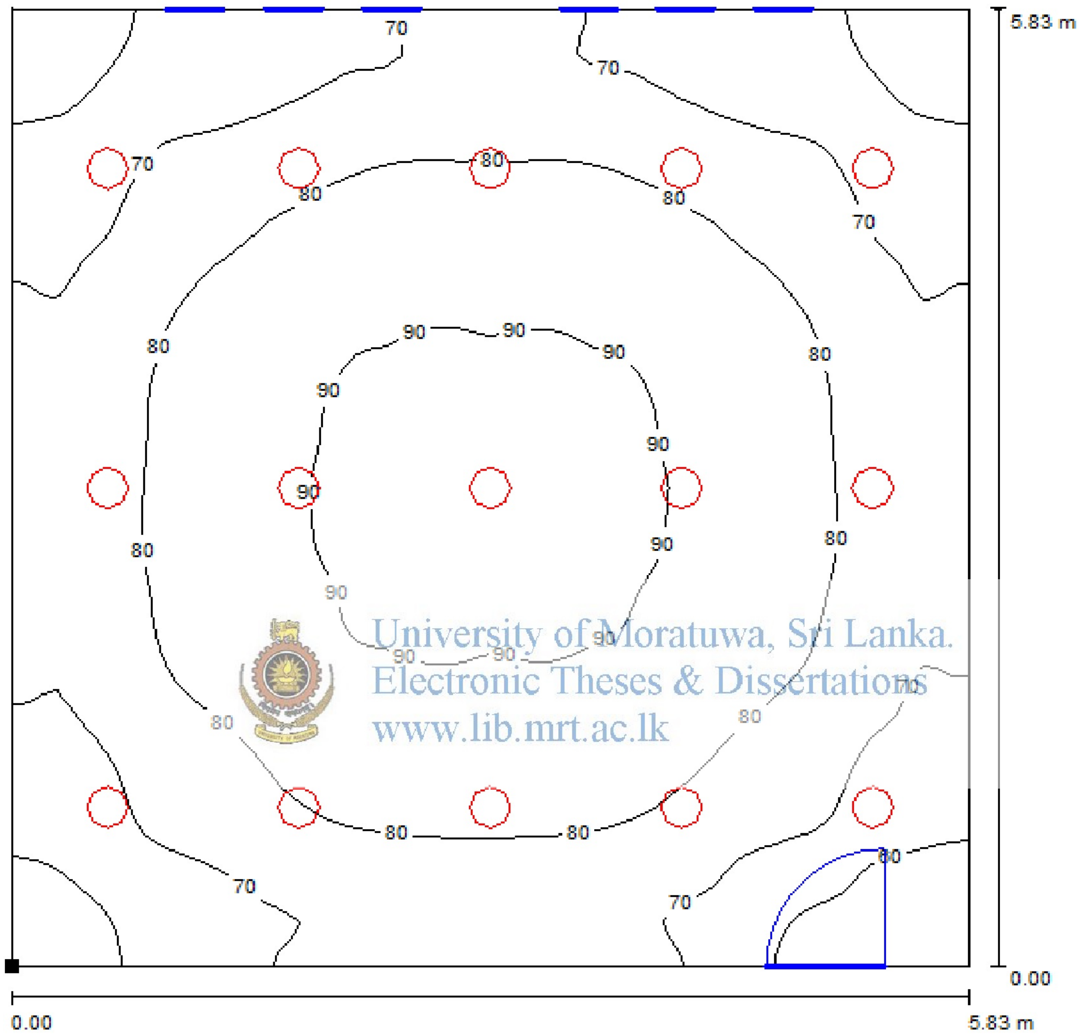
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
1049	599	1366	0.571	0.438

Luminaire type -

Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
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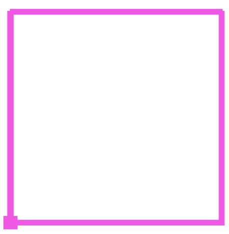


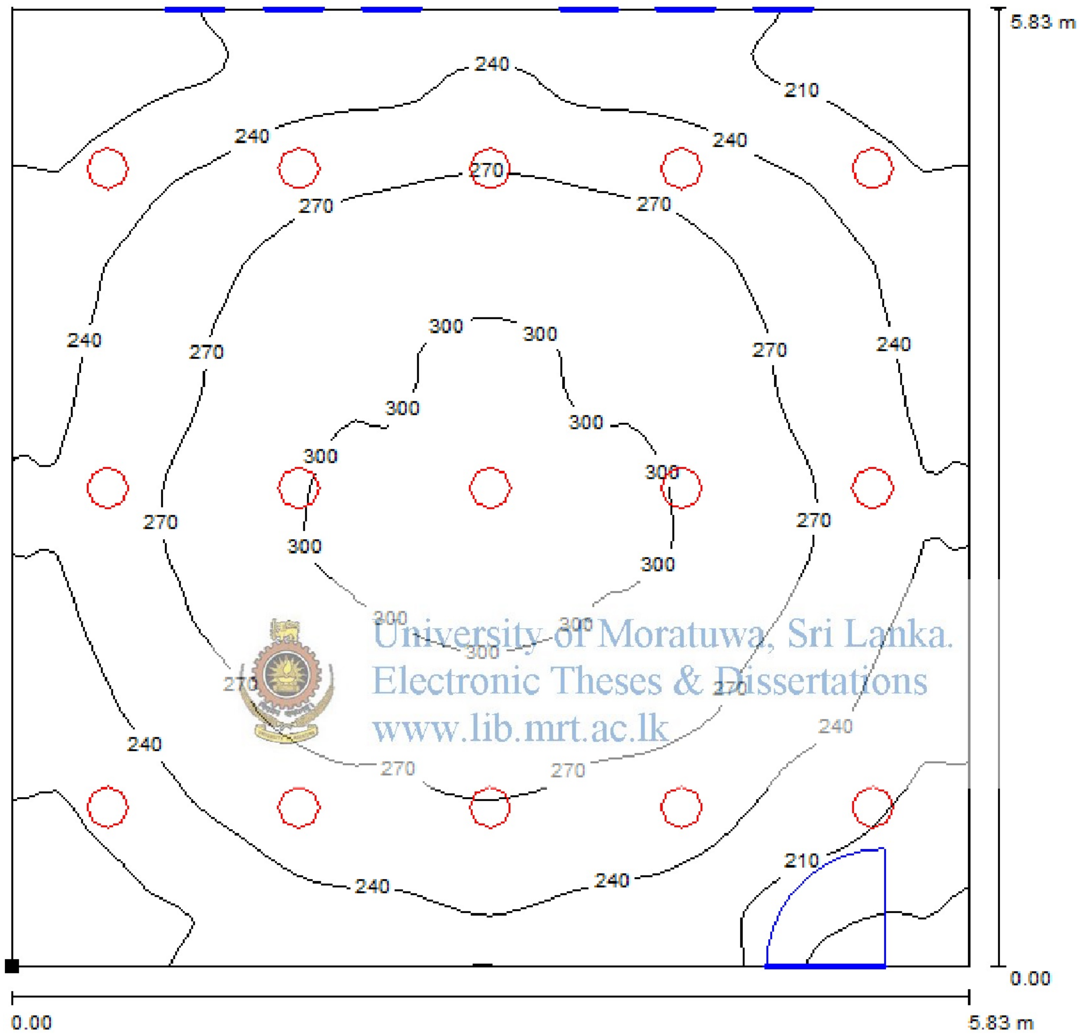
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
77	51	93	0.664	0.551

Luminaire type -
d s d h 9
07.00 hrs

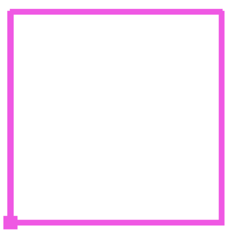
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



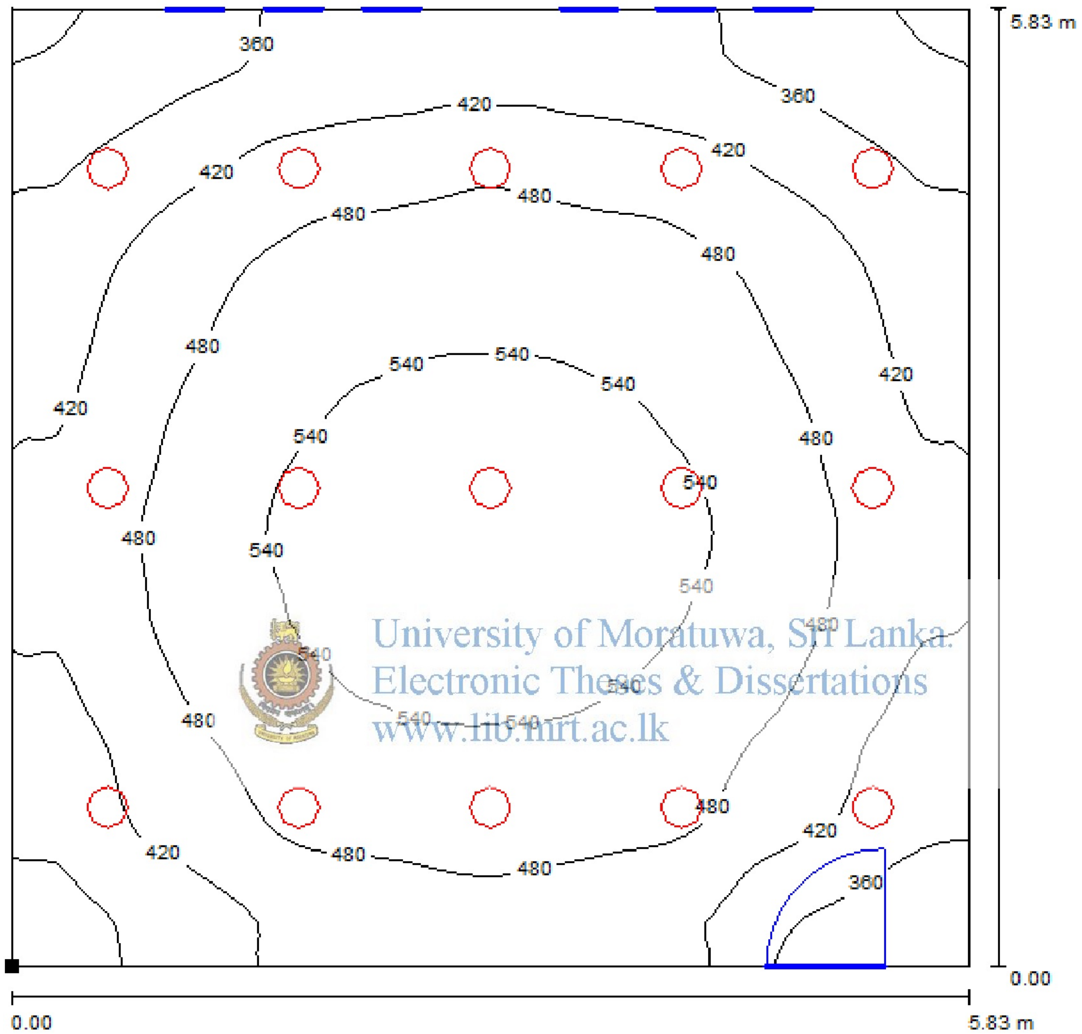
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
254	166	313	0.653	0.529

Luminaire type -
d s d h 9
08.20 hrs

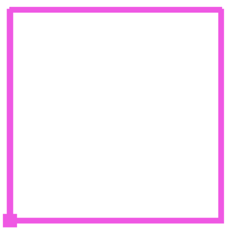
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
458	290	579	0.633	0.501

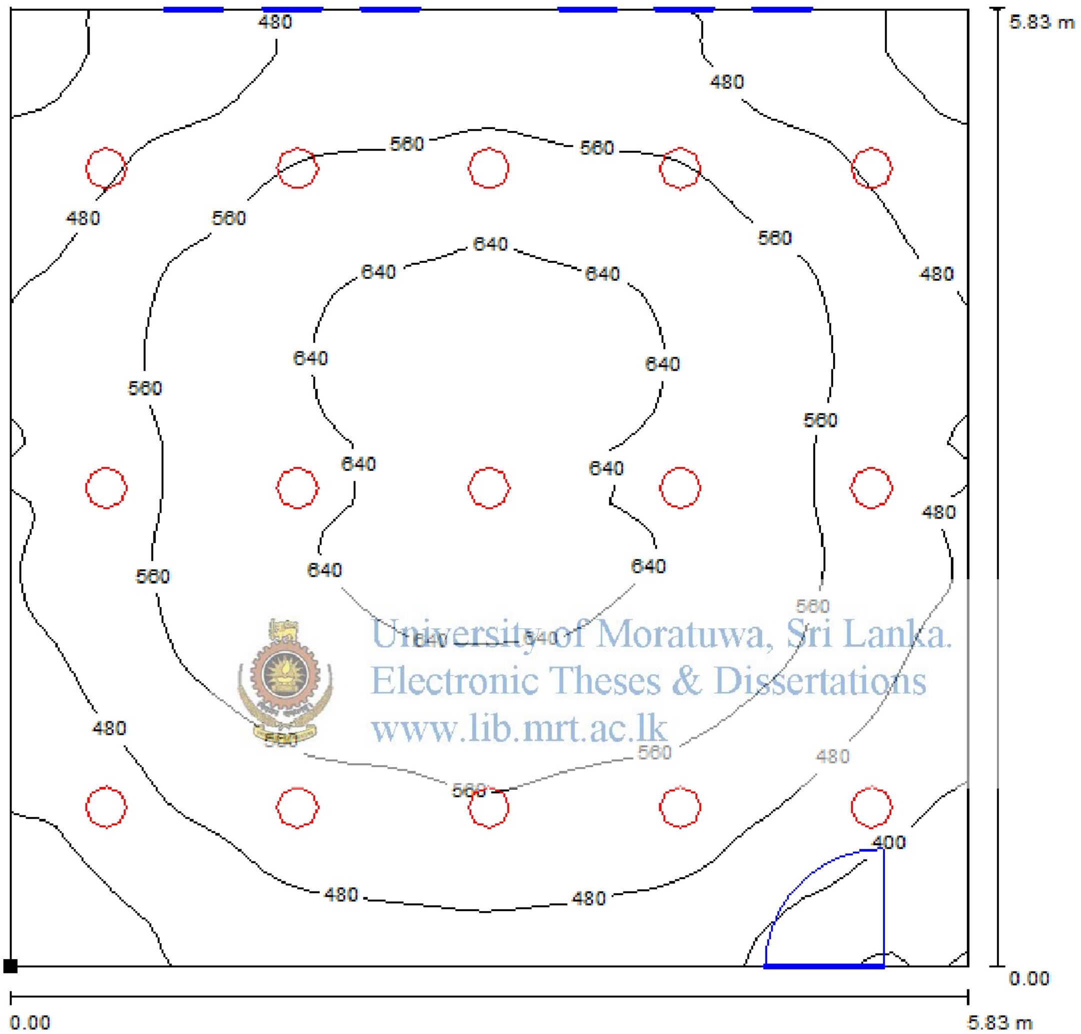
Luminaire type -

d s d h 9

09 4 hrs

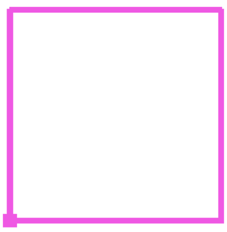
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
535	310	664	0.579	0.467

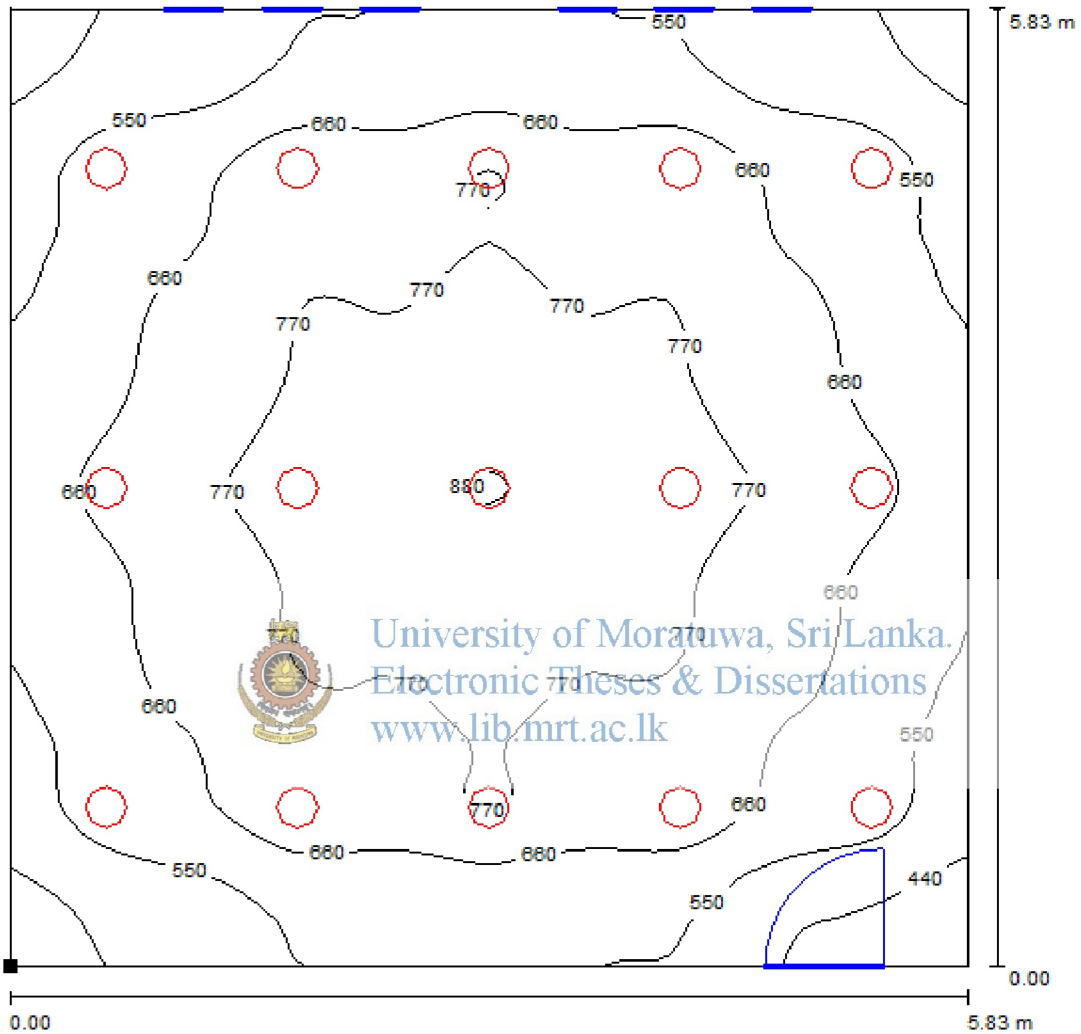
Luminaire type -

d s d h 9

11.00 hrs

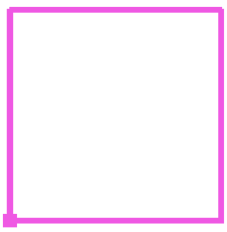
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



