IMPROVING ENERGY SAVING EVALUATION IN LIGHTING USING DAYLIGHT UTILIZATION WITH AREA SEGREGATION TECHNIQUE

MOHAMMAD ASIF UL HAQ

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Dedicated to my loving family,

Who have missed me, yet supported me,

With Patience and Prayer.

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ABSTRACT

Lighting control is one of the key areas for energy saving in lighting system. Automatic control systems reduce energy consumption by decreasing load and operating time of lamps based on various factors like occupancy, time and daylight illuminance. Daylight-linked control systems can provide substantial savings in rooms with daylight availability. This approach to energy saving is called Daylight Utilization. Different methods to estimate energy savings from daylighting exist. The existing methods use simulations along with complex calculations which are suitable for research projects, but difficult to adopt for electrical designers. Moreover, some issues within these methods prevent them from estimating the maximum potential of savings. Particularly, these methods often consider the whole room as one workplane, whereas in reality the actual task area is considerably smaller. Also, the existing methods take annual average daylight penetration without considering variation of daylight penetration throughout the day or year. These problems lead to inaccurate assessment and ultimately reduced savings. This study aims to develop a new method using simulation data that considers segregation of the workplane and daylight variation for improved daylight utilization assessment. The proposed method uses two approaches to overcome the above problems of previous studies. Firstly, dividing the workplane of the room into task and surrounding area, and associating different illuminance level requirements for the two areas. Secondly, dividing the daylight penetration into three different ranges of daylight illuminance levels, thus taking into account variation in daylight illuminance. The method was applied on the simulated model of a small office room, and the annual savings potential was found to be 83.67%. The results show that the proposed method gives estimation of 73.45% savings for an office room, which is 10% higher than the results of an existing method. This shows that the new method is a viable solution for estimation of energy savings potential from daylighting.

ABSTRAK

Kawalan lampu adalah salah satu bidang utama bagi penjimatan tenaga dalam sistem pencahayaan. Sistem kawalan automatik mengurangkan penggunaan tenaga dengan mengurangkan beban dan operasi masa lampu berdasarkan kepada pelbagai faktor seperti penginapan, dan pencahayaan siang. Sistem kawalan berkaitan pencahayaan siang dapat memberi penjimatan besar di bilik-bilik dengan adanya pencahayaan siang. Pendekatan untuk penjimatan tenaga ini dipanggil Penggunaan Pencahayaan Siang. Kaedah yang berbeza untuk menganggarkan penjimatan tenaga dari pencahayaan wujud. Kaedah-kaedah yang sedia ada menggunakan simulasi bersama-sama dengan pengiraan yang kompleks yang sesuai untuk projek-projek penyelidikan, tetapi sukar untuk diterima pakai untuk pereka elektrik. Selain itu, beberapa isu dalam kaedah ini menghalang mereka daripada menganggar potensi penjimatan yang maksimum. Terutamanya, kaeadah ini sering menganggap seluruh ruangan sebagai satah kerja, sedangkan pada hakikatnya kawasan tugas sebenar adalah jauh lebih kecil. Selain itu, kaedah yang sedia ada mengambil penembusan cahaya matahari purata tahunan tanpa mengambil kira perubahan dari penembusan cahaya matahari sepanjang hari atau tahun. Masalah-masalah ini membawa kepada penilaian yang tidak tepat dan akhirnya mengurangkan penjimatan. Kajian ini bertujuan membangunkan satu kaedah baru menggunakan data simulasi yang mengambil kira pengasingan satah kerja dan perubahan pencahayaan untuk meningkatkan penilaian penggunaan pencahayaan siang. Kaedah yang dicadangkan menggunakan dua pendekatan untuk mengatasi masalah-masalah yang telah dibincangkan dalam kajian sebelum ini. Pertama, membahagikan satah kerja bilik kepada kawasan tugas dan kawasan persekitaran, dan mengaitkan keperluan tahap pencahayaan yang berbeza bagi kedua-dua kawasan. Kedua, membahagikan penembusan cahaya matahari kepada tiga julat yang berbeza dari tahap pencahayaan siang hari, dengan mengambil kira perubahan dalam pencahayaan siang hari. Kaedah ini telah digunakan pada model simulasi bilik pejabat kecil, dan potensi penjimatan tahunan didapati 83.67%. Perbandingan dengan kes dari kaedah yang sedia ada juga dijalankan dan kaedah yang dicadangkan memberi anggaran penjimatan sebanyak 73.45%. Keputusan ini adalah 10% lebih tinggi daripada hasil kajian asal. Ini menunjukkan bahawa kaedah baru adalah penyelesaian yang baik untuk anggaran potensi penjimatan tenaga dari cahaya matahari.

