Intelligent Lighting Controller for Domestic and Office Environments

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ABSTRACT

The use of natural light instead of artificial light to conduct activities has been shown to have positive physical and psychological effects in humans. Thus the growing trend of incorporating natural light in office spaces and households has created a need for control between the sources of natural and artificial light. Providing autonomous adequate natural light when it is present and compensating when the light level does not meet the required level, is the primary task of such controllers.

Furthermore, saving energy by operating intelligently according to user presence and demand is the other aspect such controllers strive to achieve. The aim of the project is to develop a system which addresses aspects of controlling both natural and artificial light inside a room efficiently and at the same time being cost effective in installation. The project aims to develop a system which is adapted to conditions found in Sri Lanka and to research on the preference of light levels in defined groups of people (consisting of Sri Lankans). After which a mathematical model is developed to achieve the aforementioned criteria of balancing light sources to a user.

Introduction

In industrial environments and domestic environments proper illuminance of enclosed spaces is important for the work being carried out. For this requirement both natural and artificial light sources are used. But in most applications there is a lack of systems which monitors the presence of people inside the illuminated space and their required light level. This can be demonstrated in the case of artificial lighting where lights are normally switched 'ON' and 'OFF' by the user .This can be irksome to the user and sometimes a user can forget to turn off lights when leaving the premises, leading to a waste of energy. Furthermore, the amount of light preferred may differ significantly from one person to another or from one category of people to another where the category mentioned above can be based on gender, age etc. Therefore, it may lead to ineffective usage of energy. In addition to that there can be difficulty and time wastage due to manually adjusting the complicated systems.

Because controlling natural light is a hassle for users, most office spaces use artificial light even when abundant natural light is available outside. This control of natural light is by the way of opening or closing of shutters, louvers, or controlling the opacity of the window glass so as to limit the amount of light energy entering the room.

Therefore, the integrated controller tries to solve this problem by controlling the natural light source (window blinds) depending on the light level required by the user. In the case were natural light does not **fulfill** the users requirement, artificial light source such as bulbs are switched ON and dimmed according to need. Considering the applicability to the situation, adaptive controlling is studied in which the system learns from past results and updates the operating procedure or parameters accordingly. Although a broad spectrum of such controllers exists, mainly they can be grouped into models incorporating probabilistic logic as in (Granderson et al. 2004); fuzzy logic as in (Sperduto, Priolo and Sciuto 2001)neural network;

linear programming in (Yao-Jung, Agogino 2008), or by a combination of all decision making algorithms. The obvious advantage of such systems is the capability for dynamic behavior in the method of operation of the system depending on the operating conditions and changes in user preference and also the ability to adapt to environments which are not fully defined beforehand. Adaptive controllers are automated with predefined user set points or preferences. These devices tend to create a rich and helpful environment (Ramos et al. 2010) for humans to interact with.

Methodology

Identifying the Key Parameters That Defines Vision

Illuminance Engineers Society of North America's handbooks definition declares Lighting as "what should provide visual conditions in which people can function effectively, efficiently, and comfortably". The human vision system processes an image by the interaction of the eye and the brain and interprets the visual environment. Hence visual comfort is when the visual environment generated in human brain for a certain activity is satisfactory for the user. At the same time it is a necessity in the present time that the users are conscious about saving energy while establishing their attitude towards self-defined comfort levels with regard to interior illuminance.

For the intended controlling of the light levels it is required to assess the users' visual capability and the level of comfort as he/she perceives it. There are several existing methods around the world that are commonly referred to as visual tests. The Snellen chart developed by ophthalmologist Herman Snellen is very commonly used in the field of medicine. Another such eye chart recommended is the Landolt C chart developed by the Swiss born ophthalmologist Edmund Landolt. The requirement for such study in the local level was deemed a necessity in the process of developing the control system.

Visual Performance Tests and Survey

The auditorium of the Mechanical Engineering Hub at the University of Moratuwa was chosen as the base to the study. The results obtained from 90 subjects from the age group 18-27 are used in viewing. In order to identify the user required lighting levels the main activities at office and domestic environments were chosen. Reading the computer monitor, identifying the keyboard, identifying printed material and hand writing using the blue/black colour carbon pen are some main activities identified with an office environment.

The survey revealed that up to 80% of office related work is done on the computer screen. Hence the visual acuity and contrast test were carried out using Freiburg Vision Test ('FrACT') developed by (Bach 2007) which is conducted on a computer screen with a refresh rate of 60Hz.