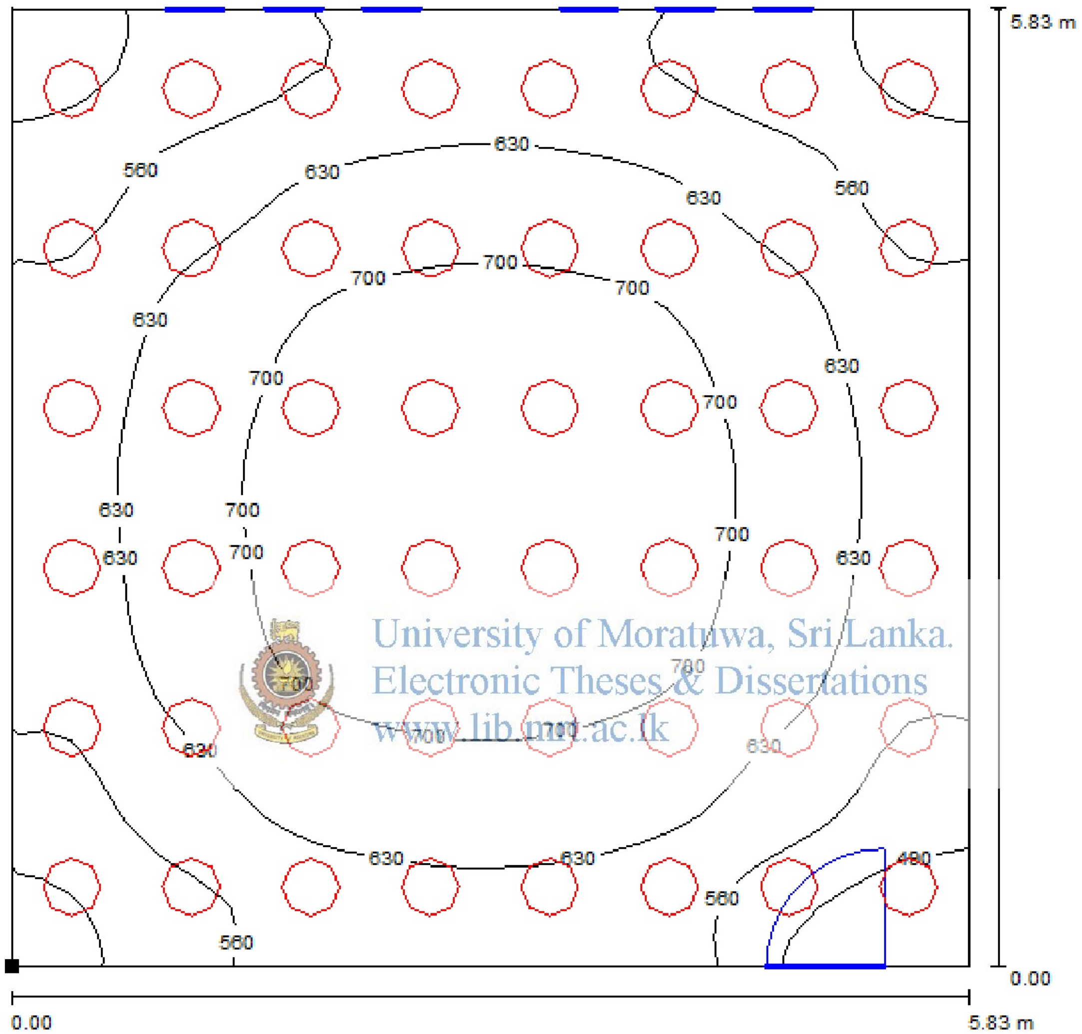
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
660	374	898	0.567	0.416

Luminaire type - □□□□□□□□□□□ □
□□□□□□□□d□□□s□d□□□□h□□□□□□□□□9□□
□□ □□□□□□□□□□12.20□hrs□□

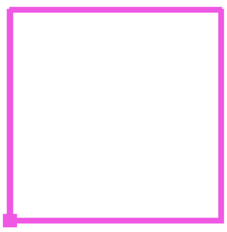
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



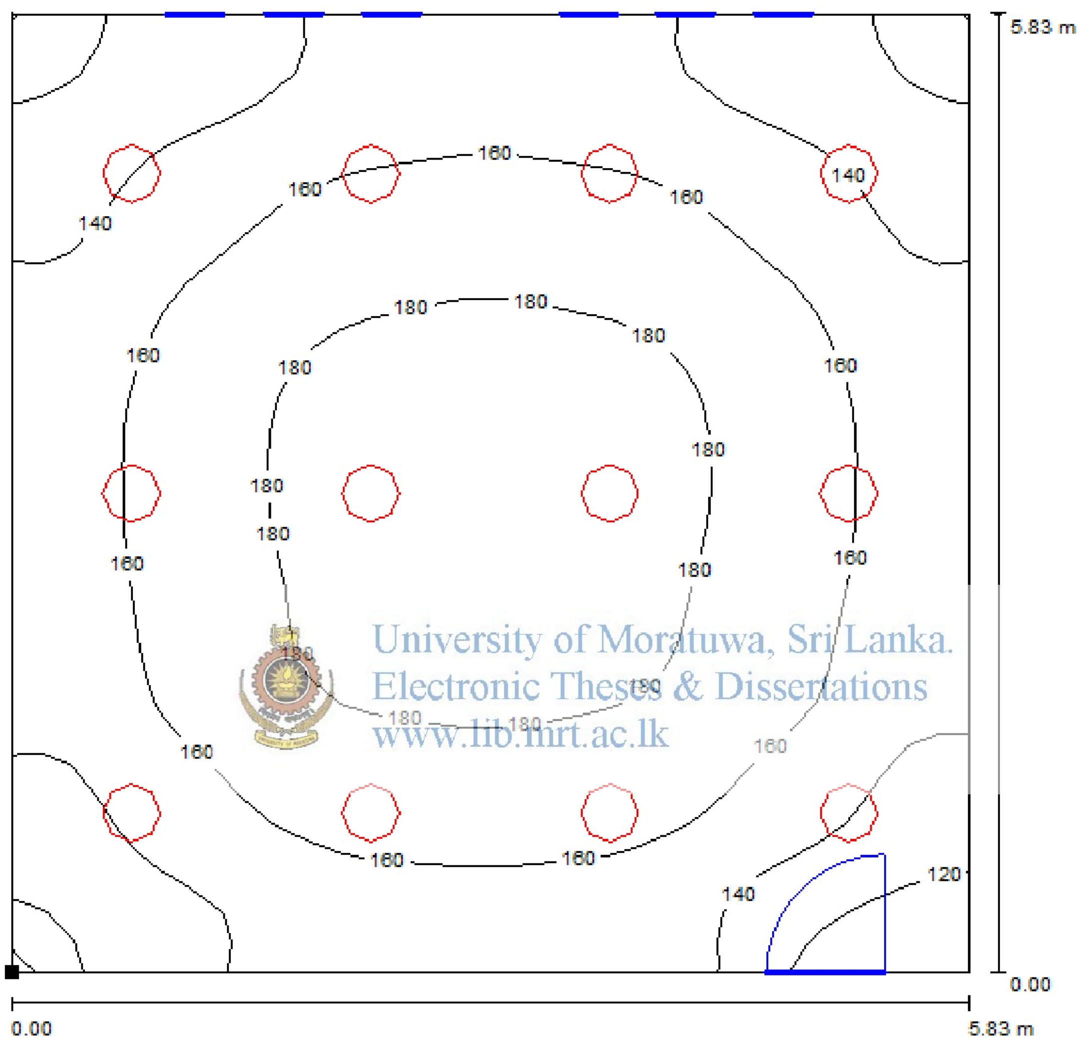
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
627	430	753	0.686	0.571

Luminaire type - □□□□□□□□3□□□ □
□□□□□□□□d□□□s□d□□□□h□□□□□□□□1□□
□□ □□□□□□□□07.00□hrs□□

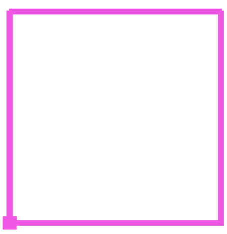
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



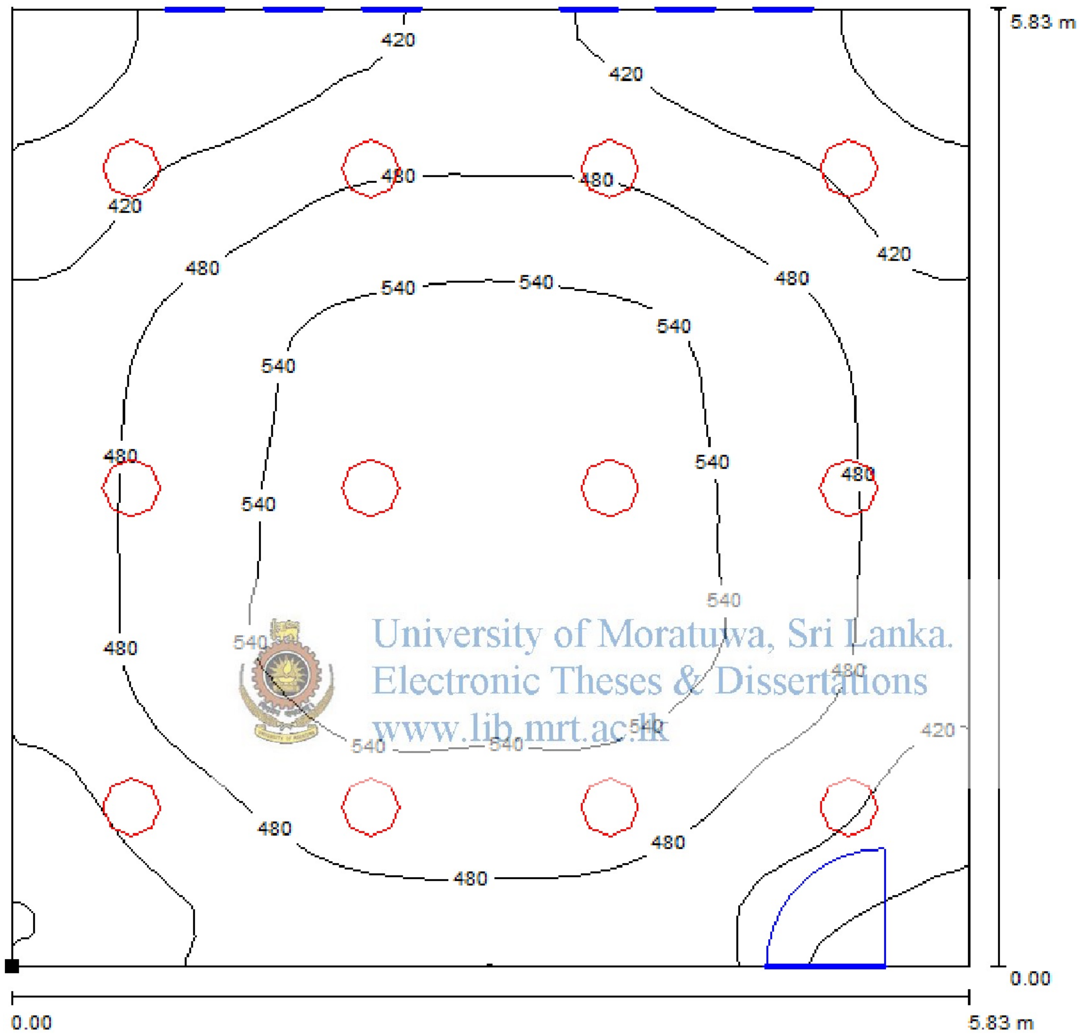
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
158	107	190	0.676	0.563

Luminaire type -

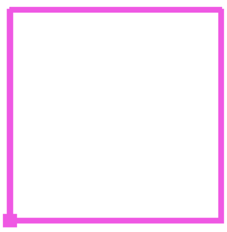
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



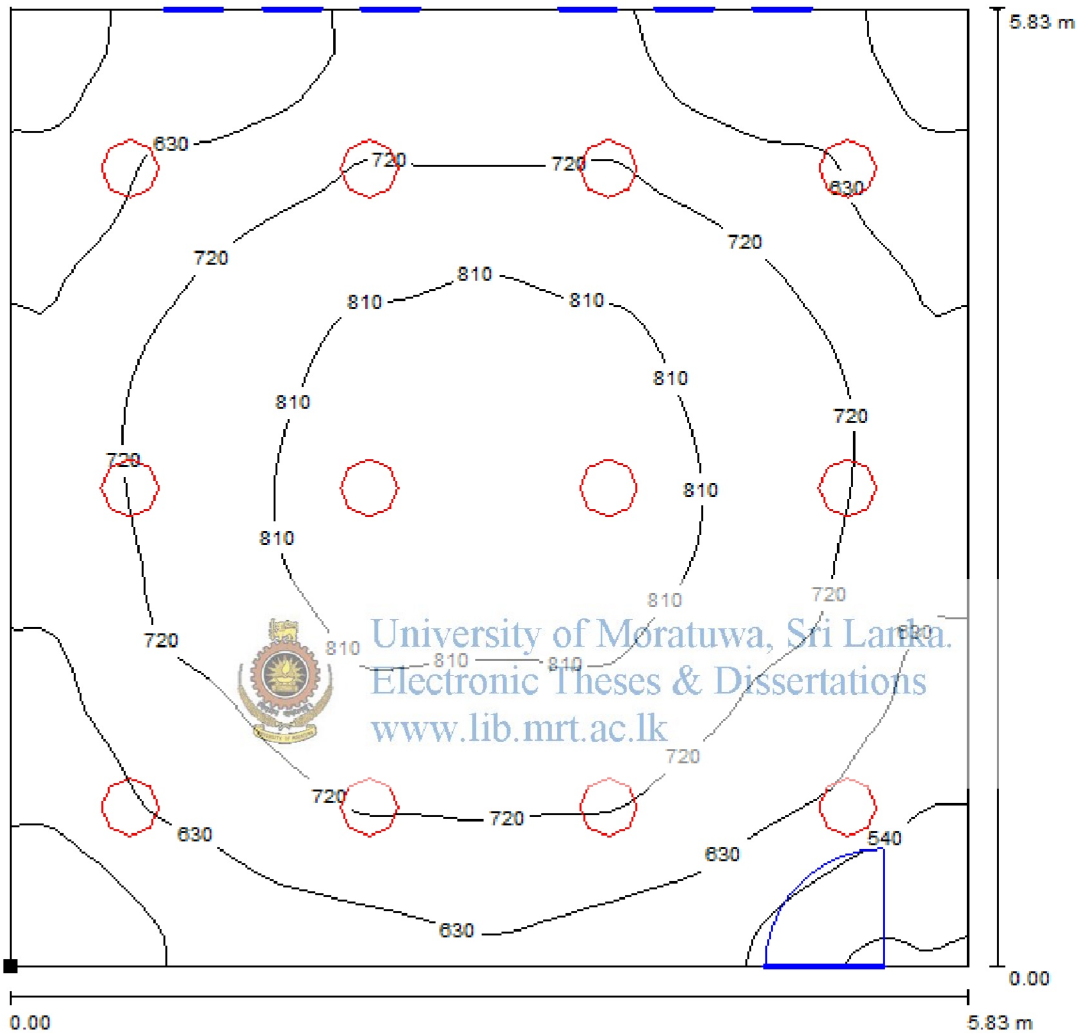
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
477	325	584	0.682	0.557

Luminaire type -

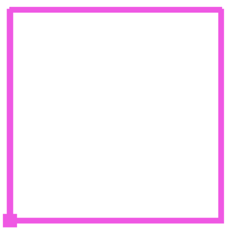
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



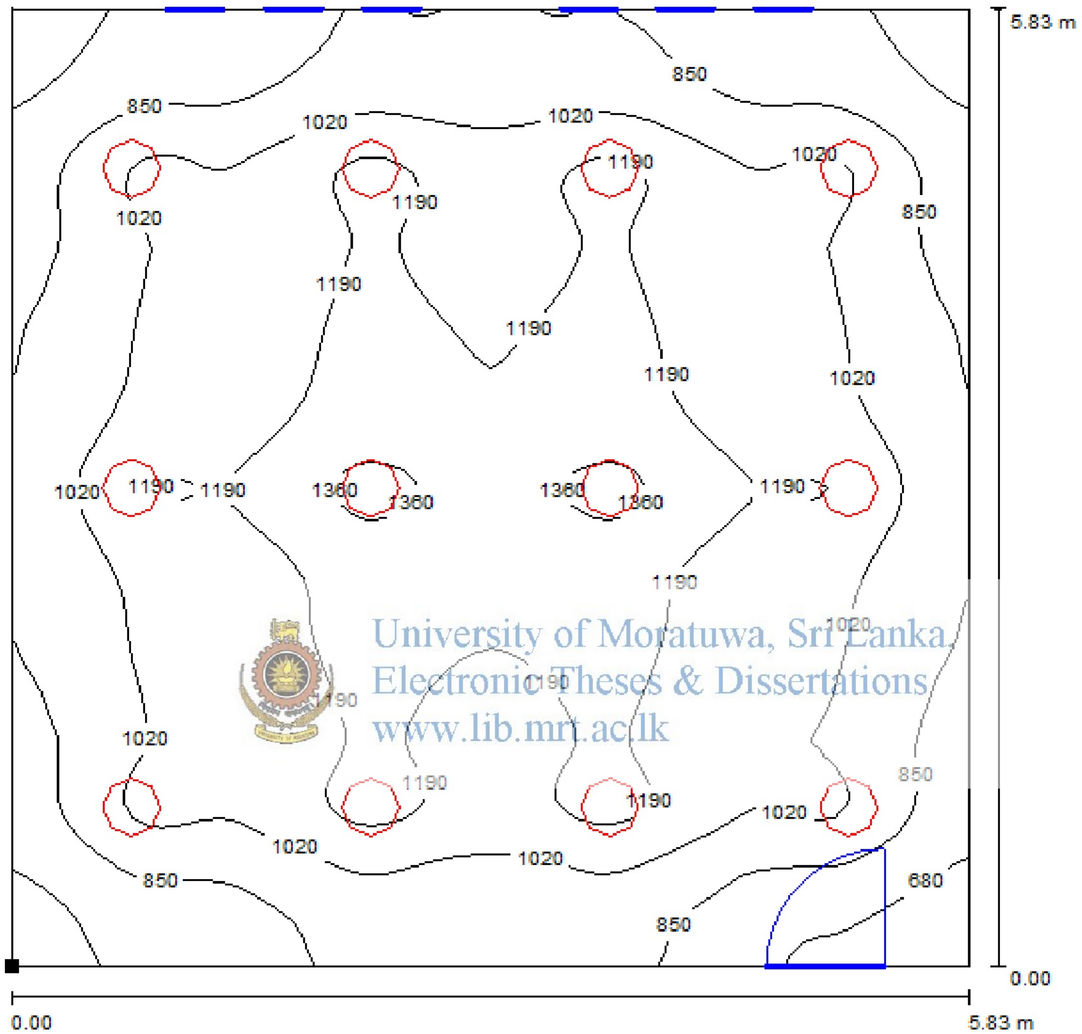
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
693	429	858	0.620	0.500

Luminaire type -

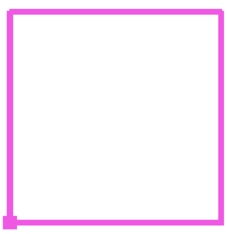
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



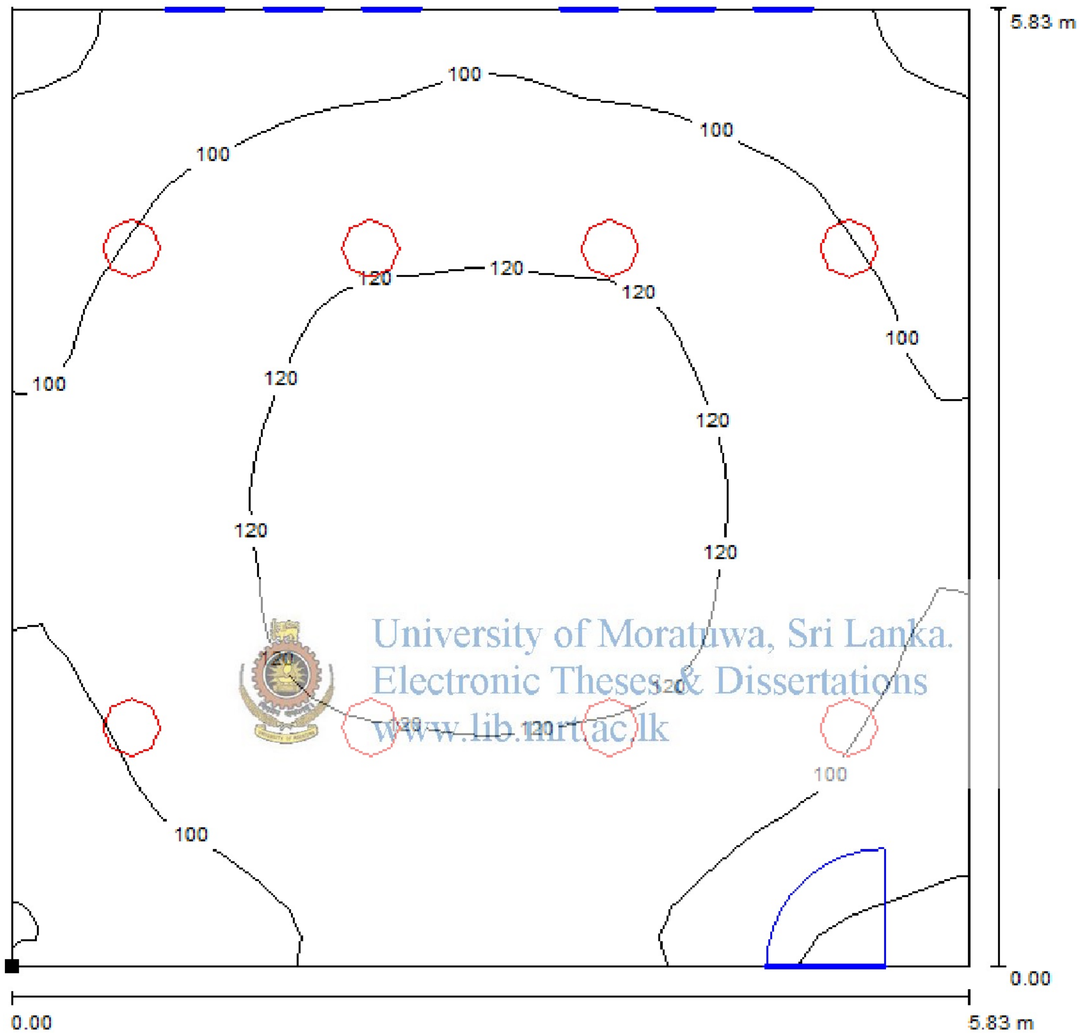
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
1025	578	1404	0.564	0.412