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LIST OF ABBREVIATIONS

CAD	-	Computer Aided Design
CFL	-	Compact Fluorescent Lamp
DC	-	Daylight Coefficient
DF	-	Daylight Factor
D/L	-	Daylight
EEFL	-	External Electrode Fluorescent Lamp
HVAC	-	Heating, Ventilating, and Air Conditioning
IESNA	-	Illuminating Engineering Society of North America
LED	-	Light Emitting Diode
LPD	-	Lighting Power Density

LIST OF SYMBOLS

A_w	-	Window area
A_p	-	Perimeter floor area
A_f	-	Total floor area
D	-	Annual Working Days
$D_{\theta\phi}$	-	Daylight Coefficient
E_I	-	Total Initial Annual Energy Consumption
E_G	-	Total Annual Energy Consumption After General Dimming
E_{DT}	-	Annual Energy Consumption After Daylight Dimming (Task Area)
E_{DS}	-	Annual Energy Consumption After Daylight Dimming (Surr. Area)
E_D	-	Total Annual Energy Consumption After Daylight Dimming
E	-	Total daylight illuminance at a point in the room
E_{av}	-	Average illuminance
$\Delta E_{\theta\phi}$	-	Illuminance (lx) produced at a point in a room
F_{RT}	-	Power Reduction Factor (Task Area)
F_{RS}	-	Power Reduction Factor (Surr. Area)
F_{LT}	-	Annual Low D/L Penetration (Task Area)
F_{MT}	-	Annual Medium D/L Penetration (Task Area)
F_{HT}	-	Annual High D/L Penetration (Task Area)
F_{LS}	-	Annual Low D/L Penetration (Surr. Area)
F_{MS}	-	Annual Medium D/L Penetration (Surr. Area)
F_{HS}	-	Annual High D/L Penetration (Surr. Area)
$F_{RT,LD/L}$	-	Power Reduction Factor at Low D/L (Task Area)

$F_{RT,MD/L}$	-	Power Reduction Factor at Medium D/L (Task Area)
$F_{RT,HD/L}$	-	Power Reduction Factor at High D/L (Task Area)
$F_{RS,LD/L}$	-	Power Reduction Factor at Low D/L (Surr. Area)
$F_{RS,MD/L}$	-	Power Reduction Factor at Medium D/L (Surr. Area)
$F_{RS,HD/L}$	-	Power Reduction Factor at High D/L (Surr. Area)
f_d	-	Percent energy saving potential
L_{TI}	-	Initial Lamps Illuminance Level (Task Area)
L_{SI}	-	Initial Lamps Illuminance Level (Surr. Area)
L_T	-	Required Illuminance Level (Task Area)
L_S	-	Required Illuminance Level (Surr. Area)
$L_{T,LD/L}$	-	Low D/L Average Illuminance Level (Task Area)
$L_{T,MD/L}$	-	Medium D/L Average Illuminance Level (Task Area)
$L_{T,HD/L}$	-	High D/L Average Illuminance Level (Task Area)
$L_{S,LD/L}$	-	Low D/L Average Illuminance Level (Surr. Area)
$L_{S,MD/L}$	-	Medium D/L Average Illuminance Level (Surr. Area)
$L_{S,HD/L}$	-	High D/L Average Illuminance Level (Surr. Area)
$L_{T,L}$	-	Required Lamp Illuminance Level At Low D/L (Task Area)
$L_{T,M}$	-	Required Lamp Illuminance Level At Medium D/L (Task Area)
$L_{T,H}$	-	Required Lamp Illuminance Level At High D/L (Task Area)
$L_{S,L}$	-	Required Lamp Illuminance Level At Low D/L (Surr. Area)
$L_{S,M}$	-	Required Lamp Illuminance Level At Medium D/L (Surr. Area)
$L_{S,H}$	-	Required Lamp Illuminance Level At High D/L (Surr. Area)
$L_{\theta\phi}$	-	Luminance of the sky element