Illuminance, which quantifies the light level is the primary measurement in this study. Illuminance level of the working plane is used as the quantifying unit in the calculations, results and assumptions. The working plane is usually the surface that eye concentrates upon while working which is incorporated in case studies by (International Energy Agency 2010) .Tests were conducted at a plane 760mm off the floor. Tests were conducted under six different illuminance levels.

Order of tests is as indicated below:

Snellen test to determine the near field vision and legibility-Objective being to select suitable subjects for the further tests and to recommend the subjects to seek consultancy if there is a clear defect of eyesight which has not been previously identified.

Landolt ‘C’ test for six illuminance levels considering the ability to differentiate between lighting levels for the user. The Landolt C chart assists to measure the vision characteristic of visual acuity. Measurement unit is Dec VA.

Contrast test for the same illuminance levels selected above – measures threshold contrast (Michelson contrast) as represented by eqn. 1.

Equation 1

$$The\ Michelsons\ contrast\ = \frac{(Lmax\ - Lmin) * 100\%}{(Lmax\ +\ Lmin)}$$

The test gives contrast threshold values in which lower values indicate high contrast sensitivity.

Parallel to the series of visual performance tests a survey was conducted to assess the user. For each illuminance level the user comfort level data was acquired.

In this study in which the Sri Lankan community is taken as the target population, we are seeking to develop a model that could utilise the availability of natural lighting in the region and incorporate such natural lighting optimally in internal illuminance hand in hand with artificial lighting. The results obtained in the research phase are ultimately used in optimizing the controller inputs.

Fuzzy Control Algorithm

The mathematical model for the fuzzy logic controller works to maintain visual comfort inside the room while taking into account the required illuminance level for the user. The controller focuses on using maximum solar illuminance as possible while reducing the glare effect due to direct solar radiation. It achieves this by taking in to account the solar position relative to the window and adjusting the blind angle α so as to avoid letting direct solar glare pass in to the room. When solar radiation is not sufficient to illuminate the room, artificial lights are turned on automatically and dimmed (β – dimming value) to fill the illuminance requirement. This block activates when the user is present inside the room and shuts down when the user is absent. To avoid unnecessary shutdowns and start-ups the controller waits 10 minutes before shutting down if a user steps out of the room. In figure 3 the overview of the fuzzy control structure in shown.

Solar Position Model

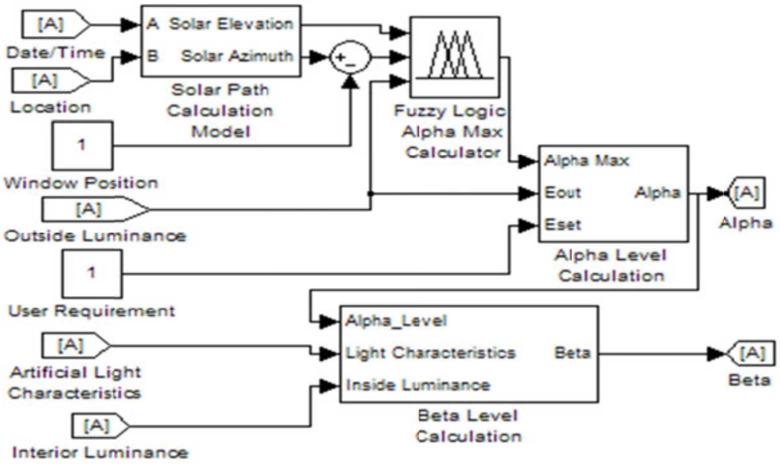
This model calculates the solar position angles at the current local date and time to the given local position (latitude, longitude) and feeds the decision making variables of the Fuzzy Inference System. The solar angles are calculated using equations developed (Duffie, Beckman 1991) verified using the NOAA Solar calculator (National Oceanic & Atmospheric Administration)

Alpha Max Calculator

When developing the blind controller, the task was to control the blind as if a human would adjust it. Making controlled movements depending on how the light was coming through the window. The fuzzy controller coupled with the solar path model provides the ability to distinguish scenarios when the solar radiation is directly incident on the window (or illuminating the user). Therefore, with adaptation of the fuzzy model it can produce different outputs depending on the user feedback.

The following input, outputs are used in the fuzzy controller.