Luminaire type -
d s d h 5
12 2 hrs

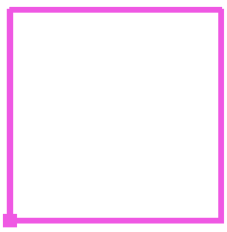
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
107	74	128	0.691	0.577

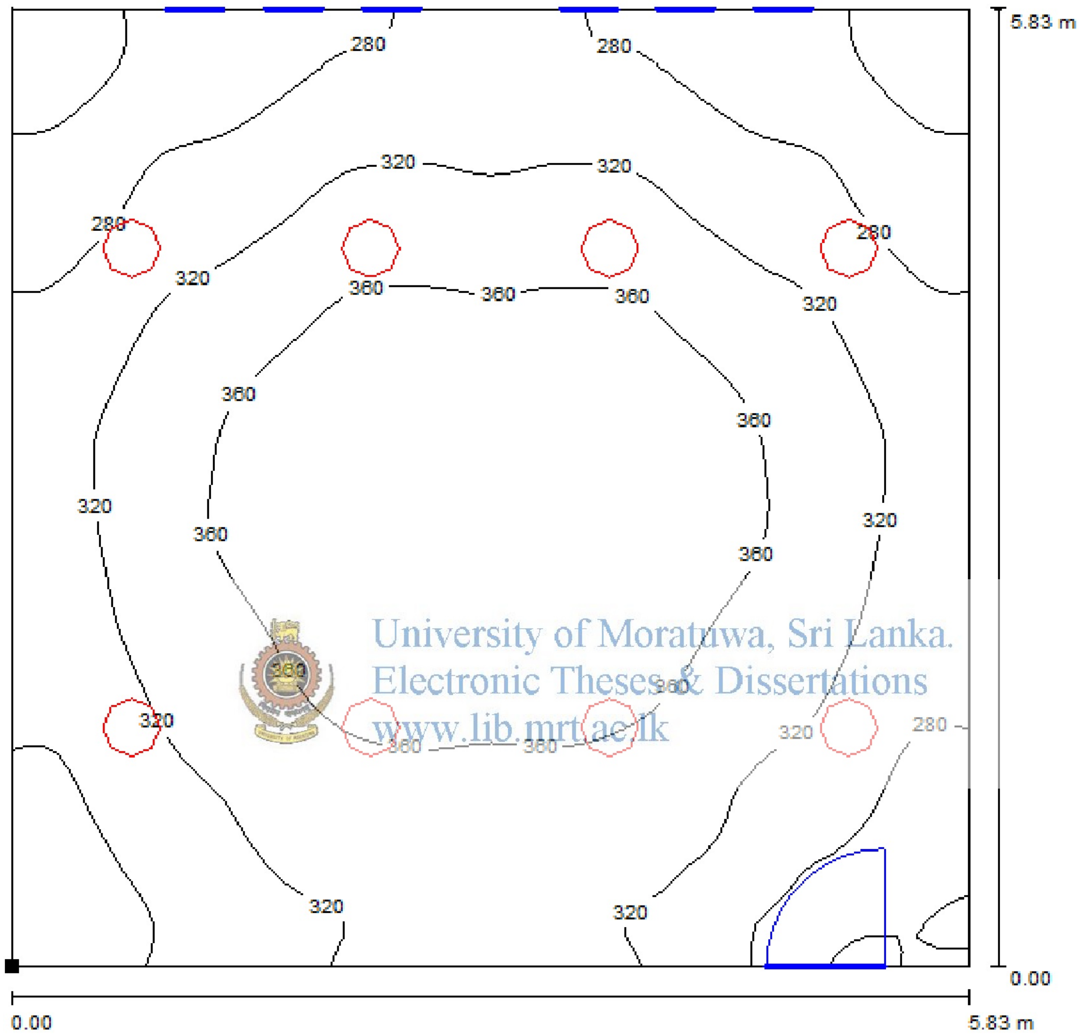
Luminaire type -

d s d h 9

hrs

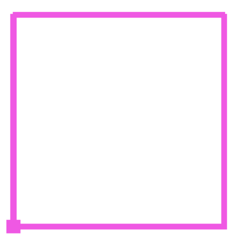
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



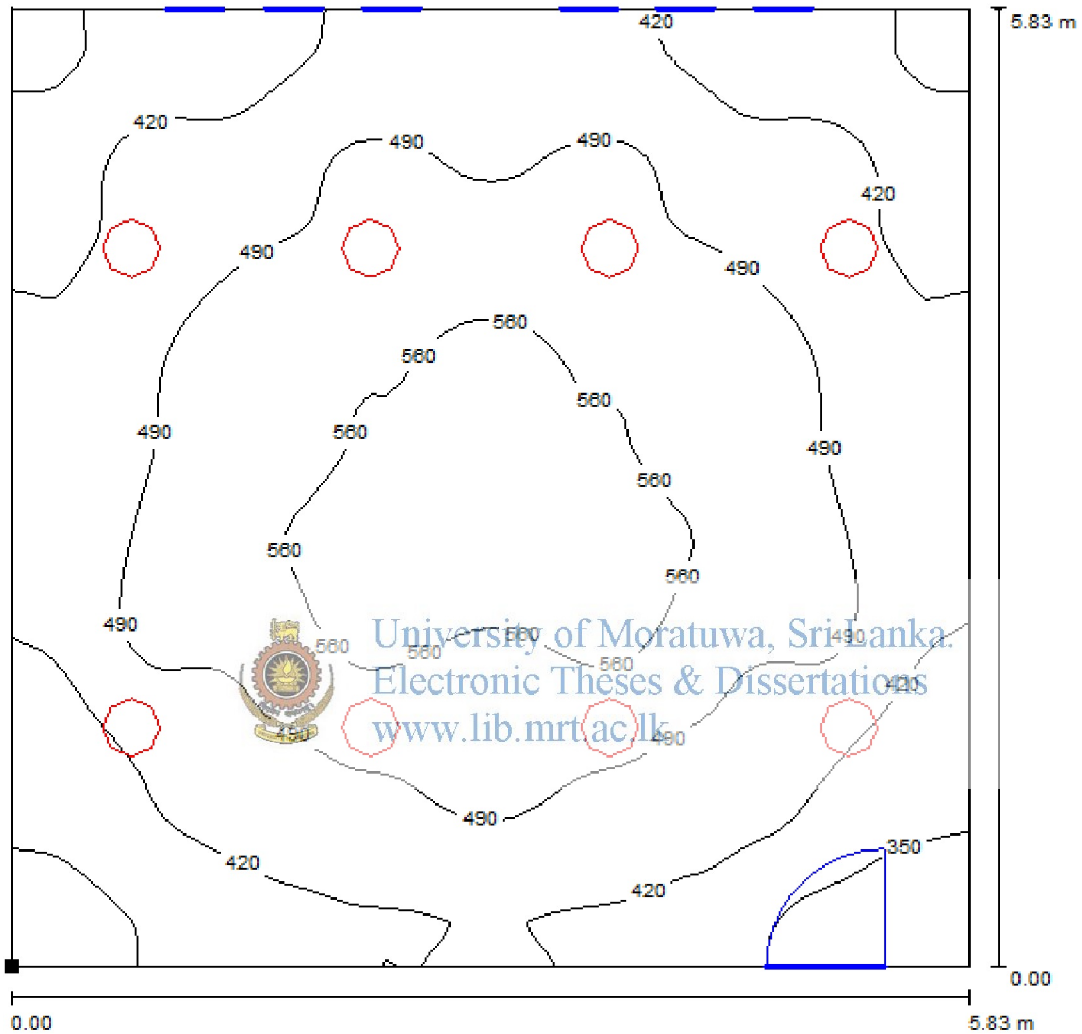
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
322	218	397	0.676	0.548

Luminaire type -

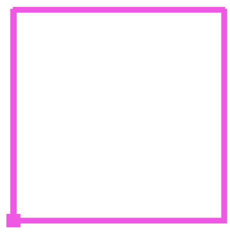
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



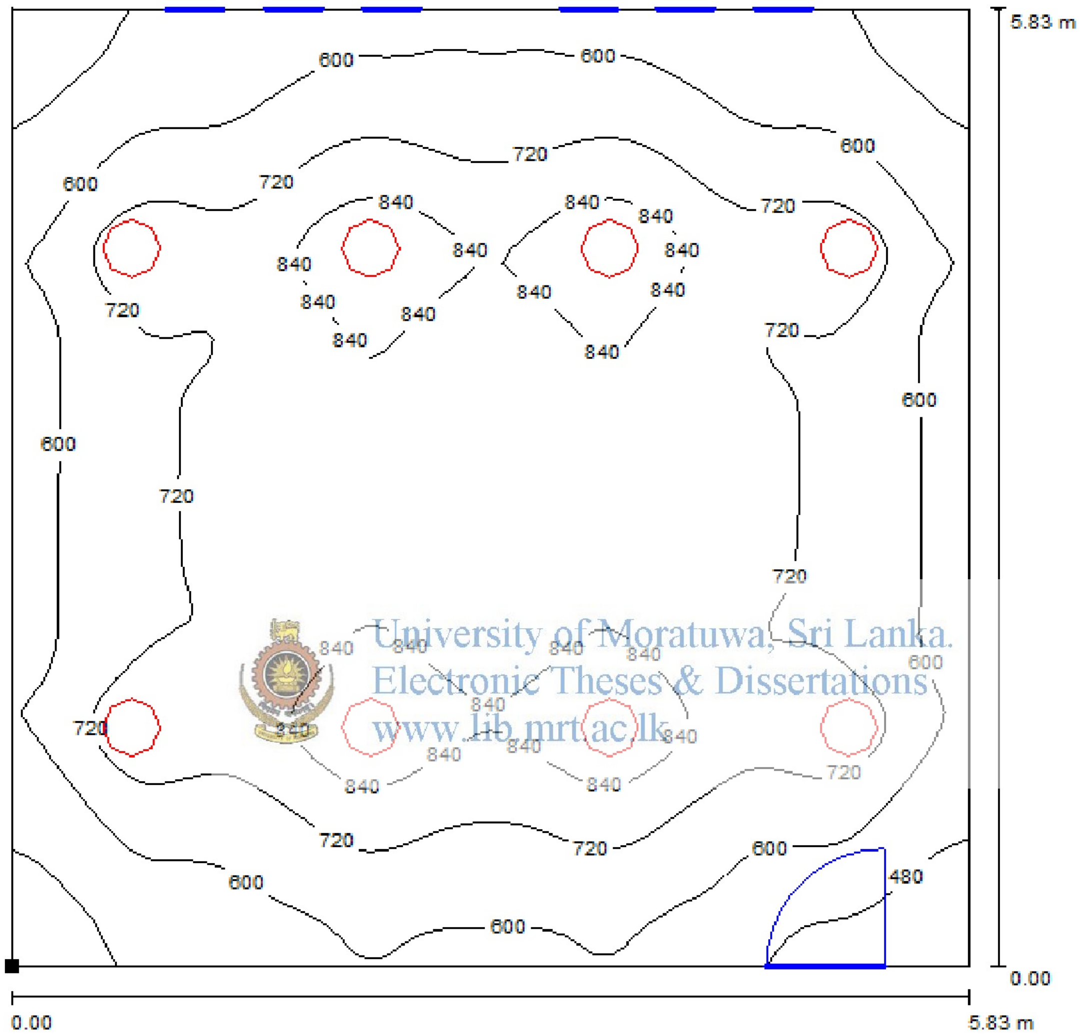
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
468	286	589	0.612	0.486

Luminaire type -

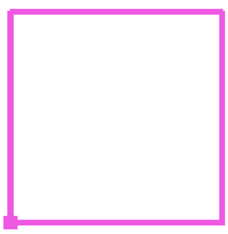
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



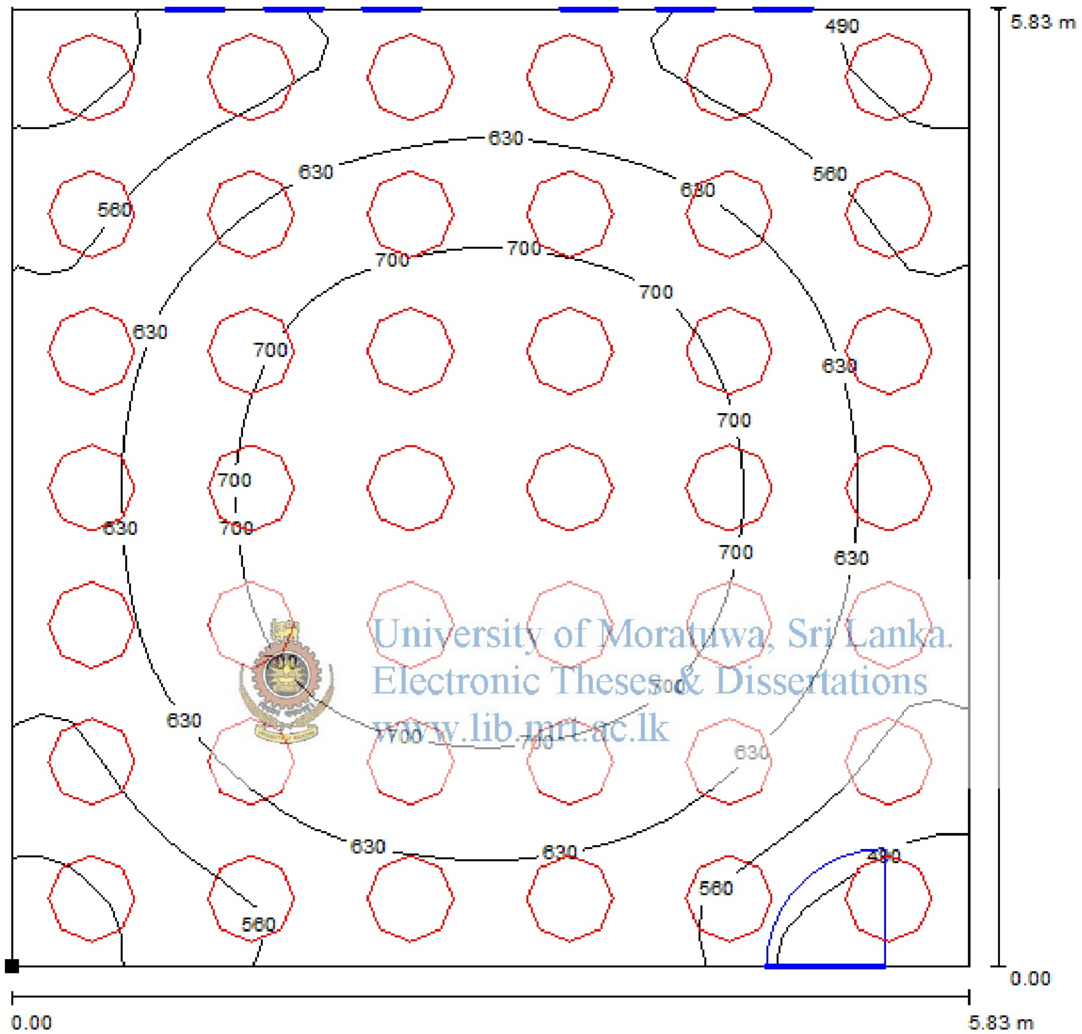
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
698	397	973	0.570	0.409

Luminaire type - [illegible]
[illegible]
[illegible] 12 2 hrs

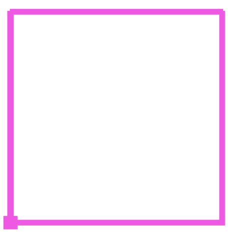
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



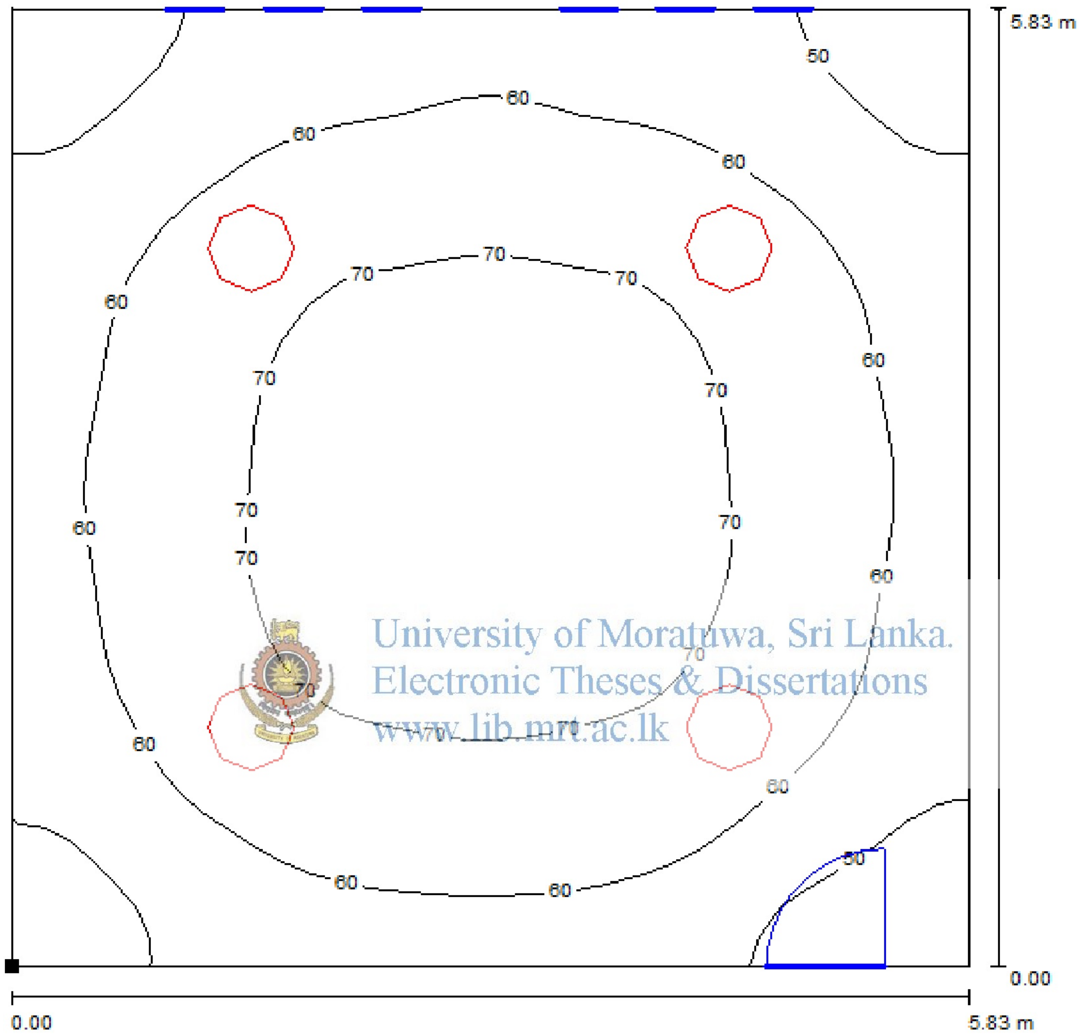
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
626	418	765	0.667	0.546

Luminaire type - 525
d s d h 1
07.00 hrs

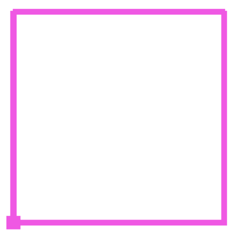
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