N_T	-	No. of Luminaires for Task Area
N_S	-	No. of Luminaires for Surr. Area
P	-	Installed lighting power
P_L	-	Load per Luminaire
P_{TI}	-	Initial Task Area Lamps Load
P_{SI}	-	Initial Surr. Area Lamps Load
P_I	-	Total Installed Initial Lamps Load
P_T	-	Current Task Area Lamps Load
P_S	-	Current Surr. Area Lamps Load
P_G	-	Total Installed Lamp Load After General Dimming
$P_{T,LD/L}$	-	Task Area Load at Low D/L Condition
$P_{T,MD/L}$	-	Task Area Load at Medium D/L Condition
$P_{T,HD/L}$	-	Task Area Load at High D/L Condition
$P_{S,LD/L}$	-	Surr. Area Load at Low D/L Condition
$P_{S,MD/L}$	-	Surr. Area Load at Medium D/L Condition
$P_{S,HD/L}$	-	Surr. Area Load at High D/L Condition
S	-	Energy Saving Potential From Daylight Utilization
$\Delta S_{\theta\phi}$	-	Angular size of the sky element
T	-	Operating time
T_D	-	Daily Working Hours
T_A	-	Total Working Hours per Year
T_{LT}	-	Total Hours at Low D/L Condition (Task Area)
T_{MT}	-	Total Hours at Medium D/L Condition (Task Area)
T_{HT}	-	Total Hours at High D/L Condition (Task Area)
T_{LS}	-	Total Hours at Low D/L Condition (Surr. Area)
T_{MS}	-	Total Hours at Medium D/L Condition (Surr. Area)
T_{HS}	-	Total Hours at High D/L Condition (Surr. Area)
τ_w	-	Visible transmittance of the window glazing
W	-	Electrical energy consumption
θ	-	Elevation of sky element
φ	-	Azimuth of sky element

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

One of the key focuses of research in Electrical Engineering at the present time is Energy Efficiency. Due to growing concerns over diminishing resources and environmental impact of the conventional energy sources, there has been increased attention in the last few decades to investigate more efficient ways to use electrical energy. Reduction in electrical energy consumption means lower energy bills as well as reduced load on the grid. The reduced electricity demand also in turns means less impact on the environment.

Lighting is the most common and naturally the most constant form of load. It represents a significant portion of the total electricity consumption for all building types, and it is more prominent in commercial buildings. For example, according the United States Department of Energy, lighting load represented 14% energy consumption in commercial buildings on average [1]. Other studies showed that average lighting load can be significantly higher in some cases [2]. A European study shows that in case of medium and large buildings, about 40% of the total electricity is used for interior lighting [3].

Commercial buildings hold great importance when it comes to energy consumption. Out of the total primary energy requirement of the United States, for example, over one-third is consumed by commercial buildings [2]. If office buildings are considered separately, the contribution of lighting energy demand on overall energy consumption can be 25%-35% [4]. So, reduction in lighting load in commercial buildings can have significant positive impact in decreasing the electricity demand, which in turn helps reduce carbon footprint [5], [6], which is a key focus for energy engineers at the current time. Taking the energy impact of lighting systems into perspective, various governments, international and regional organizations promote specific energy saving guidelines for lighting systems [7], [8]. Hence researchers have been continuously thriving to achieve better efficiency in lighting, which means maintaining optimum lighting conditions using as less energy as possible.

Research shows significant savings from various types of lighting control schemes [9]. Manual lighting controls depend mostly on occupant behavior, occupancy patterns, and general awareness about energy saving [10]. At the user level, lighting installations can be controlled by different types of switching systems. The basic conventional switching systems provide simple "On and Off" options. Dimming regulators provide the users with the option to dim the intensity of the lamps, but in that case the lamps must be controlled by dimmable ballasts. More advanced electronic switches can be programmed to operate in different ways like toggling or changing intensity in steps. Advanced building automation systems provide more flexibility in terms of control by the user, as these systems offer the ability to implement computer controlled lighting systems. In such cases, the users can control the brightness level and other parameters right from computer screens. Further, products are now entering the market, which allow lights to be controlled over internet communication using smartphone apps. These technologies provide new flexible ways to control the lighting scenarios for the user. But when it comes to automation of the switching or dimming process of the lights, there are several different technologies that work beyond the user end. These technologies vary based on the parameters that are considered for the control of the lamps.