Figure 1. Fuzzy Control Structure



Inputs:

- Global Horizontal illuminance – Eout
- Solar elevation angle – Elevation
- Solar azimuth angle relative to the window – Azimuth

Output:

- Maximum possible opening angle of the blind – AlphaMax

The Fuzzy Inference system is based on MATLAB and uses 15 rules to calculate the maximum value (upper bound) of the blind angle that can be opened at that moment. This allows the controller to cut the direct solar glare and strive to let in as much diffuse light as possible. The Innovative design divides the external illuminance (Eout) into clear sky, partly cloudy (normal), cloudy (low light) illuminance conditions and modifies the behaviour to let maximum diffuse light inside. The rules are designed so that the following priorities are met:

- Let maximum diffuse sunlight in and avoid glare. This is done by taking the azimuth of the sun as well as the elevation of the sun relative to the window in question. So that when the sun is within the window area the blinds close to reduce glare. These rules are further adapted if the user changes the blind settings.
- Limit how much the blinds open depending on the external illuminance level

- Strive to let in diffuse light as much as possible.

The membership functions are created by dividing the inputs to reflect the logic of a user.

Alpha Level Calculation

The alpha level that is required to meet the user set illuminance level is calculated by assuming a quadratic relationship of the exterior light transmitted inside. The relationship is modelled by a regression model created for the room. It uses an internal light sensor and logs the natural light level and the blind angle at intervals and uses the data to evaluate the coefficients of the regression model. If exterior illuminance is Lout, and Interior illuminance is Lin and the user requirement is L_{set}, then:

Equation 2

$$L_{in} = (\boldsymbol{a}.\alpha^2 + \boldsymbol{b}.\alpha + \boldsymbol{c})L_{out} = L_{set}$$

Therefore:

Equation 3

$$\alpha \frac{-b \pm \sqrt{b^2 - 4a(c-k)}}{2a(c-k)} =$$

This alpha level is bounded as:

$$0 \leq \alpha \leq \alpha_{max} : \alpha \in \mathbb{R}_0^+ \; and \; k = \frac{L_{set}}{L_{out}}$$

Beta Level Calculator

When the external illuminance levels are not adequate to provide the user requirement, the controller switches ON the artificial light sources and then provides the dimming value to the light dimmer to correctly adjust the light intensity for the user. The system assumes a linear response of the dimming controller to the output illuminance and calculates the required beta value. Because this does not use a feedback it avoids unstable operations where sudden flickering or changes occur due to obstructed sensors.

The required Beta value is calculated using the following relationship:

Equation 4

$$L_{art}(\beta) = L_{art}^{(\beta=0.4)} + (\beta - 0.4) \times \frac{L_{art}^{(\beta=1)} - L_{art}^{(\beta=0.4)}}{0.6}$$

Equation 5

$$L_{art}(\beta) = L_{set} - L_{in} = L_{set} - (\boldsymbol{a}.\alpha^2 + \boldsymbol{b}.\alpha + \boldsymbol{c})L_{out}$$

Here the relationship of Lart (Artificial illuminance level) and β (Dimming value) is automatically determined by the controller on a daily basis.

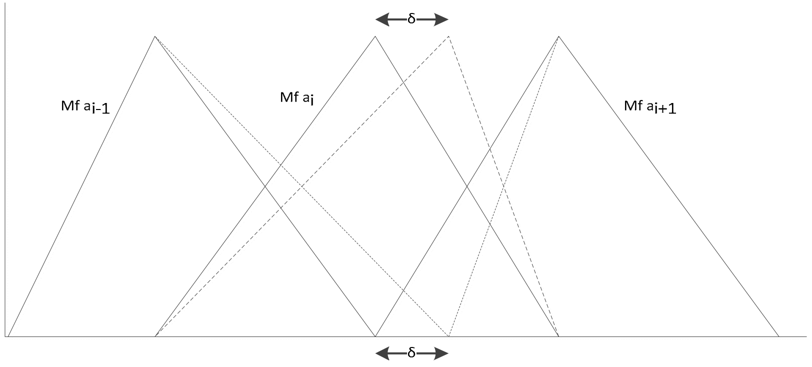
Because the system strives to maximize the use of natural light the system automatically improves energy savings by reducing lighting costs. This is achieved by turning OFF the lighting system when natural light is adequate to meet user requirement and using controlled artificial lighting to fill the gap.

Adaptation Algorithm

The algorithm improves the long term adaptation of the fuzzy inference system and also updates the parameters used on the Alpha and Beta regression model calculations.