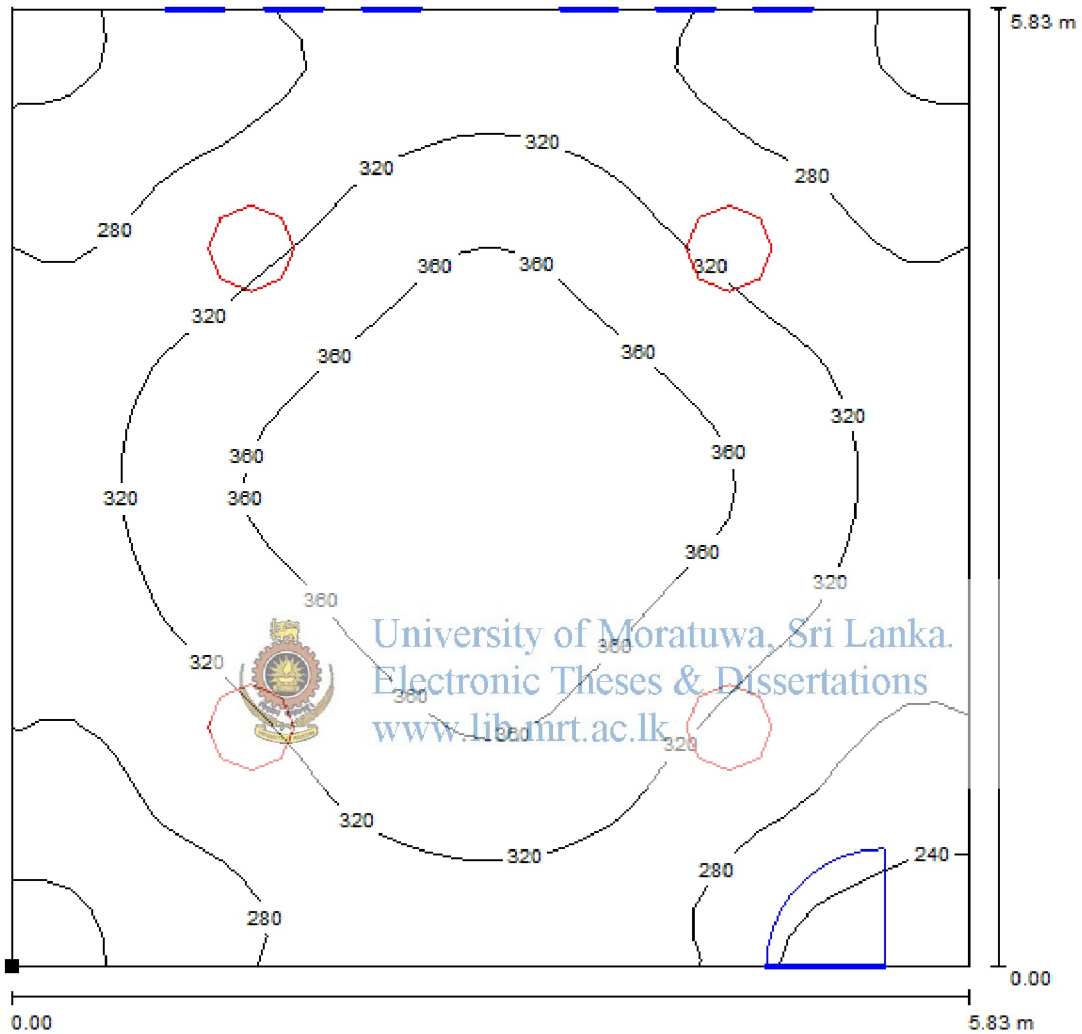
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
62	41	76	0.663	0.540

Luminaire type - □□□□□□□□525□ □
□□□□□□□□d□□□s□d□□□□h□□□□□□□□□5□□
□□ □□□□□□□□□07.00 hrs□□

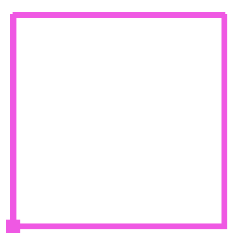
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



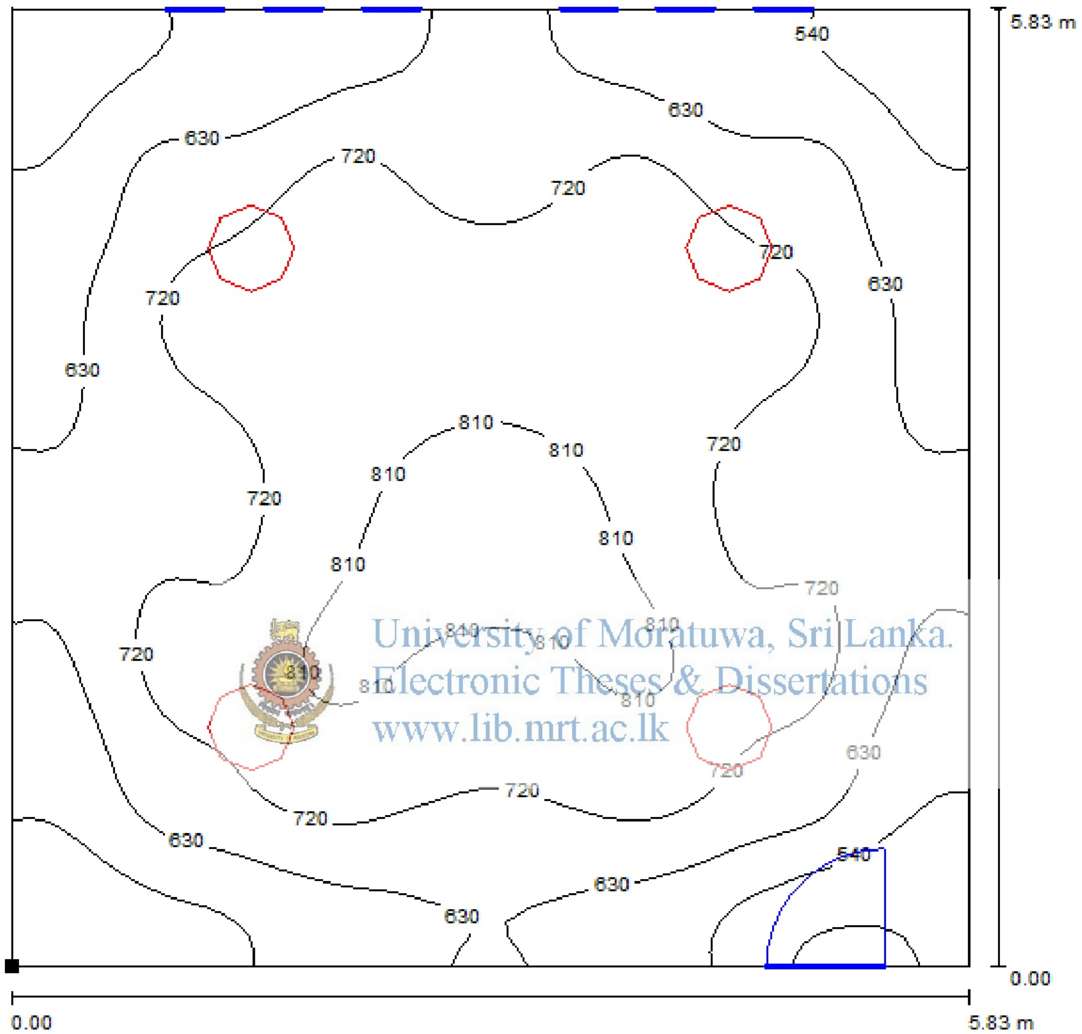
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
311	211	380	0.677	0.554

Luminaire type - 525
d s d h 5
08 2 hrs

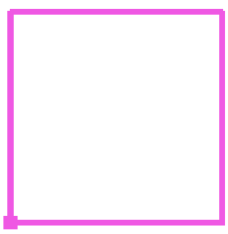
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



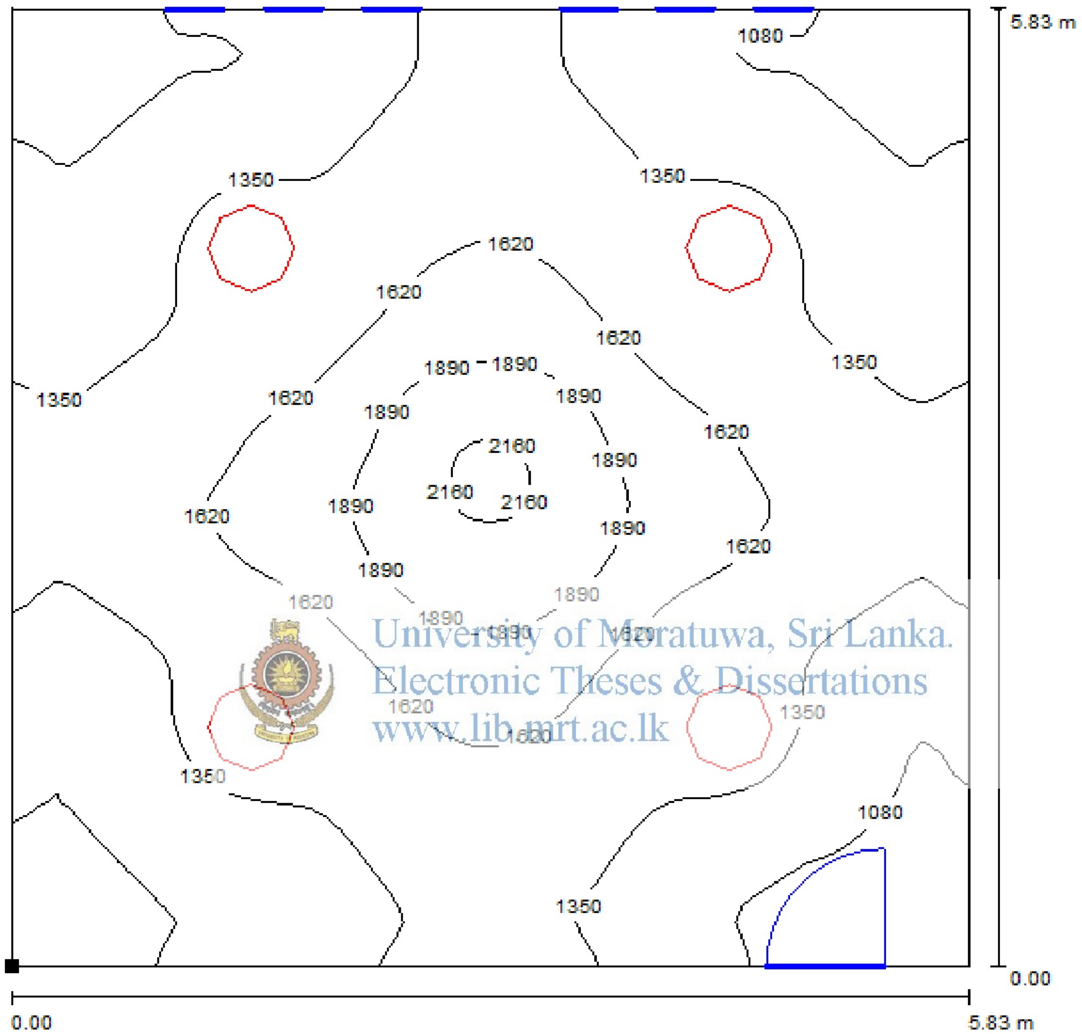
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
679	421	863	0.619	0.488

Luminaire type - 525
d s d h 5
09.40 hrs

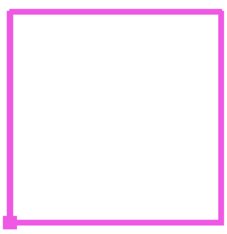
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



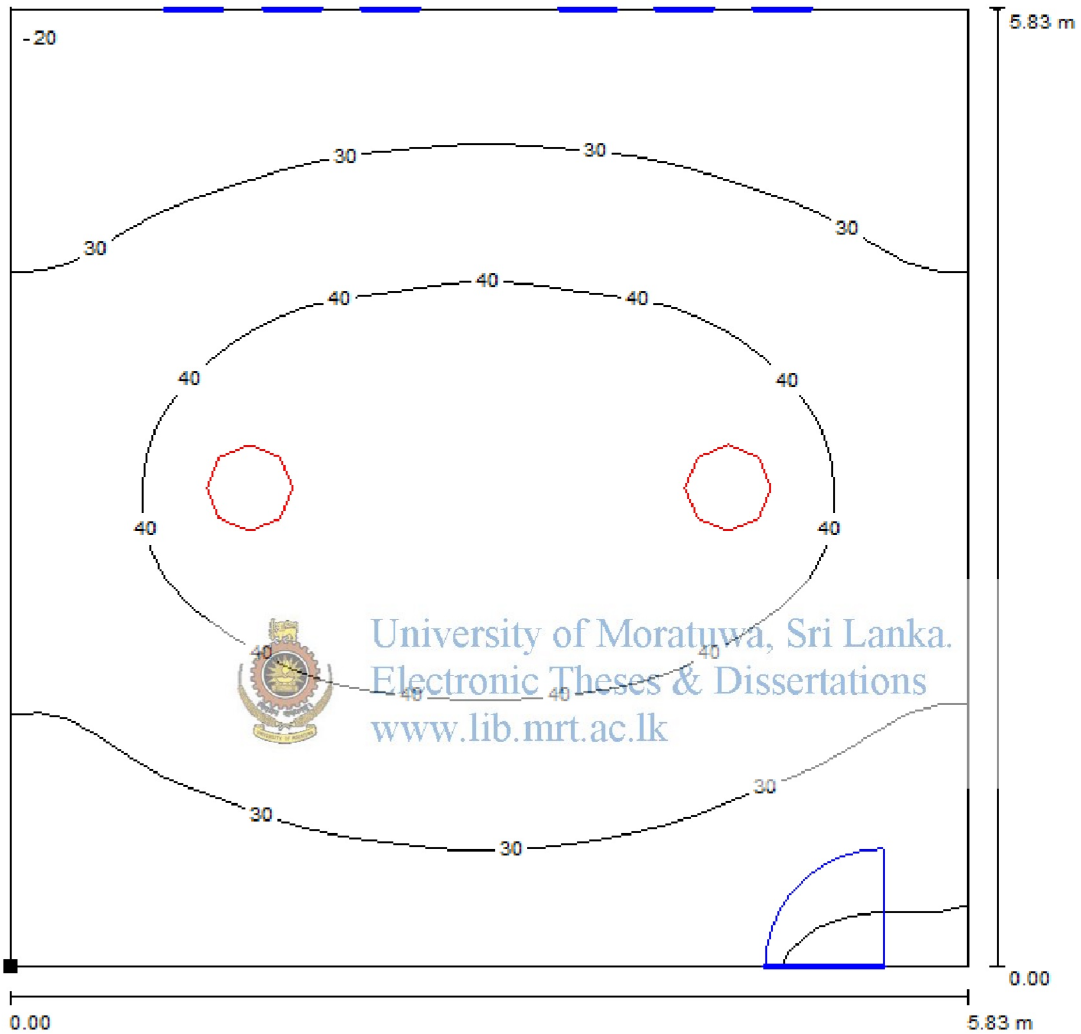
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
1409	892	2206	0.633	0.404

Luminaire type - [illegible] 525 [illegible]
[illegible] d [illegible] s d [illegible] h [illegible] 5 [illegible]
[illegible] 12 2 hrs [illegible]

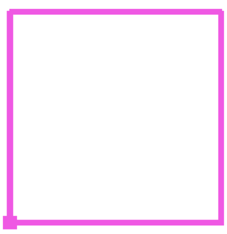
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / **Isolines (E)**



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



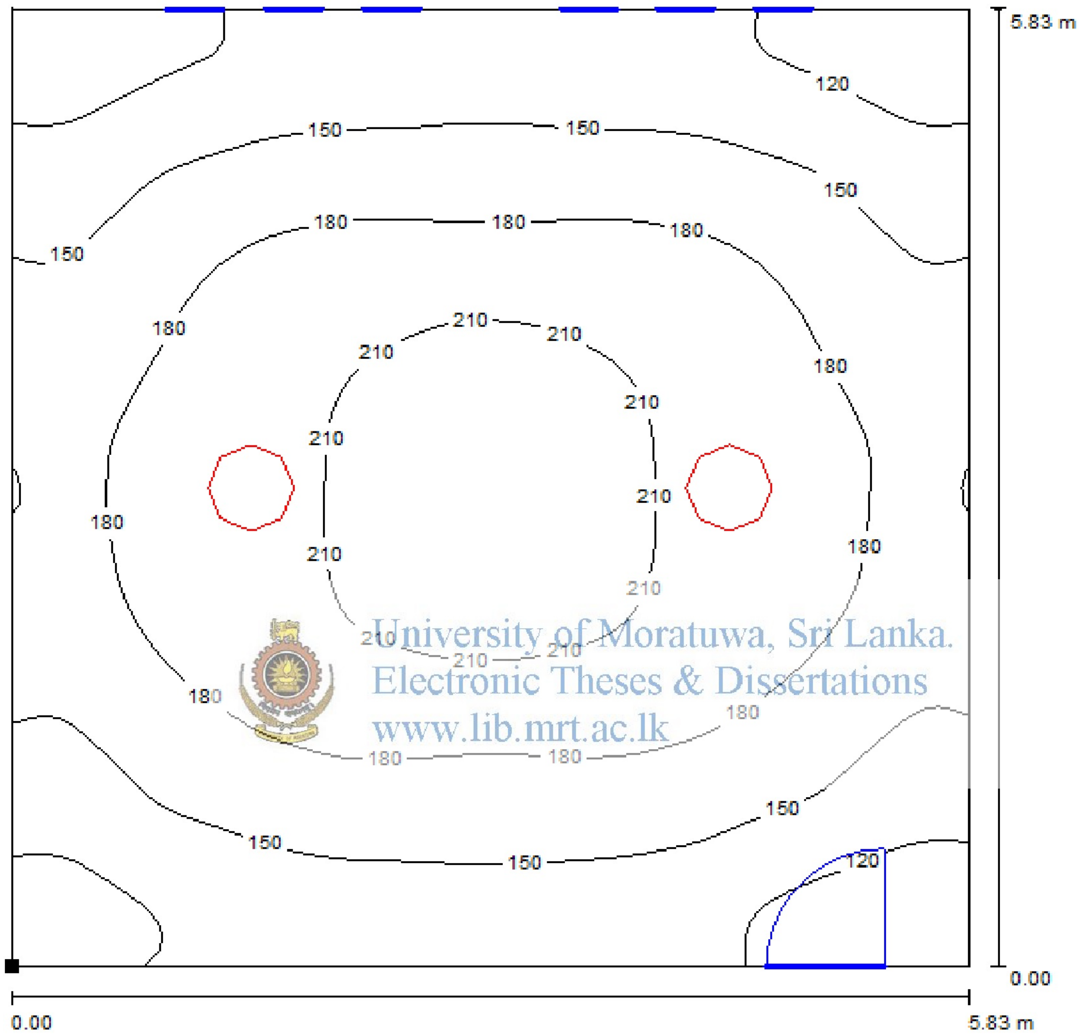
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
33	18	47	0.532	0.377

Luminaire type - 525
d s d h 9
07.00 hrs

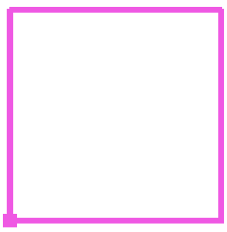
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



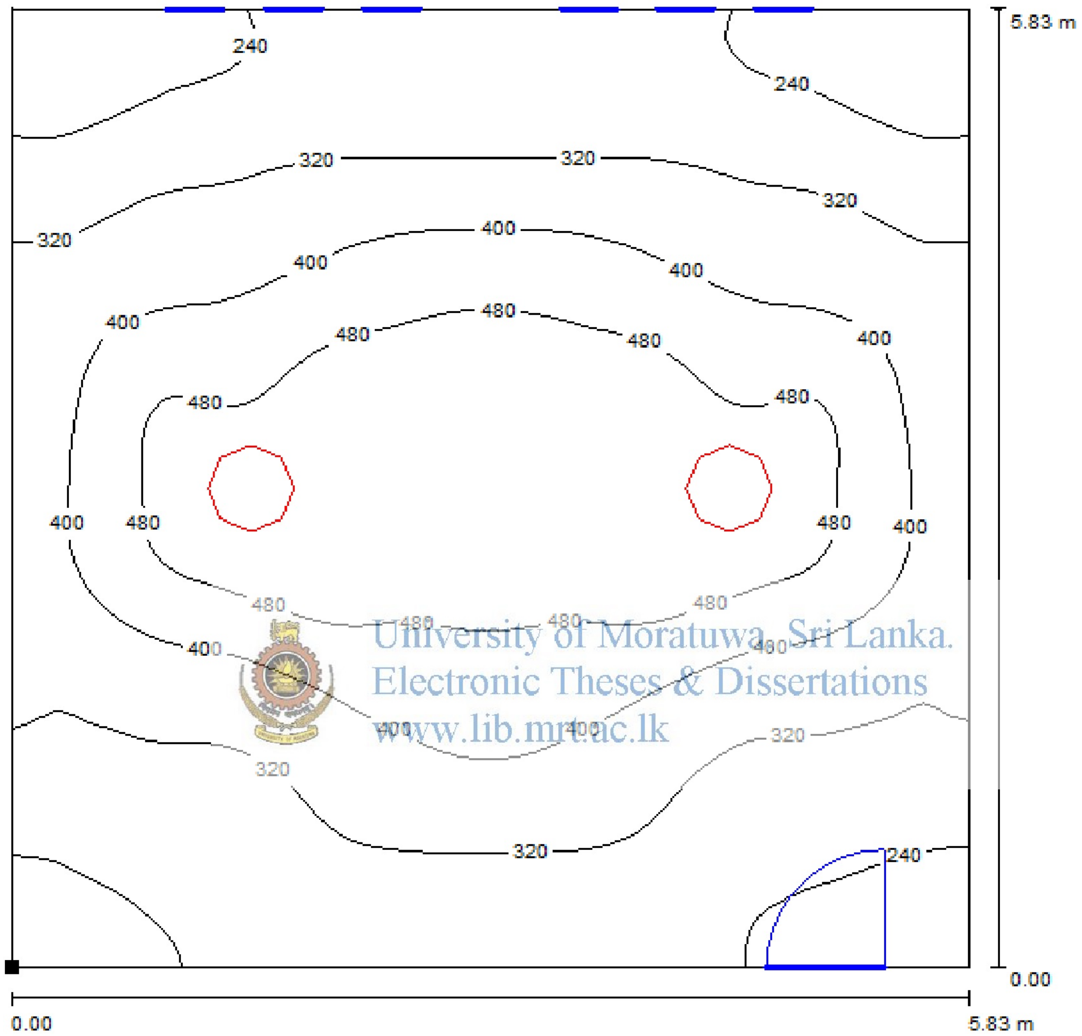
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
168	94	241	0.561	0.391