Automatic schemes vary a lot in technology and complexity. In a basic level, the automatic controls can be used to switch on or off the lights, and on a more precise level, these schemes can control the level of illumination based on requirement [9]. It needs to be remembered that any control scheme may not be suitable for application for any type of task. Different workspaces have different lighting requirements and widely varying occupant behaviour. Choice of lamps, luminaires and control schemes must be guided according to those requirements to ensure occupant satisfaction and productivity [11]. To successfully select the right lighting technology, the occupant behaviour of every type of room or building based on the type of activity must be studied. This occupancy pattern will then provide a picture about how the occupants of the room really use the energy in those spaces [12].

Including the pattern of usage by occupants, there are several factors that affect the performance of control systems, and these factors may be particular to a certain type of control system. For instance, in case of occupancy sensor-based system, time delay settings is a key issue which can have an impact on their performance; while for daylight-linked systems, choosing between switching and dimming or between open and closed loop algorithm can be decisive in the success of the implementation. Since each of the control systems uses different parameters in order to control the lighting, the affecting factors of these technologies are also different. Failure of properly understanding these affecting parameters can lead to improper commissioning of the lighting control systems and thus to unsatisfactory energy saving performance and poor user satisfaction.

For buildings or rooms with provision to receive daylight, the lighting control schemes that are linked to daylight availability can provide the maximum amount of savings, given that the factors related to daylight availability like orientation, obstacles etc. are in favor of daylight utilization [9]. Rooms with adequate daylight penetration can benefit from using the available daylight, complementing the electrical lamps to provide sufficient light levels [13]. In order for daylight-linked lighting control to be beneficial, it must be ensured that the room or space under consideration is appropriate for it. Several factors affect the actual availability of daylight that can be utilized to save energy, such as geographical location and orientation of room, dimensions of the room, obstructions to daylight etc.

In order to assess the possibility of energy savings, researchers either go for direct measurements of energy consumption from using daylight-linked controls, i.e. with pilot projects and field studies, or employ some type of methodology to acquire a savings estimation. It is clearly understandable that experiments on actual buildings would give the most accurate results as to energy saving possibilities from daylight utilization. But setting up such experiments is tedious and time consuming. For that reason, researchers and electrical engineers turn to various evaluation methods to predict energy savings from a particular building or room.

There have been quite a lot of studies performed on the estimation of energy savings from simulations or other analyses. The estimated energy savings and measured savings can vary in consistency, as daylight linked controls depend on many factors, which can be difficult to simulate with accuracy [9]. Li and Tsang [14] used the lighting simulation software RADIANCE to simulate the daylight scenario of a corridor. Energy savings estimations were also calculated based on the illumination. The results of the estimations were compared with on-site measurements. The results showed that for most part the savings were overestimated. On the other hand, other researchers have found daylight simulations to be reliably accurate. Krarti et al. [15] developed a method of analysis that takes the factors affecting daylight availability into account, such us building geometry, window area and window type. This approach provided energy savings estimations that agreed well with experimental measurements. To enhance the accuracy of daylight control simulations, Bourgeois et al. [16] proposed adding advanced behavioral models to incorporate occupancy pattern predictions into the simulation. But the obvious problem with this method is that it requires hardware setup and ample time to observe the occupants' behavior in order to develop the occupancy pattern.

A review on the previously used methods by researchers show that some assessments methods are either too simplistic or too complicated. The simple methods are easy to apply, but often neglect many important parameters, leading to inaccuracies. On the other end, some methods are comprised of complex mathematical analysis that make these methods difficult to use for engineers working in planning. A method needs to exist that is easy to set up to acquire necessary data and comparatively simple in analyzing the data. The method would take into account the important parameters of the room under study, and give a fair understanding about the daylight-linked energy saving possibility from the room.