The membership function parameters of the Alpha Max fuzzy output [a1 to a6] are adjusted using a moving point average algorithm so that when the user changes blind position, the corresponding Alpha Max value operating at that time is changed and remembered in the users' profile.

Figure 2. Adjustments to the Membership Function as the System Adapts



The parameters used in Equation 2 and 4 are derived using a regression model of the rooms' lighting conditions which the controller measures using an internal illuminance sensor. These provide way-points to derive the regression coefficients.

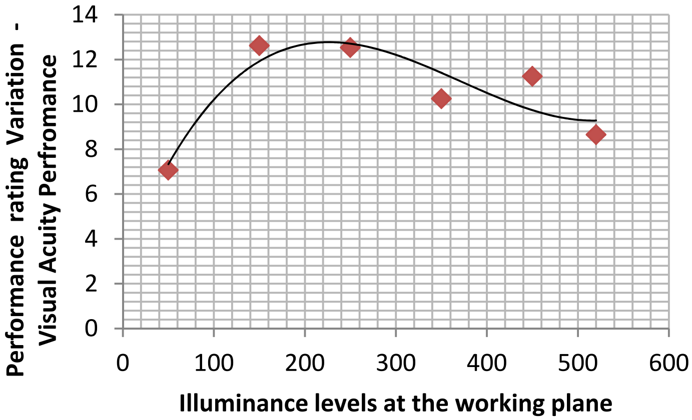
Results and Conclusions

Human Performance and Behaviour towards Lighting Levels

There are human behaviour patterns that have a certain correlation to the illuminance levels such as visual acuity, contrast sensitivity and the visual comfort level while illuminance levels increase.

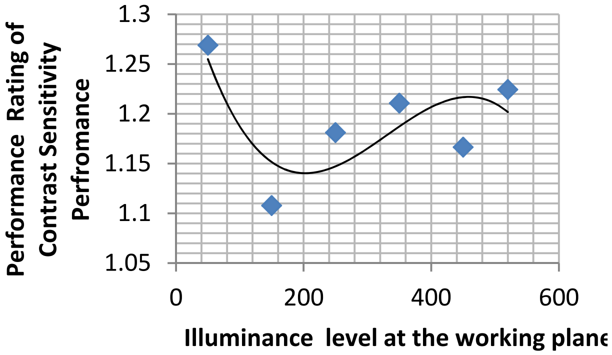
The analysis of Visual Acuity performances indicates that the performance levels show a peak at the Illuminance range 190lux – 220lux as indicated in Figure 5

Figure 3. Performance Rating Of Visual Acuity Performance Varying With Illuminance Level on the Working Plane



When the contrast sensitivity performance is plotted against the illuminance levels on the working plane it depicts a similar characteristic as the visual acuity performance giving a maximum performance level/minimum threshold contrast performance in the range of 180 lux – 220 lux as shown in Fig.5.

Figure 4. Performance Rating of Contrast Sensitivity Varying With Illuminance Level on the Working Plane



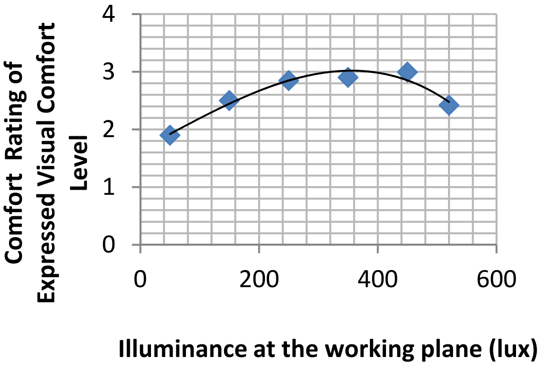
The Michelson formula for contrast sensitivity incorporates the maximum and minimum luminance of the brightest and darkest portions on the tested area. The study links Michelson contrast with the illuminance. Michelson contrast gives a threshold value in which a minimum value indicates a high performance level.

The Pearson correlation measurement between visual acuity performance and contrast sensitivity shows a strong positive relationship for the sample concerned. This indicates that the performance maximization is centred within the 180lux – 220 lux range. The analysis of visual comfort data obtained through the survey is indicated in Figure7.

The visual comfort level is maximized in the illuminance level range 360lux – 400 lux, which is a significantly higher illuminance level than the level that maximized performance.