Luminaire type - 525
d s d h 9
08 2 hrs

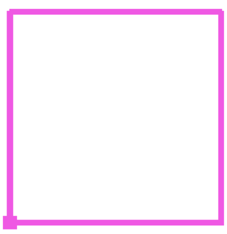
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



Grid: 64 x 64 Points

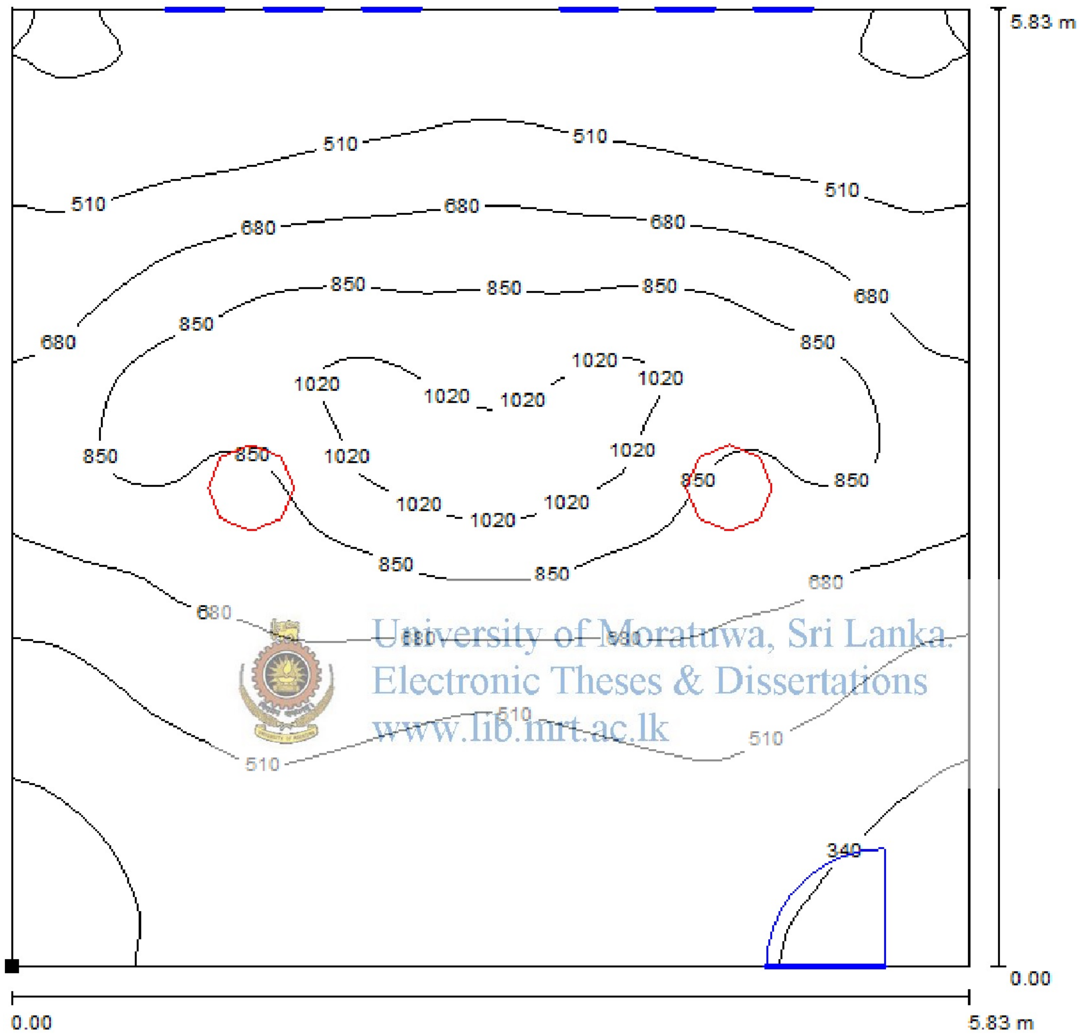
E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
366	182	564	0.498	0.324

Luminaire type - 525

09.40 hrs

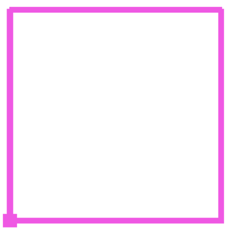
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



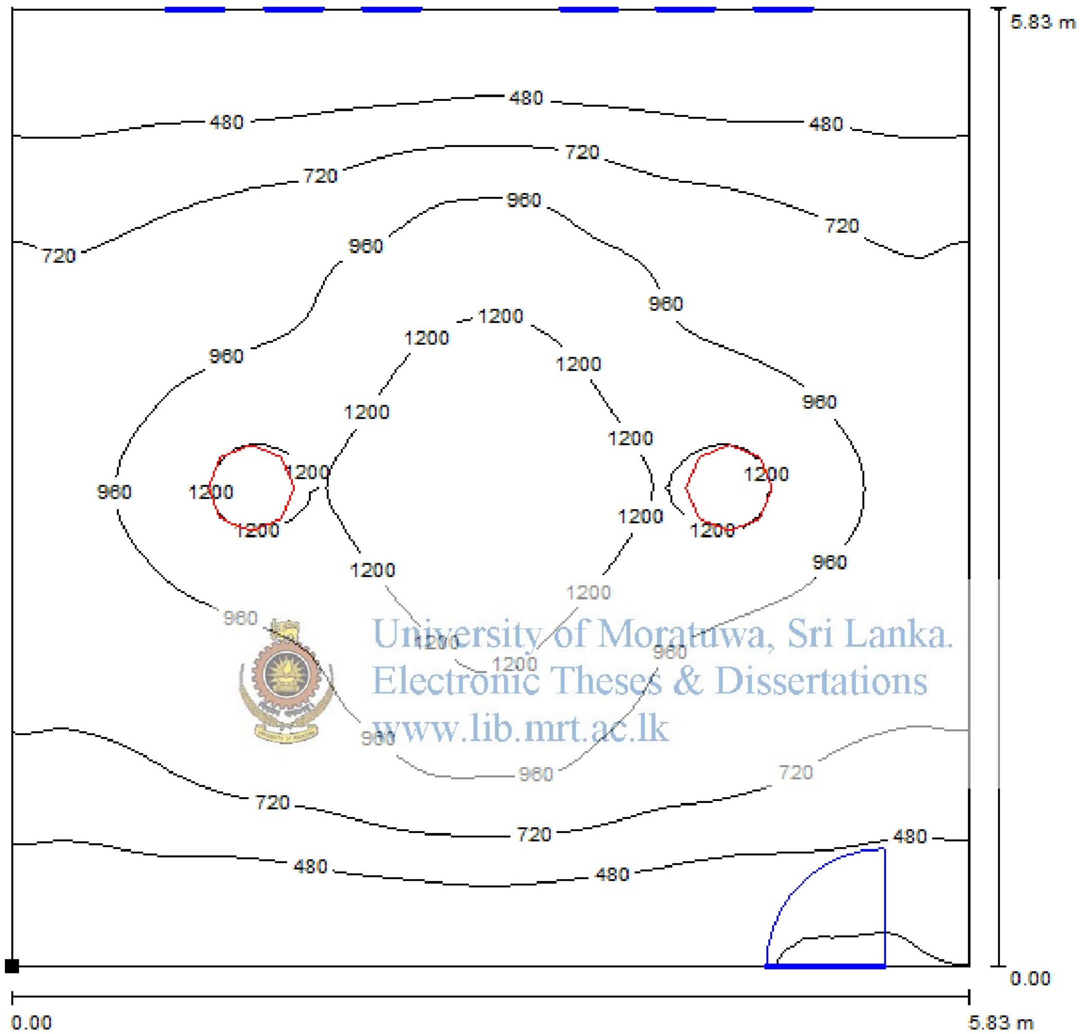
Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
607	254	1085	0.419	0.234

Luminaire type - 525
d s d h 9
11.00 hrs

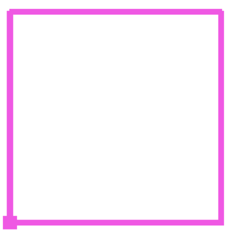
Operator
Telephone
Fax
e-Mail

Library / Light scene 1 / Workplane / Isolines (E)



Values in Lux, Scale 1 : 46

Position of surface in room:
Marked point:
(-13.661 m, 3.056 m, 0.800 m)



Grid: 64 x 64 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
781	207	1388	0.265	0.149

Luminaire type - [illegible] 525 [illegible]
[illegible] d [illegible] s [illegible] d [illegible] h [illegible] 9 [illegible]
[illegible] 12 2 [illegible] hrs [illegible]

Appendix 2 - Energy Consumption Evaluations

Table 1 – Energy consumption in the library with current lighting plan for artificial lighting

Time Interval	No of 4xTL5-14W luminaires to be operated	Power Consumption	Energy Consumption
		(W)	(kWh)
7.00 to 7.40	9	504	0.336
7.40 to 8.20	9	504	0.336
8.20 to 9.00	9	504	0.336
9.00 to 9.40	9	504	0.336
9.40 to 10.20	9	504	0.336
10.20 to 11.00	9	504	0.336
11.00 to 11.40	9	504	0.336
11.40 to 12.20	9	504	0.336
12.20 to 13.00	9	504	0.336
13.00 to 13.40	9	504	0.336
13.40 to 14.20	9	504	0.336
14.20 to 15.00	9	504	0.336
15.00 to 15.40	9	504	0.336
15.40 to 16.20	9	504	0.336
16.20 to 17.00	9	504	0.336
Total Energy Consumption			5.040

Appendix 2

Table 2- Energy consumption for lighting the Library with TS1 Tubular skylights installed under clear sky conditions, planned for 10º Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS1 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	672	7.00 to 7.40	-122.00	0	0	0.000
20	1761	7.40 to 8.20	-1211.00	0	0	0.000
30	2208	8.20 to 9.00	-1658.00	0	0	0.000
40	3181	9.00 to 9.40	-2631.00	0	0	0.000
50	3976	9.40 to 10.20	-3426.00	0	0	0.000
60	4035	10.20 to 11.00	-3485.00	0	0	0.000
70	4637	11.00 to 11.40	-4087.00	0	0	0.000
80	5520	11.40 to 12.20	-4970.00	0	0	0.000
90	5712	12.20 to 13.00	-5162.00	0	0	0.000
100	5520	13.00 to 13.40	-4970.00	0	0	0.000
110	4637	13.40 to 14.20	-4087.00	0	0	0.000
120	4035	14.20 to 15.00	-3485.00	0	0	0.000
130	3976	15.00 to 15.40	-3426.00	0	0	0.000
140	3181	15.40 to 16.20	-2631.00	0	0	0.000
150	2208	16.20 to 17.00	-1658.00	0	0	0.000
Total Energy Consumption						**0.000**

Table 3- Energy consumption for lighting the Library with TS1 Tubular skylights installed under clear sky conditions, planned for 50º Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS1 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	123	7.00 to 7.40	427.00	8	448	0.299
20	322	7.40 to 8.20	228.00	6	336	0.224
30	404	8.20 to 9.00	146.00	3	168	0.112
40	583	9.00 to 9.40	-33.00	0	0	0.000
50	729	9.40 to 10.20	-179.00	0	0	0.000
60	740	10.20 to 11.00	-190.00	0	0	0.000
70	850	11.00 to 11.40	-300.00	0	0	0.000
80	1012	11.40 to 12.20	-462.00	0	0	0.000
90	1049	12.20 to 13.00	-499.00	0	0	0.000
100	1012	13.00 to 13.40	-462.00	0	0	0.000
110	850	13.40 to 14.20	-300.00	0	0	0.000
120	740	14.20 to 15.00	-190.00	0	0	0.000
130	729	15.00 to 15.40	-179.00	0	0	0.000
140	583	15.40 to 16.20	-33.00	0	0	0.000
150	404	16.20 to 17.00	146.00	3	168	0.112
Total Energy Consumption						0.747

Appendix 2

Table 4- Energy consumption for lighting the Library with TS1 Tubular skylights installed under clear sky conditions, planned for 90º Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS1 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	77	7.00 to 7.40	473.00	9	504	0.336
20	202	7.40 to 8.20	348.00	8	448	0.299
30	254	8.20 to 9.00	296.00	6	336	0.224
40	366	9.00 to 9.40	184.00	4	224	0.149
50	458	9.40 to 10.20	92.00	2	112	0.075
60	465	10.20 to 11.00	85.00	2	112	0.075
70	535	11.00 to 11.40	15.00	1	56	0.037
80	637	11.40 to 12.20	-87.00	0	0	0.000
90	660	12.20 to 13.00	-110.00	0	0	0.000
100	637	13.00 to 13.40	-87.00	0	0	0.000
110	535	13.40 to 14.20	15.00	1	56	0.037
120	465	14.20 to 15.00	85.00	2	112	0.075
130	458	15.00 to 15.40	92.00	2	112	0.075
140	366	15.40 to 16.20	184.00	4	224	0.149
150	254	16.20 to 17.00	296.00	6	336	0.224
Total Energy Consumption						1.755

Table 5- Energy consumption for lighting the Library with TS2 Tubular skylights installed under clear sky conditions, planned for 10º Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS2 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	627	7.00 to 7.40	-327.00	0	0	0.000
20	Eav > 627	7.40 to 8.20	Eav<-327	0	0	0.000
30	Eav > 627	8.20 to 9.00	Eav<-327	0	0	0.000
40	Eav > 627	9.00 to 9.40	Eav<-327	0	0	0.000
50	Eav > 627	9.40 to 10.20	Eav<-327	0	0	0.000
60	Eav > 627	10.20 to 11.00	Eav<-327	0	0	0.000
70	Eav > 627	11.00 to 11.40	Eav<-327	0	0	0.000
80	Eav > 627	11.40 to 12.20	Eav<-327	0	0	0.000
90	Eav > 627	12.20 to 13.00	Eav<-327	0	0	0.000
100	Eav > 627	13.00 to 13.40	Eav<-327	0	0	0.000
110	Eav > 627	13.40 to 14.20	Eav<-327	0	0	0.000
120	Eav > 627	14.20 to 15.00	Eav<-327	0	0	0.000
130	Eav > 627	15.00 to 15.40	Eav<-327	0	0	0.000
140	Eav > 627	15.40 to 16.20	Eav<-327	0	0	0.000
150	Eav > 627	16.20 to 17.00	Eav<-327	0	0	0.000
Total Energy Consumption						0.000

Table 6- Energy consumption for lighting the Library with TS2 Tubular skylights installed under clear sky conditions, planned for 50º Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS2 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	158	7.00 to 7.40	392.00	8	448	0.299
20	311	7.40 to 8.20	239.00	6	336	0.224
30	477	8.20 to 9.00	73.00	2	112	0.075
40	565	9.00 to 9.40	-15.00	0	0	0.000
50	693	9.40 to 10.20	-143.00	0	0	0.000
60	715	10.20 to 11.00	-165.00	0	0	0.000
70	799	11.00 to 11.40	-249.00	0	0	0.000
80	985	11.40 to 12.20	-435.00	0	0	0.000
90	1025	12.20 to 13.00	-475.00	0	0	0.000
100	985	13.00 to 13.40	-435.00	0	0	0.000
110	799	13.40 to 14.20	-249.00	0	0	0.000
120	715	14.20 to 15.00	-165.00	0	0	0.000
130	693	15.00 to 15.40	-143.00	0	0	0.000
140	565	15.40 to 16.20	-15.00	0	0	0.000
150	477	16.20 to 17.00	73.00	2	112	0.075
Total Energy Consumption						0.672

Table 7- Energy consumption for lighting the Library with TS2 Tubular skylights installed under clear sky conditions, planned for 90º Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS2 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	107	7.00 to 7.40	443.00	9	504	0.336
20	210	7.40 to 8.20	340.00	8	448	0.299
30	322	8.20 to 9.00	228.00	6	336	0.224
40	382	9.00 to 9.40	168.00	3	168	0.112
50	468	9.40 to 10.20	82.00	2	112	0.075
60	485	10.20 to 11.00	65.00	2	112	0.075
70	541	11.00 to 11.40	9.00	1	56	0.037
80	670	11.40 to 12.20	-120.00	0	0	0.000
90	698	12.20 to 13.00	-148.00	0	0	0.000
100	670	13.00 to 13.40	-120.00	0	0	0.000
110	541	13.40 to 14.20	9.00	1	56	0.037
120	485	14.20 to 15.00	65.00	2	112	0.075
130	468	15.00 to 15.40	82.00	2	112	0.075
140	382	15.40 to 16.20	168.00	3	168	0.112
150	322	16.20 to 17.00	228.00	6	336	0.224
Total Energy Consumption						1.680

Appendix 2

Table 8- Energy consumption for lighting the Library with TS3 Tubular skylights installed under clear sky conditions, planned for 10° Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS3 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	626	7.00 to 7.40	-76.00	0	0	0.000
20	Eav > 626	7.40 to 8.20	Eav<-76	0	0	0.000
30	Eav > 626	8.20 to 9.00	Eav<-76	0	0	0.000
40	Eav > 626	9.00 to 9.40	Eav<-76	0	0	0.000
50	Eav > 626	9.40 to 10.20	Eav<-76	0	0	0.000
60	Eav > 626	10.20 to 11.00	Eav<-76	0	0	0.000
70	Eav > 626	11.00 to 11.40	Eav<-76	0	0	0.000
80	Eav > 626	11.40 to 12.20	Eav<-76	0	0	0.000
90	Eav > 626	12.20 to 13.00	Eav<-76	0	0	0.000
100	Eav > 626	13.00 to 13.40	Eav<-76	0	0	0.000
110	Eav > 626	13.40 to 14.20	Eav<-76	0	0	0.000
120	Eav > 626	14.20 to 15.00	Eav<-76	0	0	0.000
130	Eav > 626	15.00 to 15.40	Eav<-76	0	0	0.000
140	Eav > 626	15.40 to 16.20	Eav<-76	0	0	0.000
150	Eav > 626	16.20 to 17.00	Eav<-76	0	0	0.000
Total Energy Consumption						0.000

Table 9- Energy consumption for lighting the Library with TS3 Tubular skylights installed under clear sky conditions, planned for 50° Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS3 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	62	7.00 to 7.40	488.00	9	504	0.336
20	160	7.40 to 8.20	390.00	8	448	0.299
30	311	8.20 to 9.00	239.00	6	336	0.224
40	493	9.00 to 9.40	57.00	1	56	0.037
50	679	9.40 to 10.20	-129.00	0	0	0.000
60	900	10.20 to 11.00	-350.00	0	0	0.000
70	1132	11.00 to 11.40	-582.00	0	0	0.000
80	1258	11.40 to 12.20	-708.00	0	0	0.000
90	1409	12.20 to 13.00	-859.00	0	0	0.000
100	1258	13.00 to 13.40	-708.00	0	0	0.000
110	1132	13.40 to 14.20	-582.00	0	0	0.000
120	900	14.20 to 15.00	-350.00	0	0	0.000
130	679	15.00 to 15.40	-129.00	0	0	0.000
140	493	15.40 to 16.20	57.00	1	56	0.037
150	311	16.20 to 17.00	239.00	6	336	0.224
Total Energy Consumption						1.157

Appendix 2

Table 10- Energy consumption for lighting the Library with TS3 Tubular skylights installed under clear sky conditions, planned for 90º Sun altitude angle