1.2 Problem Statement

Successful implementation in terms of energy savings from daylight-linked lighting controls depend on prior assessment of the room or building. The energy performance of the lighting system controlled by daylight availability depends on several factors, which is evident from literature review. Determination of savings from direct implementation of controls and energy measurements is time consuming and requires investment even before actual implementation. In order to assess the daylight availability and possibility of energy savings from its utilization, researchers have come up with different methodologies. These methods depend on two key components, i.e. a) prediction of daylight illuminance levels and b) estimation of energy savings based on those predictions.

There are a few established methods to predict daylight illuminance levels on a particular geographic location, but these methods are very complex in calculation. In terms of calculating energy savings from these predictions, there are no standard methods. The procedures taken by researchers involved in the academic field are difficult to recreate by electrical engineers in the planning field. That is why estimation of energy savings from daylight utilization is often not properly carried out, which leads to lack of interest in implementing these technologies, or dissatisfaction on actual savings.

Moreover, the methods used by researchers are often influenced by the technologies or planning currently used in the room. This means the true potential of energy savings, which is the maximum savings achievable, is not reflected in the final calculation result. The potential for energy savings can be recognized further by focusing on some issues often overlooked in such studies. One is to identify differences in daylight availability throughout the working hours, instead of considering just the average illuminance levels. And the other is to consider the area where the critical tasks of a room is performed to be separate from the whole workplane.

1.3 Research Objectives

The main objectives of this research are –

1. To assess the impact of area segregation and daylight variation on daylight-linked energy saving.

2. To develop a comprehensive method that incorporates area segregation and daylight variation to estimate energy saving potential from daylight utilization.

1.4 Scope of the Study

The study uses the simulation software DIALux for prediction of daylight illuminance levels. This particular software was chosen from amongst other choices of software due to its ease of access. This software takes into account important room parameters necessary for accurate simulation of a room and daylight prediction. Moreover, this software allows researchers to specify task and surrounding areas of the room, and performs separate calculations for these areas. This is one of the important factors for achieving the research objectives. DIALux does not require any coding and the simulation can be set up with a user-friendly interface. But other software like RADIANCE and DAYSIM offer more features in terms of accuracy of simulation, particularly in simulating varying sky conditions. But those software require a lot of time and study to learn how to simulate using the software, some of which even require knowledge of computer programming. Considering the time frame of this study, simulation using DIALux was the feasible option.

The study considers two cases for simulation and application of the evaluation method. Both of the cases are indoor rooms and have similar lighting requirements. Outdoor and public spaces like hallways, corridors, atriums etc. are not considered in the study. The design of a private office room is simple to design using the Computer Aided Design interface in DIALux, which makes it feasible for this study considering the time frame.

The rooms considered in the simulation are designed as stand-alone structures with no obstruction to daylight. In actual cases, the adjacent structures like buildings, trees and other objects need to be modelled in order to incorporate obstruction of daylight from those objects. This would ensure a more realistic prediction of daylight illuminance and energy savings potential.

1.5 Structure of Thesis

The thesis has been organized into six chapters. This first chapter discusses the background of the research and identifies the problem statement. It also outlines the main objectives of the research as well as its scope and limitations.

Chapter 2 presents the literature review starting from general concepts in energy saving in lighting through control systems and current use of different types of controls. Then the chapter focuses on daylight-linked control schemes, their different types, the savings reported in previous studies and the factors affecting their performance. Finally the chapter explores some methods that are used to evaluate the possible energy savings from daylight utilization and provides some observations on those methods.

Chapter 3 puts forward the setting up of the simulation environment for this thesis. It first discusses the requirements from a simulation software to be used in this study, and then points out how DIALux simulation software meets those requirements by presenting the steps of simulating a room in DIALux. After that this chapter shows the steps that are used to model two different cases called Test Case and Comparative Case inside DIALux.

The method proposed for evaluation of energy saving potential from daylight utilization is presented in Chapter 4. This chapter presents the four steps of the proposed method, detailed description of each step and the parameters used in those steps. The sources of the values for the parameters and the equations formulated are clearly presented.

The results from applying the proposed method on the data obtained from simulation are presented in Chapter 5. Results for all the parameters of all the steps are presented clearly for both the cases. Finally discussions on the results are presented.

Finally, Chapter 6 presents the conclusive remarks on the study. It gives a summary of the research and the findings, highlights the main contributions made by this research and also sheds light into some areas where attention can be given in the future to further advance this research.

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