It can be concluded that this observation relates to the average illuminance conditions the subjected population has adapted to work under. With adaptation the performance maximization could occur at a lighting level that is more familiar to eyes. This further implies that within the context of the tested sample, the subjects work under low illuminance levels than recommended by (Illuminating Engineering Society of North America 2000) for office environments.

Figure 5. Comfort Rating Of Expressed Visual Comfort Level Varying With Illuminance Level on the Working Plane



Furthermore it is evident that subjects are more comfortable under a higher illuminance level that lies within the recommended illuminance levels by for office environments (Illuminating Engineering Society of North America 2000).

Incorporating the outputs of the study three levels of lighting ranges are defined as below:

- User comfort is given precedence – 360 -400 lux
- Visual performance is given precedence – 180 -220 lux
- Energy saving is given precedence – 180 -220 lux

This provides the user with a scale to determine the input illuminance levels for the controller depending upon expected visual performance and user's current attitude towards lighting requirements in office or domestic environments.

The survey further reveals that ninety percent (90%) of the subjects are working in a space with availability of natural lighting. Ninety two percent (92%) of the subjects are aware of the medical benefits of the sunlight and the ability to enhance performance. But given that the room is equipped with blinds the inclination of the local users to change those blinds manually to set up appropriate illuminance levels is only fifty point four six percent (50.46%). This signifies the need of an automated and intelligent system to incorporate natural lighting without the intervention of the user.

Controller Simulation Results

The mathematical model developed as a MATHLAB Simulink model for the Fuzzy control algorithm was tested under the following conditions:

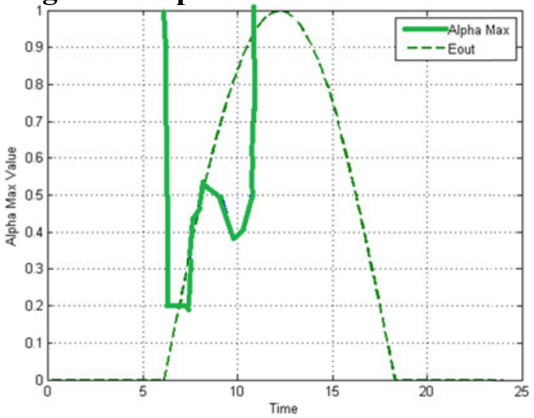
- Window position (Azimuth): East (90^0)
- Latitude / Longitude : 6.795843 / 79.898798
- Maximum External Luminance : 100,000 LUX

- User requirement: Determined from the series of visual tests and the survey the results. In the current case results are visualized for illuminance of 300lux (This value can be decided upon the output of the above study).
- Power consumed by artificial lights when fully ON: 200W
- The simulation assumes user is present at all times for the whole 24hrs.
- The simulation does not simulate radiation variation due to cloud cover. It assumes clear sky conditions.
- Assumes maximum luminance of artificial lights under full power is 400 LUX and minimum luminance under lowest dimming is 50 LUX.

The figure 6 plots the Alpha Max values calculated by the fuzzy controller as well as the daylight available during the day. As it is evident, because the window is situated facing East, after sunrise the controller limits the maximum allowable blind angle to be 0.2 because direct sunlight is then pouring in from the window.

As the sun climbs higher the controller slowly opens the blinds to let more sunlight in. However when the sun has gone past the window area the controller allows full opening of the blinds.

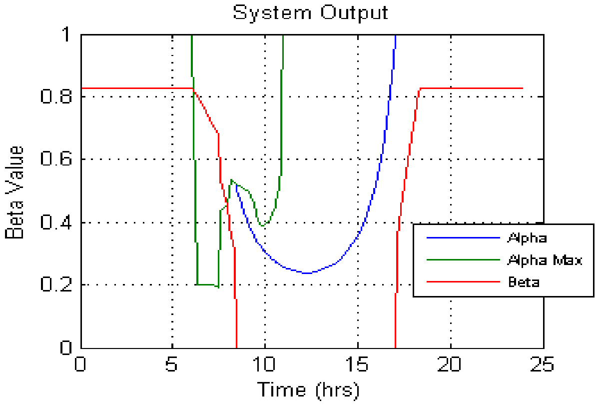
Figure 6. Alpha Max Simulation Results



The blue colour line on figure 7 shows the calculated Alpha values needed to meet the user requirement. The alpha values in the morning hours follow the level bounded by the maximum Alpha value and then deviates from it because external light is more than what is needed by the user. Afterwards it slowly opens up when it is afternoon. This value is what is sent directly to the hardware which controls the window blind mechanism.