Sun Altitude Angle	Eav(lx) Maintained by TS3 system	Time Interval	Balance Eav(lx) to maintain	No of 4xTL5-14W luminaires to be operated	Power Consumption (W)	Energy Consumption (kWh)
10	33	7.00 to 7.40	517.00	9	504	0.336
20	86	7.40 to 8.20	464.00	9	504	0.336
30	168	8.20 to 9.00	382.00	8	448	0.299
40	264	9.00 to 9.40	286.00	6	336	0.224
50	366	9.40 to 10.20	184.00	4	224	0.149
60	480	10.20 to 11.00	70.00	2	112	0.075
70	607	11.00 to 11.40	-57.00	0	0	0.000
80	690	11.40 to 12.20	-140.00	0	0	0.000
90	781	12.20 to 13.00	-231.00	0	0	0.000
100	690	13.00 to 13.40	-140.00	0	0	0.000
110	607	13.40 to 14.20	-57.00	0	0	0.000
120	480	14.20 to 15.00	70.00	2	112	0.075
130	366	15.00 to 15.40	184.00	4	224	0.149
140	264	15.40 to 16.20	286.00	6	336	0.224
150	168	16.20 to 17.00	382.00	8	448	0.299
Total Energy Consumption						2.165

Appendix 3 - Cost Estimations

Table 1 – Cost estimation for the currently planned lighting system

Initial Cost				
Type of the luminaires installed			**4xTL5-14W/ 5000lm**	
Supply cost of a luminaire		$	107.69	
Installation cost of a luminaire		$	23.08	
Number of luminaires installed		$	9.00	
Total supply cost	107.69x9	$	969.23	
Total Installation cost	23.08x9	$	207.69	
Total Initial cost	969.23+207.69	$	**1,176.92**	
Maintenance Cost				
Operational hours/day			10.00	
Number of luminaires operated			9.00	Appendix 1
Number of luminaire operational hours/day	9x10		90.00	
Number of lamps/luminaire			4.00	
Number of lamp operational hours/day	4x90		360.00	
Number of lamp operational hours/month	360x20		7,200.00	
Number of lamp operational hours/year	7200x12		86,400.00	
Lamp life (Hours)			10,000.00	
Number of lamps replaced/Year	86400/10000		9.00	
Relamping cost per lamp		$	7.69	
Total relamping cost/ year		$	69.23	
Total Maintenance cost /year	7.69x9	$	**69.23**	
Operational Cost				
Energy consumption/day (kWh)			5.04	Appendix 2
Energy rate	22/130	$	0.17	
Energy cost/ month	5.04x20x0.17	$	17.14	
Energy cost/ year	5.04x20x12x0.17	$	205.63	
Operational Cost/Year		$	**205.63**	
Total Operational and Maintenance cost	69.23+205.63	$	**274.86**	

Appendix 3

Table 2 – Cost estimation for the TS1 tubular skylight system planned for 10° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS1**	
Supply cost of a device with 4' extension tube		$	223.08	
Number of devices			132.00	Appendix 5-C1069-D4
Total cost for 4' devices	223.08x132	$	29,446.15	
Total extension tube length (ft)	(3'+4'+4'+5'+6'+7'+8'+8'+9'+10'+11')*12		900.00	Appendix 5-C1069-D4
Cost for Additional 1ft extension tube		$	17.00	
Total Cost for Additional extension tubes	(900-(132x4))x17	$	6,324.00	
Total supply cost	29446.15+6324	$	**35,770.15**	
Installation cost/ device		$	130.77	
Total Installation cost	132x130.77	$	17,261.54	
Total Initial cost	35770.15+17261.54	$	**53,031.69**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Solatubes		$	**0.00**	
Maintenace cost for T5x4 luminaires		$	Neglected	
Operating Cost				
Energy consumption/ day (kWh)			0.00	
Energy rate		$	0.17	
Energy cost/ Year		$	**0.00**	
Operational Cost/Year		$	**0.00**	
Total Operating & Maintenance Cost/ Year		$	**0.00**	

Appendix 3

Table 3 – Cost estimation for the TS1 tubular skylight system planned for 50° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS1**	
Supply cost of a device with 4' extension tube		$	223.08	
Number of devices			24.00	
Total cost for the 4' devices	223.08x24	$	5,353.85	
Total extension tube length (ft)	(3+6+8+10)x6		162.00	Appendix 5- C1069-D5
Cost for Additional 1ft extension tube		$	17.00	
Total Cost for Additional extension tubes	(162-(24x4))x17	$	1,122.00	
Total supply cost	5353.85+1122.00	$	**6,475.85**	
Installation cost/ device		$	130.77	
Total Installation cost	130.77x24	$	**3,138.46**	
Total Initial cost	6475.85+3138.46	$	**9,614.31**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Tubular sky lights			**0.00**	
Total Number of artificial luminaire operational hours/day			13.33	Appendix2
Number of lamps/luminaire			4.00	
Number of lamp operational hours/day			53.33	
Number of lamp operational hours/month			1,066.67	
Number of lamp operational hours/year			12,800.00	
Lamp life (Hours)			10,000.00	
Number of lamps replaced/Year	12800/10000		1.00	
Relamping cost per lamp			7.69	
Total relamping cost /Year			**7.69**	
Total maintenance cost	0.00+7.69	$	**7.69**	
Operational Cost				
Energy consumption/ day (kWh)			0.747	Appendix 2
Energy rate			0.17	
Energy cost/ Year	0.747x20x12x0.17	$	30.48	
Operational Cost/Year		$	**30.48**	
Total Operating & Maintenance Cost/ Year		$	**38.17**	

Appendix 3

Table 4 – Cost estimation for the TS1 tubular skylight system planned for 90° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS1**	
Supply cost of a device with 4' extension tube		$	223.08	
Number of devices			9.00	
Total cost for the 4' devices	223.08x9	$	2,007.69	
Total extension tube length (ft)	(4+7+10)x3		63.00	Appendix 5-C1069-D6
Cost for Additional 1ft extension tube		$	17.00	
Total Cost for Additional extension tubes	(63-(9x4))x17	$	459.00	
Total supply cost	2007.69+459.00	$	**2,466.69**	
Installation cost/ device		$	130.77	
Total Installation cost	130.77x9	$	1,176.92	
Total Initial cost	2466.69+1176.92	$	**3,643.62**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Tubular sky lights			**0.00**	
Total Number of artificial luminaire operational hours/day			31.33	Appendix2
Number of lamps/luminaire			4.00	
Number of lamp operational hours/day			125.33	
Number of lamp operational hours/month			2,506.67	
Number of lamp operational hours/year			30,080.00	
Lamp life (Hours)			10,000.00	
Number of lamps replaced/Year			3.00	
Relamping cost per lamp			7.69	
Total relamping cost /Year			**23.08**	
Total maintenance cost	0.00+23.08	$	**23.08**	
Operational Cost				
Energy consumption/ day (kWh)			1.755	Appendix2
Energy rate			0.17	
Energy cost/ Year	1.755x20x12x0.17	$	**71.60**	
Operational Cost/Year		$	**71.60**	
Total Operating & Maintenance Cost/ Year		$	**94.68**	

Appendix 3

Table 5 – Cost estimation for the TS2 tubular skylight system planned for 10° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS2**	
Supply cost of a device with 4' extension tube		$	316.73	
Number of devices			48.00	
Total cost for 4' devices	316.73x48	$	15,203.08	
Total extension tube length (ft)	(3'+5'+6'+8'+9'+10')x8		328.00	Appendix 5-C1069-D7
Cost for Additional 1ft extension tube		$	24.23	
Total Cost for Additional extension tubes	(328-(48x4))x17	$	3,295.38	
Total supply cost	15203.08+3295.38	$	18,498.46	
Installation cost/ device		$	130.77	
Total Installation cost	48x130	$	6,276.92	
Total Initial cost	18498.46+6240	$	**24,775.38**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Solatubes		$	**0.00**	
Maintenace cost for T5x4 luminaires		$	Neglected	
Operational Cost				
Energy consumption/ day (kWh)			0.00	
Energy rate		$	0.17	
Energy cost/ Year		$	**0.00**	
Operational Cost/Year		$	**0.00**	
Total Operating & Maintenance Cost/ Year		$	**0.00**	

Appendix 3

Table 6 – Cost estimation for the TS2 tubular skylight system planned for 50° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS2**	
Supply cost of a device with 4' extension tube		$	316.73	
Number of devices			12.00	
Total cost for the 4' devices	316.73x12	$	3,800.77	
Total extension tube length (ft)	(4+7+10)x4		84.00	Appendix 5- C1069-D6
Cost for Additional 1ft extension tube		$	24.23	
Total Cost for Additional extension tubes	(84-(12x4))x24.23	$	872.31	
Total supply cost	3800.77+872.31	$	4,673.08	
Installation cost/ device		$	130.77	
Total Installation cost	130.77x12	$	1,569.23	
Total Initial cost		$	**6,242.31**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Tubular sky lights			**0.00**	
Total Number of artificial luminaire operational hours/day			12.00	Appendix 2
Number of lamps/luminaire			4.00	
Number of lamp operational hours/day			48.00	
Number of lamp operational hours/month			960.00	
Number of lamp operational hours/year			11,520.00	
Lamp life (Hours)			10,000.00	
Number of lamps replaced/Year			1.00	
Relamping cost per lamp			7.69	
Total relamping cost /Year			**7.69**	
Total maintenance cost	0.00+7.69	$	**7.69**	
Operational Cost				
Energy consumption/ day (kWh)			0.672	Appendix 2
Energy rate			0.17	
Energy Cost/Year	0.672x20x12x0.17		27.42	
Operational Cost/Year			**27.42**	
Total Operating & Maintenance Cost/ Year			**35.11**	

Appendix 3

Table 7 – Cost estimation for the TS2 tubular skylight system planned for 90° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS2**	
Supply cost of a device with 4' extension tube		$	316.73	
Number of devices			8.00	
Total cost for the 4' devices	316.73x8	$	2,533.85	
Total extension tube length (ft)	(9+5)x4		56.00	Appendix 5-C1069-D8
Cost for Additional 1ft extension tube		$	24.23	
Total Cost for Additional extension tubes	(56-(8x4))x24.23	$	581.54	
Total supply cost	2533.85+581.54	$	3,115.38	
Installation cost/ device		$	130.77	
Total Installation cost	130.77x8	$	1,046.15	
Total Initial cost		$	**4,161.54**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Tubular sky lights			**0.00**	
Total Number of artificial luminaire operational hours/day			30.00	Appendix 2
Number of lamps/luminaire			4.00	
Number of lamp operational hours/day			120.00	
Number of lamp operational hours/month			2,400.00	
Number of lamp operational hours/year			28,800.00	
Lamp life (Hours)			10,000.00	
Number of lamps replaced/Year			3.00	
Relamping cost per lamp			7.69	
Total relamping cost /Year			**23.08**	
Total maintenance cost	0.00+23.08	$	**23.08**	
Operational Cost				
Energy consumption/ day (kWh)			1.68	Appendix 2
Energy rate			0.17	
Energy Cost/Year	1.68x20x12x0.17		68.54	
Operational Cost/Year			**68.54**	
Total Operating & Maintenance Cost/ Year			**91.62**	

Appendix 3

Table 8 – Cost estimation for the TS3 tubular skylight system planned for 10° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS3**	
Supply cost of a device with 4' extension tube		$	330.77	
Number of devices			42.00	
Total cost for 4' devices	330.77x42	$	13,892.31	
Total extension tube length (ft)	(3'+4'+6'+7'+8'+9'+11)x6		288.00	Appendix 5-C1069-D9
Cost for Additional 1ft extension tube		$	30.00	
Total Cost for Additional extension tubes	(288-(42x4))x30	$	3,600.00	
Total supply cost	13892.31+3600	$	17,492.31	
Installation cost/ device		$	138.46	
Total Installation cost	42x138.46	$	5,815.32	
Total Initial cost	17492.31+5815.32	$	**23,307.63**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Solatubes		$	**0.00**	
Maintenace cost for T5x4 luminaires		$	Neglected	
Operational Cost				
Energy consumption/ day (kWh)			0.00	
Energy rate		$	0.17	
Operational Cost/Year		$	**0.00**	
Total Operating & Maintenance Cost/ Year		$	**0.00**	

Appendix 3

Table 9 – Cost estimation for the TS3 tubular skylight system planned for 50° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS3**	
Supply cost of a device with 4' extension tube		$	330.77	
Number of devices			4.00	
Total cost for the 4' devices	330.77x4	$	1,323.08	
Total extension tube length (ft)	(9'+5')x2		28.00	Appendix 5-C1069-D8
Cost for Additional 1ft extension tube		$	30.00	
Total Cost for Additional extension tubes	(28-(4x4))x30.00	$	360.00	
Total supply cost	1323.08+360	$	1,683.08	
Installation cost/ device		$	138.46	
Total Installation cost	138.46x4	$	553.84	
Total Initial cost	1683.08+553.84	$	**2,236.92**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Tubular sky lights			**0.00**	
Total Number of artificial luminaire operational hours/day			20.67	Appendix 2
Number of lamps/luminaire			4.00	
Number of lamp operational hours/day			82.67	
Number of lamp operational hours/month			1,653.33	
Number of lamp operational hours/year			19,840.00	
Lamp life (Hours)			10,000.00	
Number of lamps replaced/Year			2.00	
Relamping cost per lamp			7.69	
Total relamping cost /Year			**15.38**	
Total maintenance cost	0.00+15.38	$	**15.38**	
Operational Cost				
Energy consumption/ day (kWh)			1.157	Appendix 2
Energy rate			0.17	
Energy Cost/Year	1.157x20x12x0.17		47.21	
Operational Cost/year			**47.21**	
Total Operating & Maintenance Cost/ Year			**62.59**	

Appendix 3

Table 10 – Cost estimation for the TS3 tubular skylight system planned for 90° Sun altitude angle with clear sky conditions

Initial Cost				
Type of luminaires installed			**TS3**	
Supply cost of a device with 4' extension tube		$	330.77	
Number of devices			2.00	
Total cost for the 4' devices	330.77x2	$	661.54	
Total extension tube length (ft)	(7)x2		14.00	Appendix 5-C1069-D10
Cost for Additional 1ft extension tube		$	30.00	
Total Cost for Additional extension tubes	(14-(4x2))x30.00	$	180.00	
Total supply cost	661.54 + 180.00	$	841.54	
Installation cost/ device		$	138.46	
Total Installation cost	138.46x2	$	276.92	
Total Initial cost	841.54+276.92	$	**1,118.46**	
Maintenance cost/ Year (up to 10 years)				
Maintenace cost for Tubular sky lights			**0.00**	
Total Number of artificial luminaire operational hours/day			38.67	Appendix 2
Number of lamps/luminaire			4.00	
Number of lamp operational hours/day			154.67	
Number of lamp operational hours/month			3,093.33	
Number of lamp operational hours/year			37,120.00	
Lamp life (Hours)			10,000.00	
Number of lamps replaced/Year			4.00	
Relamping cost per lamp			7.69	
Total relamping cost /Year		$	**30.77**	
Total maintenance cost	0.00+30.77	$	**30.77**	
Operational Cost				
Energy consumption/ day (kWh)			2.165	Appendix 2
Energy rate		$	0.17	
Energy Cost/Year	2.165x20x12x0.17	$	88.33	
Operational Cost/Year			**88.33**	
Total Operating & Maintenance Cost/ Year			**119.10**	

Appendix 4 – Life Cycle Payback Evaluations

Table 1- TS1 arrangement planned for 10° altitude and clear sky conditions

TS1 arrangement planned for 10° altitude and clear sky conditions				
Target Cost to recover		**$53,031.69**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	274.86	274.86		
2	302.35	577.21		
3	332.58	634.93		
4	365.84	698.42		
5	402.42	768.26		
6	442.66	845.09		
7	486.93	929.60		
8	535.62	1022.56		
9	589.19	1124.81		
10	648.11	1237.29	No payback	

Table 2- TS1 arrangement planned for 50° altitude and clear sky conditions

TS1 arrangement planned for 50° altitude and clear sky conditions				
Target Cost to recover		**$9,614.31**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	236.69	236.69		
2	260.36	497.05		
3	286.39	546.75		
4	315.03	601.43		
5	346.54	661.57		
6	381.19	727.73		
7	419.31	800.50		
8	461.24	880.55		
9	507.37	968.61		
10	558.10	1065.47	No payback	

Table 3- TS1 arrangement planned for 90° altitude and clear sky conditions

TS1 arrangement planned for 90° altitude and clear sky conditions				
Target Cost to recover		**$3,643.62**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	180.18	180.18		
2	198.20	378.38		
3	218.02	416.22		
4	239.82	457.84		
5	263.80	503.62		
6	290.18	553.98		
7	319.20	609.38		
8	351.12	670.32		
9	386.23	737.35		
10	424.86	811.09	No payback	

Table 4- TS2 arrangement planned for 10° altitude and clear sky conditions

TS2 arrangement planned for 10° altitude and clear sky conditions				
Target Cost to recover		**$24,775.38**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	274.86	274.86		
2	302.35	577.21		
3	332.58	634.93		
4	365.84	698.42		
5	402.42	768.26		
6	442.66	845.09		
7	486.93	929.60		
8	535.62	1022.56		
9	589.19	1124.81		
10	648.11	1237.29	No payback	

Appendix 4

Table 5- TS2 arrangement planned for 50° altitude and clear sky conditions

TS2 arrangement planned for 50° altitude and clear sky conditions				
Target Cost to recover		**$6,242.31**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	239.75	239.75		
2	263.73	503.48		
3	290.10	553.82		
4	319.11	609.20		
5	351.02	670.13		
6	386.12	737.14		
7	424.73	810.85		
8	467.20	891.94		
9	513.93	981.13		
10	565.32	1079.24	No payback	

Table 6- TS2 arrangement planned for 90° altitude and clear sky conditions

TS2 arrangement planned for 90° altitude and clear sky conditions				
Target Cost to recover		**$4,161.54**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	183.24	183.24		
2	201.56	384.80		
3	221.72	423.28		
4	243.89	465.61		
5	268.28	512.17		
6	295.11	563.39		
7	324.62	619.73		
8	357.08	681.70		
9	392.79	749.87		
10	432.07	824.86	No payback	

Appendix 4

Table 7- TS3 arrangement planned for 10° altitude and clear sky conditions

TS3 arrangement planned for 10° altitude and clear sky conditions			
Target Cost to recover		**$23,307.63**	
Year	Net Saving at the year end	Cumulative saving	Remarks
1	274.86	274.86	
2	302.35	577.21	
3	332.58	634.93	
4	365.84	698.42	
5	402.42	768.26	
6	442.66	845.09	
7	486.93	929.60	
8	535.62	1022.56	
9	589.19	1124.81	
10	648.11	1237.29	No payback

Table 8- TS3 arrangement planned for 50° altitude and clear sky conditions

TS3 arrangement planned for 50° altitude and clear sky conditions			
Target Cost to recover		**$2,236.92**	
Year	Net Saving at the year end	Cumulative saving	Remarks
1	212.27	212.27	
2	233.50	445.77	
3	256.85	490.34	
4	282.53	539.38	
5	310.78	593.32	
6	341.86	652.65	
7	376.05	717.91	
8	413.65	789.70	
9	455.02	868.67	
10	500.52	955.54	No payback

Appendix 4

Table 9- TS3 arrangement planned for 90° altitude and clear sky conditions

TS3 arrangement planned for 90° altitude and clear sky conditions			
Target Cost to recover		**$1,118.46**	
Year	Net Saving at the year end	Cumulative saving	Remarks
1	155.76	155.76	
2	171.34	327.10	
3	188.47	359.81	
4	207.32	395.79	
5	228.05	435.36	
6	250.85	478.90	
7	275.94	526.79	
8	303.53	579.47	
9	333.89	637.42	
10	367.27	701.16	No payback

Table 10- TS1 arrangement planned for 10° altitude and clear sky conditions

TS1 arrangement planned for 10° altitude and clear sky conditions				
Target Cost to recover		**$51,854.77**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	261.15	261.15		
2	287.27	548.42		
3	315.99	603.26		
4	347.59	663.58		
5	382.35	729.94		
6	420.58	802.93		
7	462.64	883.23		
8	508.91	971.55		
9	559.80	1068.71		
10	615.78	1175.58	No payback	

Appendix 4

Table 11- TS1 arrangement planned for 50° altitude and clear sky conditions

TS1 arrangement planned for 50° altitude and clear sky conditions				
Target Cost to recover		**$8,829.69**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	252.01	252.01		
2	277.21	529.22		
3	304.93	582.14		
4	335.43	640.36		
5	368.97	704.39		
6	405.86	774.83		
7	446.45	852.32		
8	491.10	937.55		
9	540.21	1031.30		
10	594.23	1134.43	No payback	

Table 12- TS1 arrangement planned for 90° altitude and clear sky conditions

TS1 arrangement planned for 90° altitude and clear sky conditions				
Target Cost to recover		**$3,251.31**		
Year	Net Saving at the year end	Cumulative saving	Remarks	
1	198.56	198.56		
2	218.42	416.98		
3	240.26	458.67		
4	264.28	504.54		
5	290.71	555.00		
6	319.78	610.49		
7	351.76	671.54		
8	386.94	738.70		
9	425.63	812.57		
10	468.19	893.83	No payback	

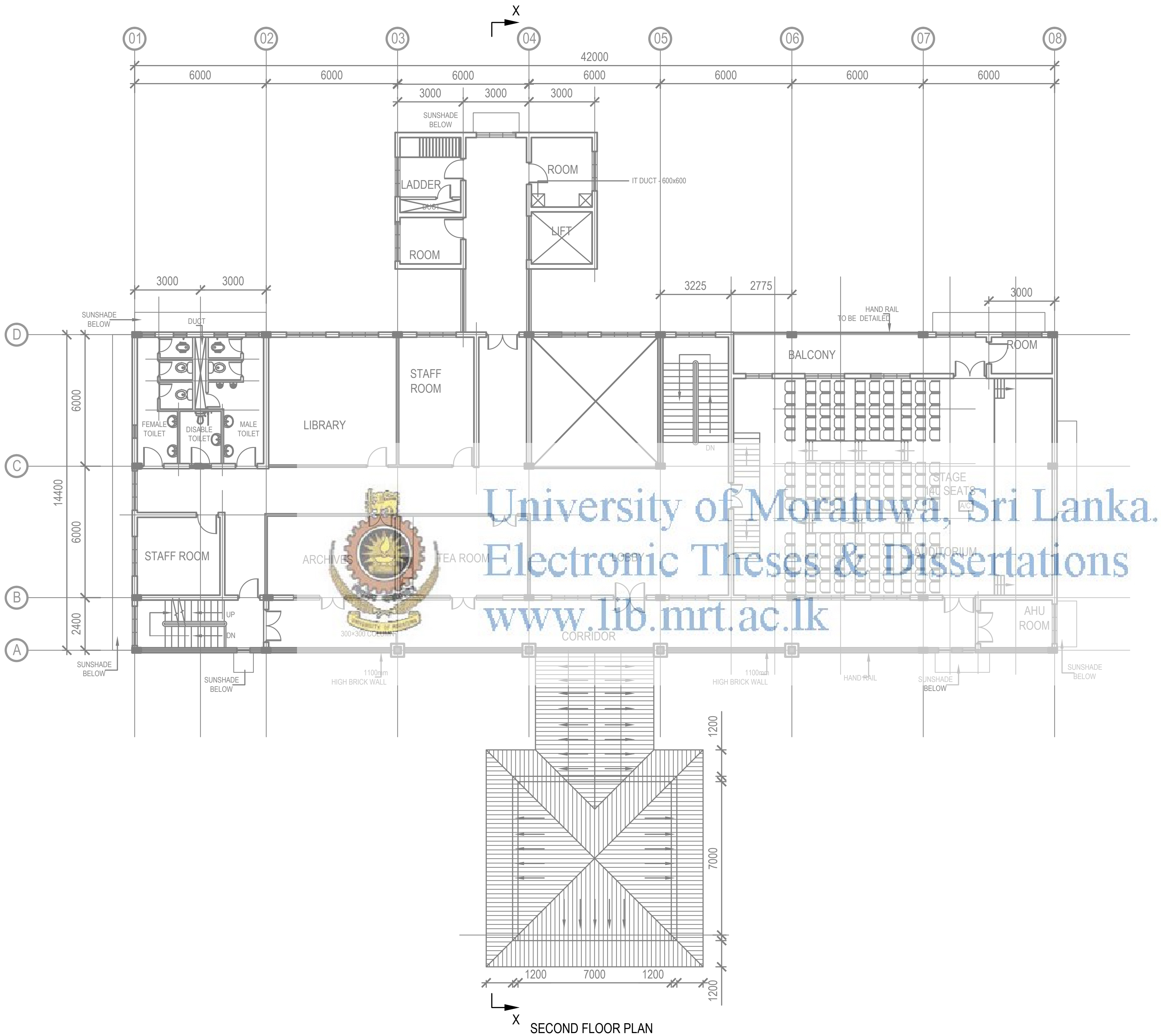
Appendix 4

Table 13- TS3 arrangement planned for 50° altitude and clear sky conditions

TS3 arrangement planned for 50° altitude and clear sky conditions			
Target Cost to recover		**$1,844.61**	
Year	Net Saving at the year end	Cumulative saving	Remarks
1	232.12	232.12	
2	255.33	487.45	
3	280.87	536.20	
4	308.95	589.82	
5	339.85	648.80	
6	373.83	713.68	
7	411.21	785.05	
8	452.34	863.55	
9	497.57	949.91	
10	547.33	1044.90	No payback

Table 14- TS3 arrangement planned for 90° altitude and clear sky conditions

TS3 arrangement planned for 90° altitude and clear sky conditions			
Target Cost to recover		**$987.69**	
Year	Net Saving at the year end	Cumulative saving	Remarks
1	171.04	171.04	
2	188.14	359.18	
3	206.96	395.10	
4	227.65	434.61	
5	250.42	478.07	
6	275.46	525.88	
7	303.01	578.47	
8	333.31	636.32	
9	366.64	699.95	
10	403.30	769.94	No payback



Rev.	Date	Desd.	Description	Drwn.	Chk'd	App'd

THE DEMOCRATIC SOCIALIST REPUBLIC OF SRI LANKA
DEPARTMENT OF IRRIGATION

Project: IMPROVEMENTS TO TRAINING CENTER AT GALGAMUWA FOR DAM OPERATION STAFF

Title: SECOND FLOOR

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Designed		Recommended - DGM(E&M)
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Drawn		Approved - AGM(E&M)
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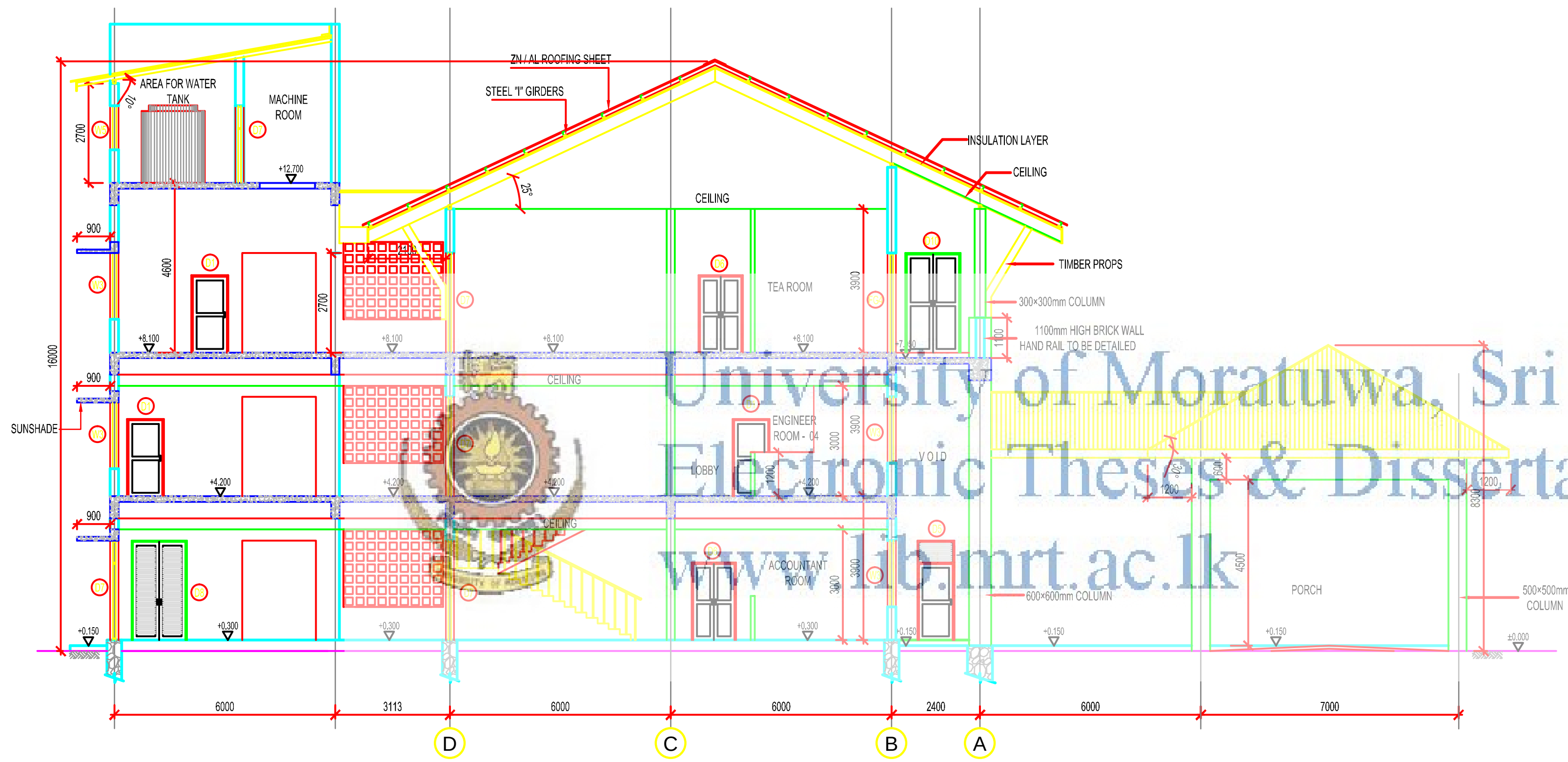

SECTION X-X
SCALE 1:200

Rev.	Date	Desd.	Description	Drwn.	Chk'd	App'd

THE DEMOCRATIC SOCIALIST REPUBLIC OF SRI LANKA
DEPARTMENT OF IRRIGATION

Project IMPROVEMENTS TO TRAINING CENTER AT GALGAMUWA FOR DAM OPERATION STAFF

Title SECTION X-X

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Designed			Recommended - DGM(E&M)	
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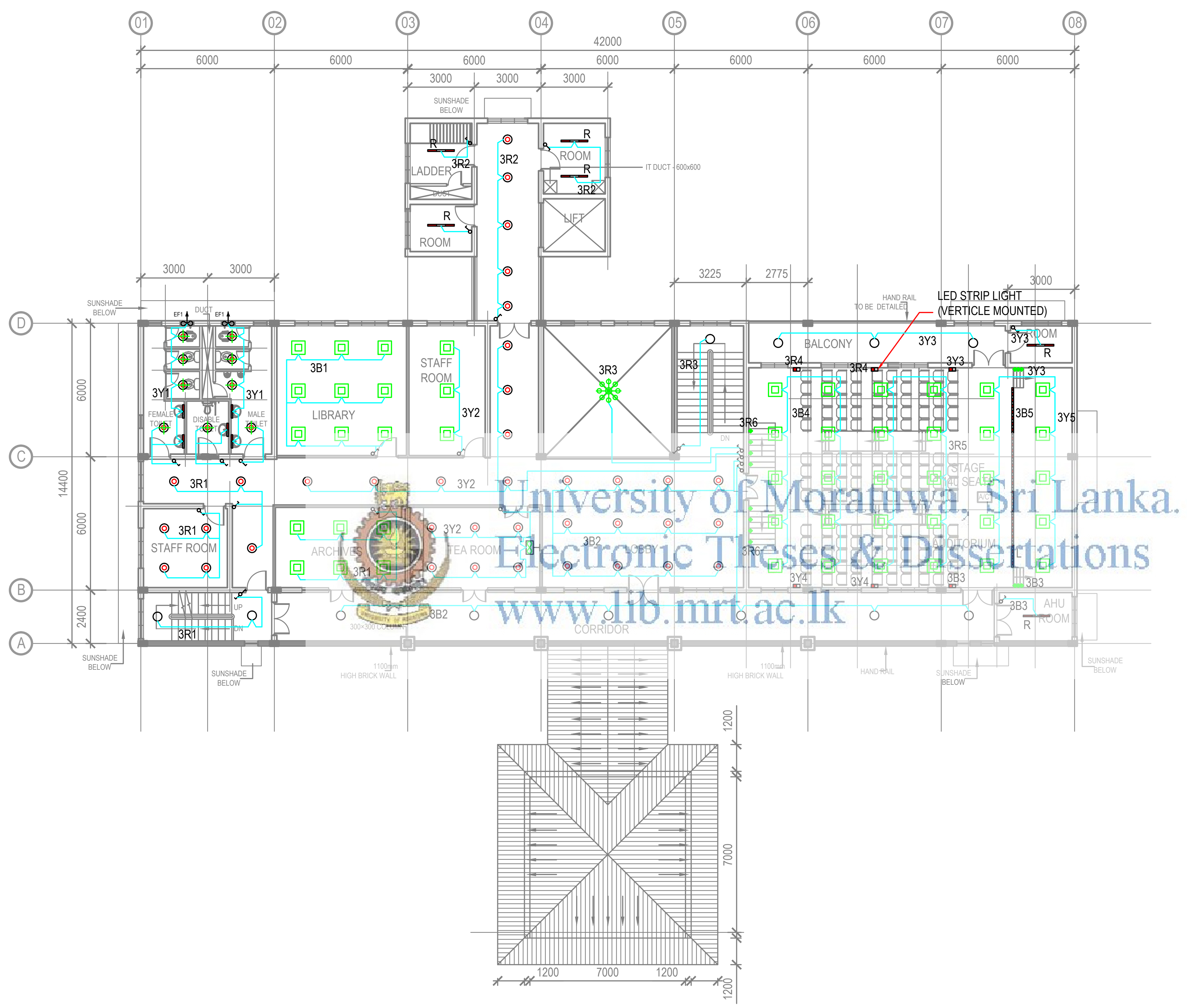

SECOND FLOOR PLAN

LEGEND:

- RECESSED MOUNTED DOWN LIGHT WITH 11W CFL (4" DIA.)
- RECESSED MOUNTED DOWN LIGHT WITH 15W CFL (6" DIA.)
- LED STRIP LIGHT (VERTICALY MOUNTED)
- MIRROR LIGHT (WITH FLOURESCENT LAMP)
- R - 1x28W RECESSED MOUNTED FLOURESCENT FITTING WITH OPAL DIFFUSER
- 1x28W SURFACE MOUNTED FLOURESCENT FITTING WITH OPAL DIFFUSER
- SURFACE MOUNTED DOWN LIGHT WITH 15W CFL (6" DIA.)
- 2x7W WALL WASHER LIGHT
- W - 1x15W WALL MOUNTED FITTING WEATHER PROOF (OUTDOOR TYPE, IP65)
- CHANDLER
- NITCH LIGHT (RECESSED MOUNTED, 1x7W)
- L - LED STRIP LIGHT
- 4x14W RECESSED MOUNTED FLOURESCENT, FITTING WITH AL REFLECTOR
- PENDENT TYPE LIGHT FITTING
- WALL FAN
- TWO WAY SWITCH
- ONE WAY SWITCH
- CU-X - CONSUMER UNIT
- EF - EXHAUST FAN

Rev.	Date	Desd.	Description	Drwn.	Chk'd	App'd

THE DEMOCRATIC SOCIALIST REPUBLIC OF SRI LANKA
DEPARTMENT OF IRRIGATION

Project: IMPROVEMENTS TO TRAINING CENTER AT GALGAMUWA FOR DAM OPERATION STAFF

Title: LIGHTING ARRANGEMENT SECOND FLOOR

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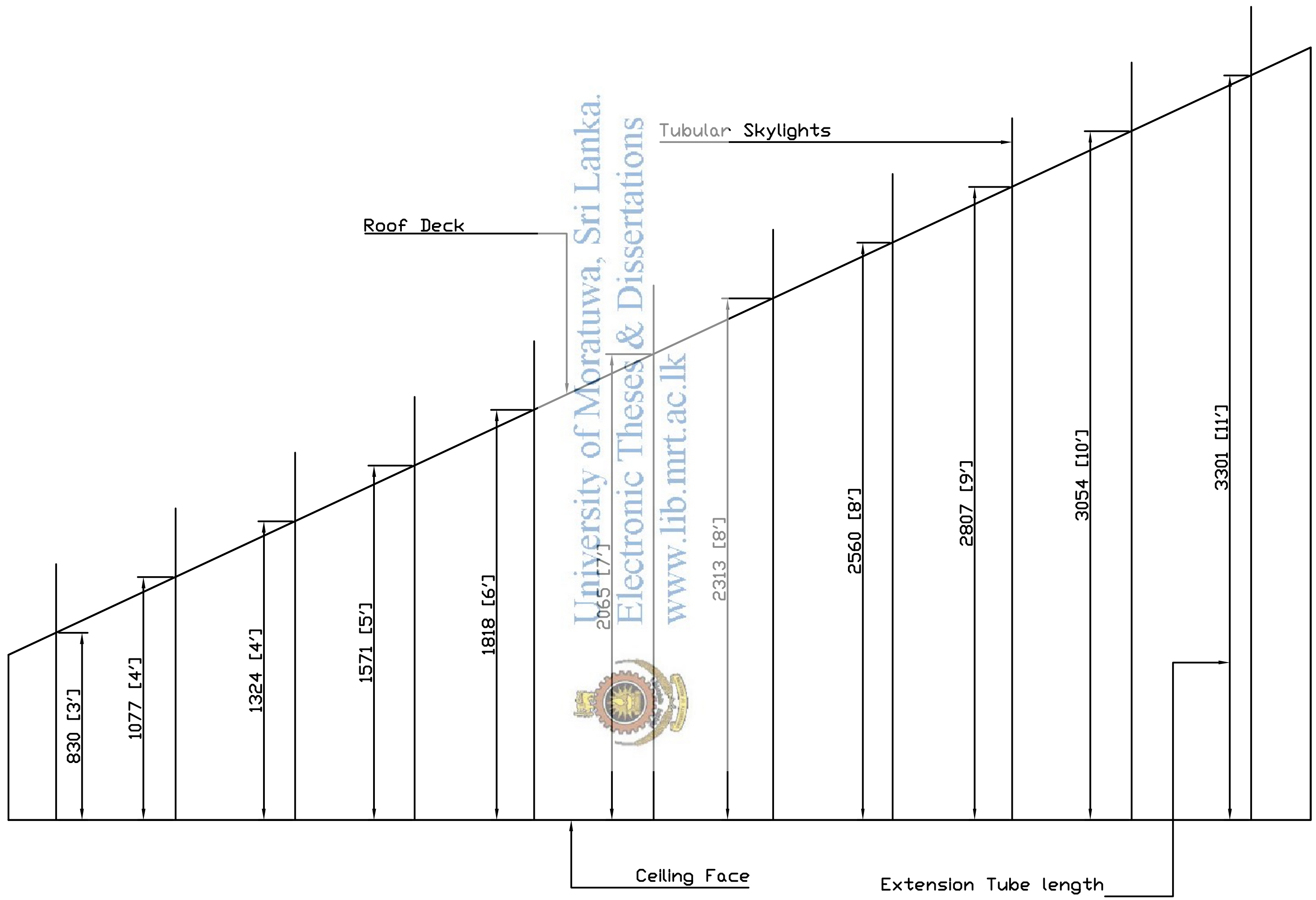
Tubular skylights shown in section of ceiling void



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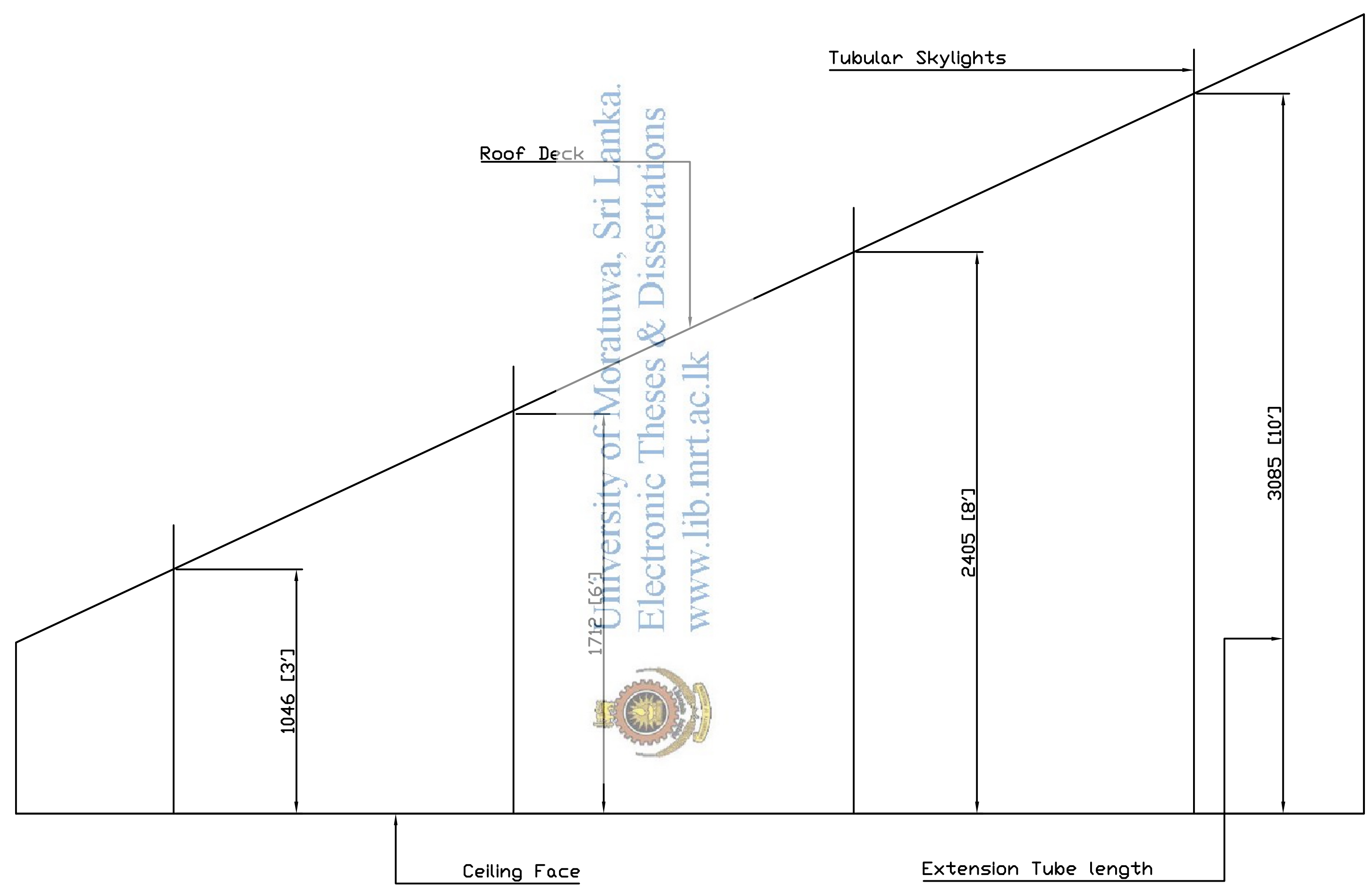
Tubular skylights shown in section of ceiling void