The red colour plot in fig.9 is the beta value. The graph shows that in the morning hours when the sun is low the controller has switched ON the lights and is slowly dimming it to while keeping the lighting at an adequate level.

Figure 7. Controller Output Signals



Furthermore once enough light is coming through the windows it automatically switches OFF the lights and turns back ON, only when it is evening.

This graph clearly shows the time of the day when energy is saved. During the time between 8.15 am to 5pm the artificial lights are turned OFF from the system and light is provided by the solar radiation. Because this time period is the working hours in many industries, the energy saving the system will provide is evident.

The area between the beta plot and horizontal line y =1 can be calculated using the expression:

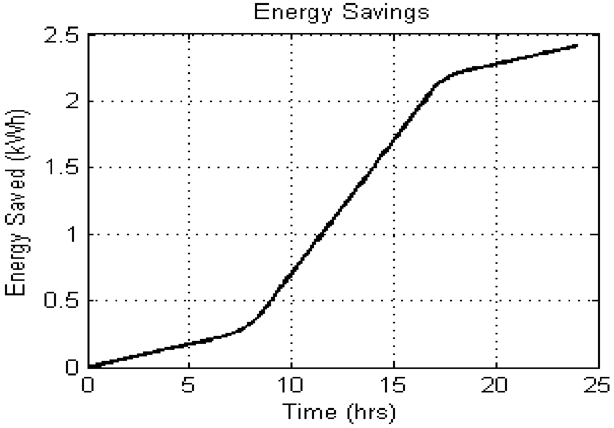
Equation 6

$$E_{saved} = \frac{(VI)_{\beta=1}}{1000} \int_{t_1}^{t_2} \{1 - \beta(t)\}. dt$$

Where $(VI)_{\beta=1}$ is the power consumed by the lighting system at full power. This relationship gives the power saved by the system for a given time period in kilowatt hours. In the simulation model the lighting system was assumed to consume 200W of power at full power. Therefore, if the lighting system was turned ON for the whole duration of 24hrs as was done in the simulation it will consume 4.8kW of power.

The energy saved by the system, by using the controller can be seen from figure 7, to be 2.413kW of energy at the end of 24 hrs. This implies an energy savings of 50.27%; more than half the energy cost in lighting is eliminated by the system. Furthermore, this was simulated to be operational for 24 hours whereas conventional industries operate during working hours of 8.00am to 5.00pm.

Figure 8. Energy Savings with Time (from 0 to 24 hour interval representing a single day)



It is therefore evident from the graph that power savings in lighting will be close to 100% (in this scenario) when operating during working hours. But it should be noted that this is a simulated value and that in real situations the operating power of the system must also be accounted for and the results can vary depending on the illuminance requirement. On the other hand, because the system is to use resources such as servers and networks currently existing in the building itself, these costs will be marginal.

Conclusion

The objective of the study was to identify the visual performance and the behaviour of the local communities of Sri Lanka with regard to illuminance at the work plane. When taking an approach to create an intelligent system it is vital to understand the user expectations and needs .This is of further importance since our approach being to minimize the energy consumption by lighting through incorporating maximum natural light available through an array of windows.

Hence, as a first step user performance maximizing illuminance levels were identified to evaluate the lighting conditions that user is used to practice under regular basis. Then, the expressed, preferred illuminance levels were obtained through a constructive survey to determine the user's expectations (optimistic) for comfortable lighting conditions. After statistically analysing the obtained information two different ranges of illuminance conditions are defined for user performance maximization and user comfort maximization. Such defined ranges are published to convey how the local community of Sri Lanka perceive illuminance, and such conclusions are suggested to be incorporated for industrial lighting systems and control system designs for countries which are at a similar development stage as Sri Lanka.

From the controller perspective, development of the actual physical controller must be carried out to gather and evaluate the realistic savings and usage statistics. The controller architecture presents flexible implementation of the components and fixtures. Design stage calculations indicate that the controller can be made cheap enough to be retrofitted into most of the focused industries and building types and depending on the working hours of the particular industry, can have a significant impact on the energy consumption in electric lighting costs. The novel approach in the controller model has removed most redundant features that existing controller designs carry that make them ineffective in cost terms to implement. This is achieved because the controller is designed from a Sri Lankan context, climate and solar conditions.

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