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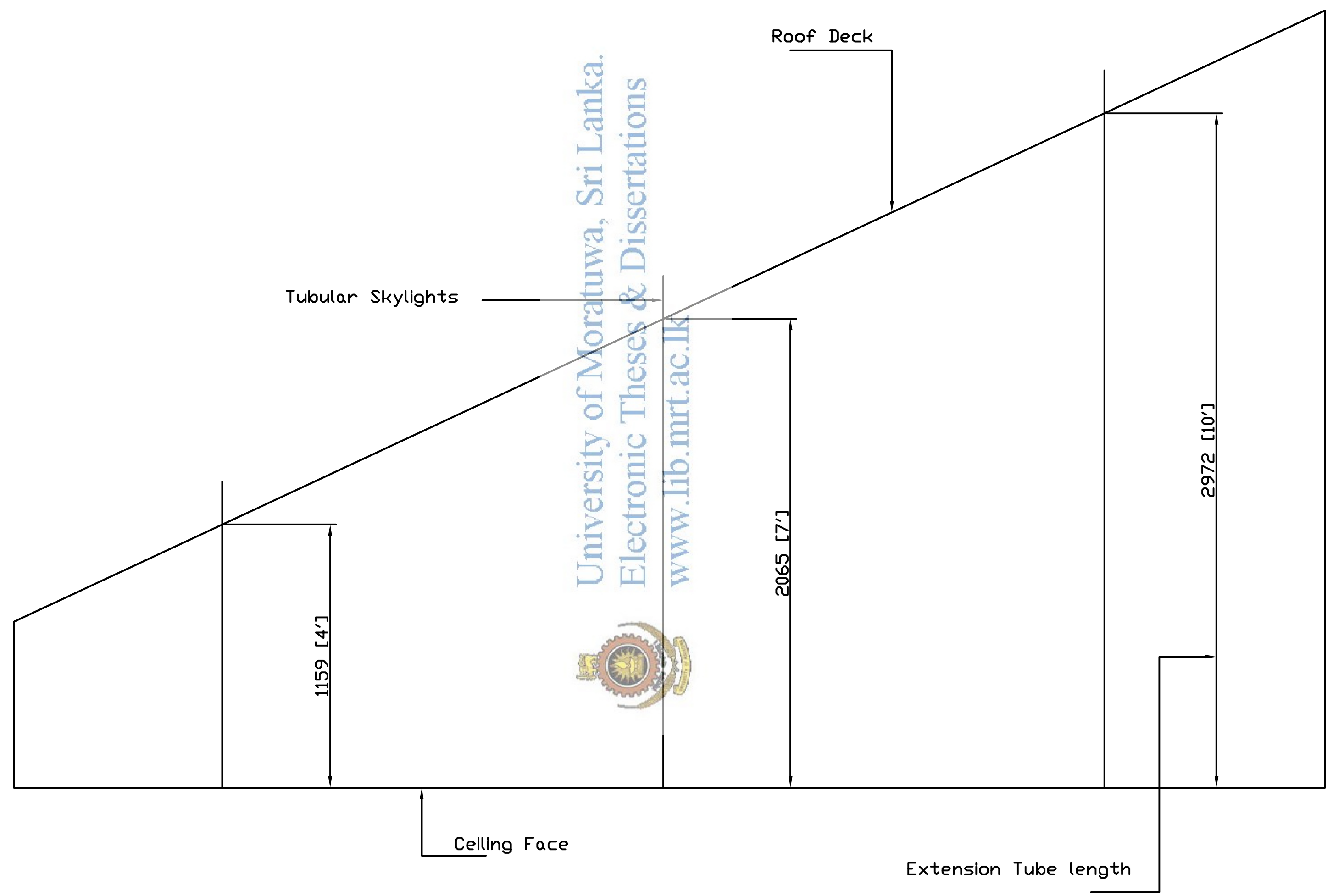
Tubular skylights shown in section of ceiling void



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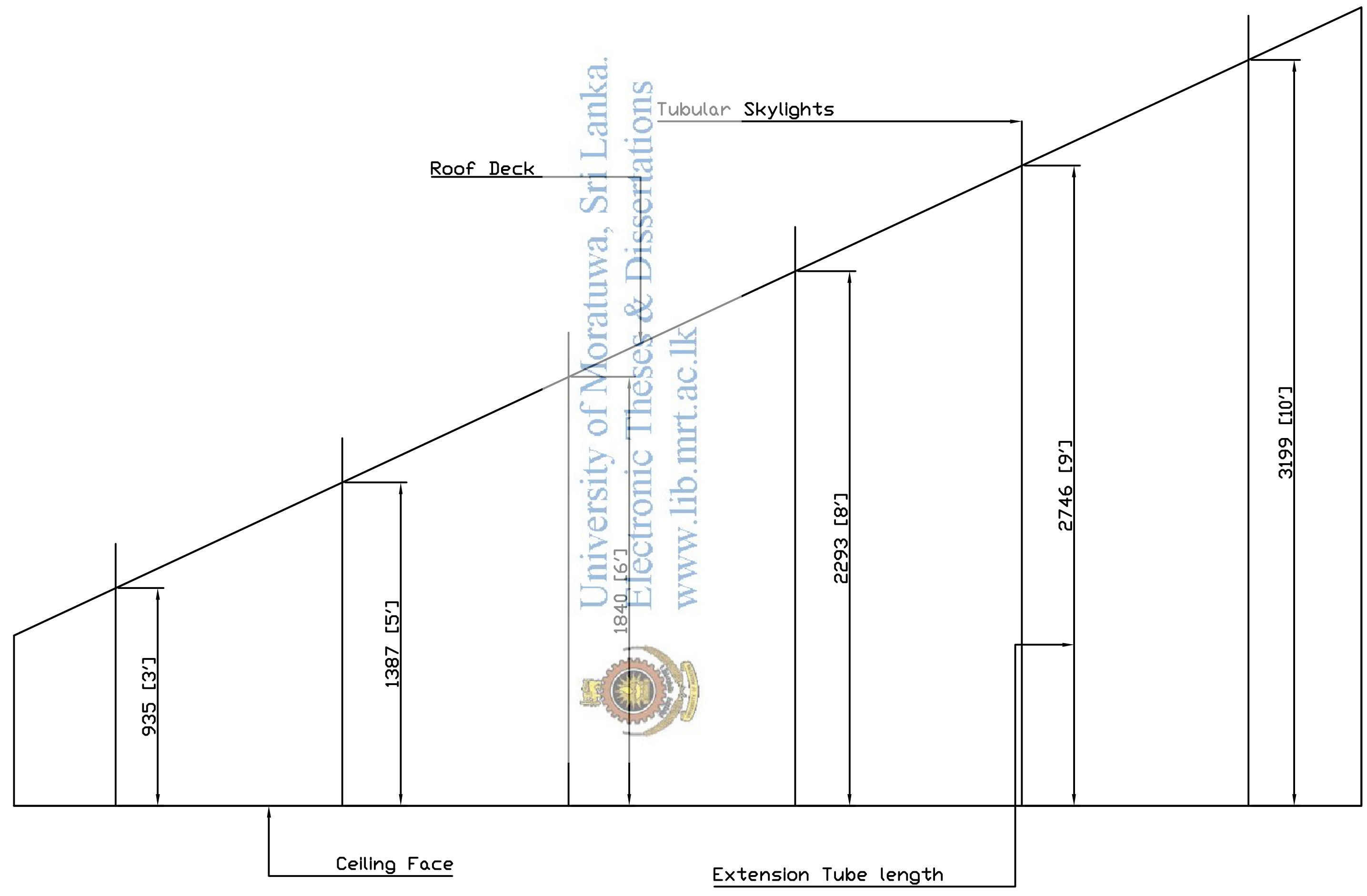
Tubular skylights shown in section of ceiling void



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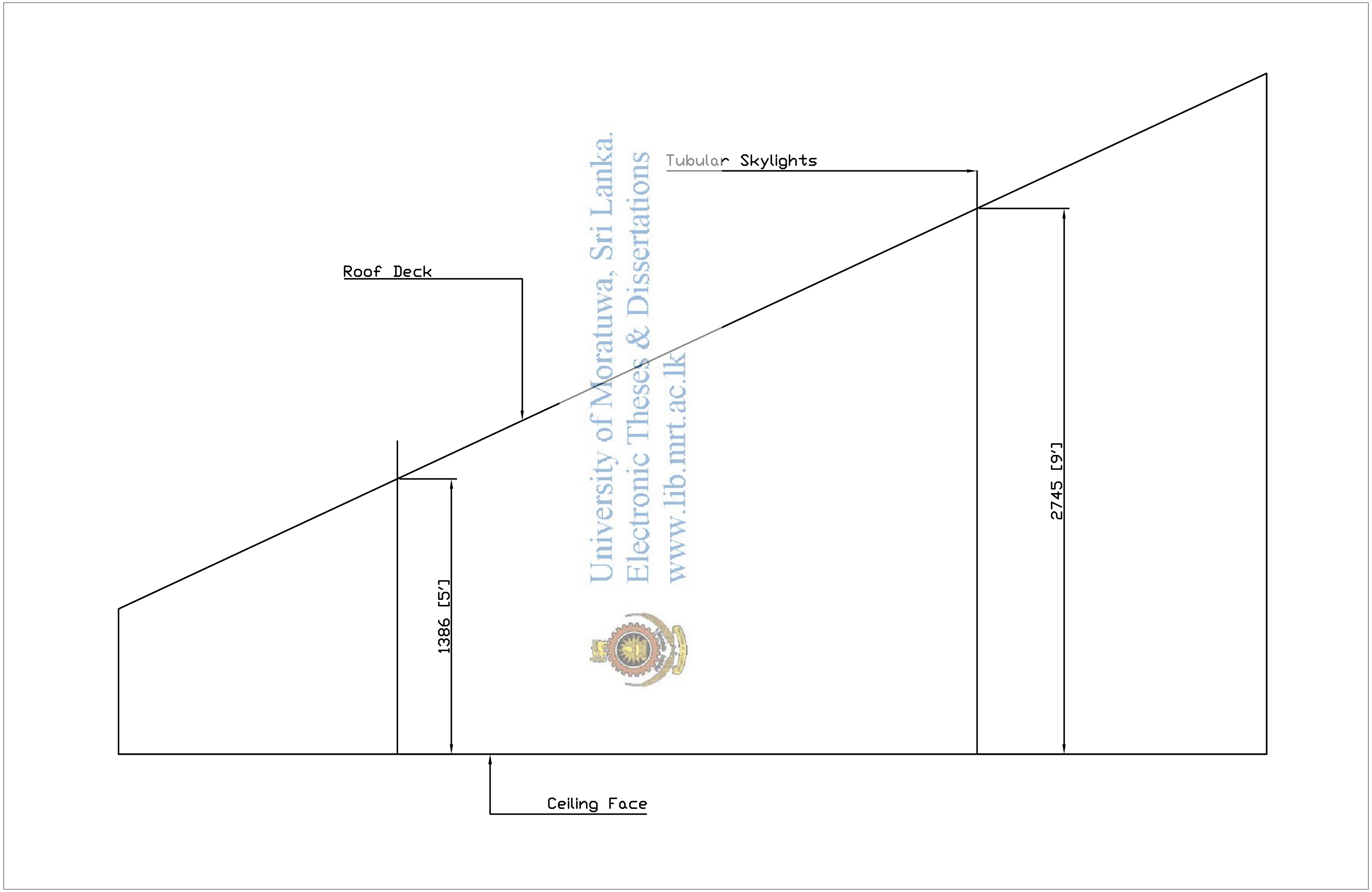
Tubular skylights shown in section of ceiling void



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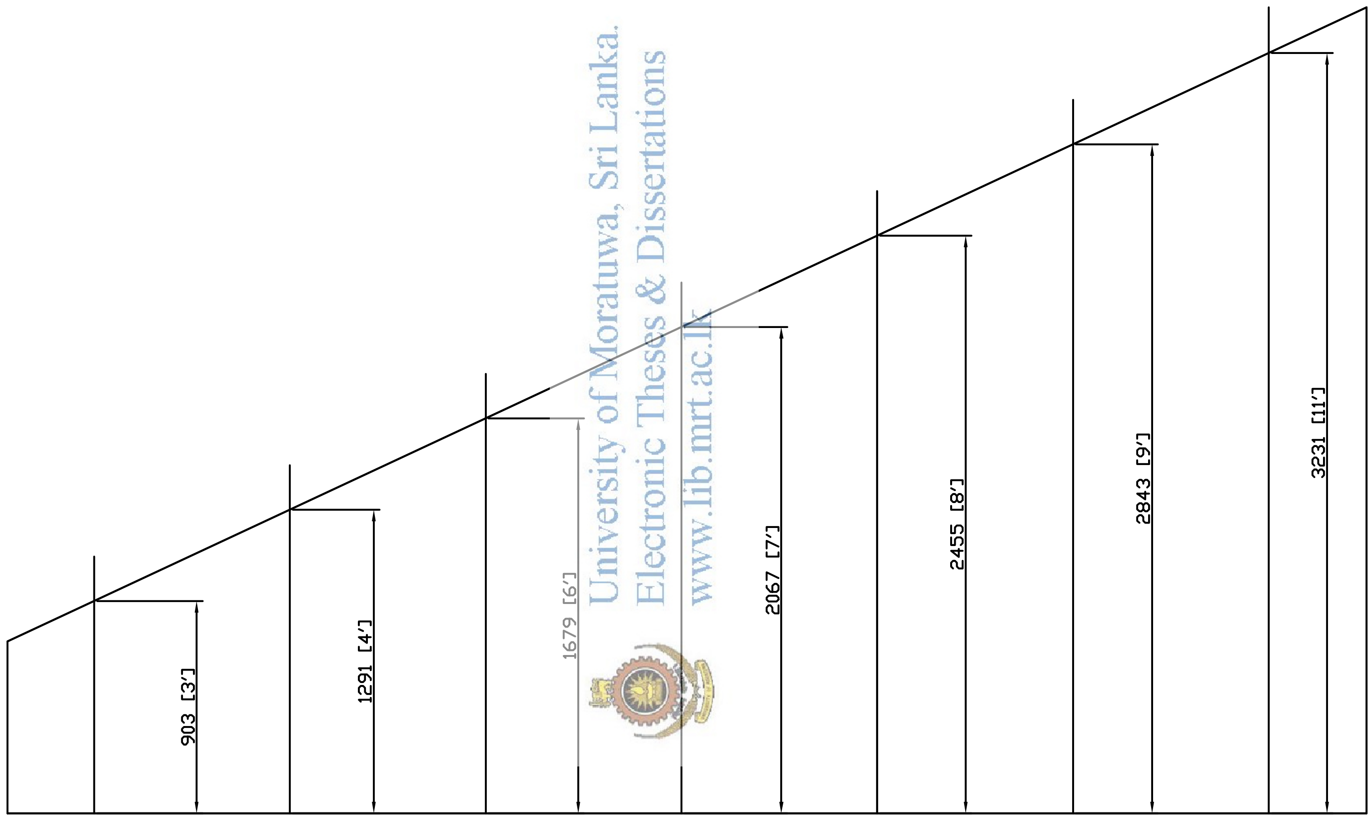
Tubular skylights shown in section of ceiling void



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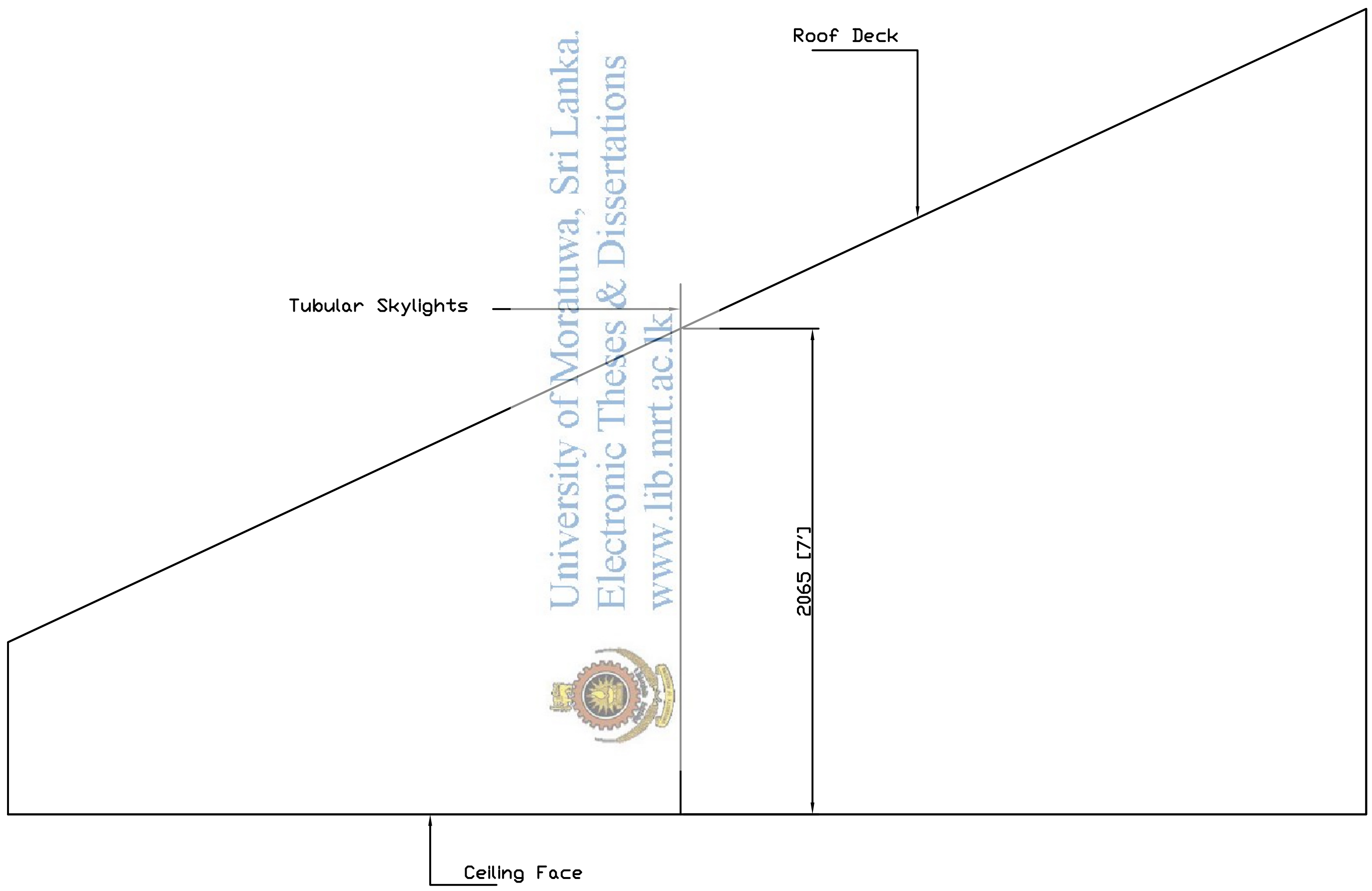
Tubular skylights shown in section of ceiling void



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