DAYLIGHT ADAPTIVE OPTIMAL LIGHTING SYSTEM CONTROL STRATEGIES FOR ENERGY SAVINGS AND VISUAL COMFORT IN COMMERCIAL BUILDINGS

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To my beloved mother, wife and children

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ABSTRACT

Artificial lighting of commercial buildings in Malaysia consumes 21% of the total electrical energy. Therefore, reducing the energy is required to achieve sustainable buildings (i.e., higher energy efficiency and visual comfort), by implementing optimal light sensor placement method and optimisation-based control strategy. However, in recent works related to light sensor placement, energy performance and illuminance uniformity (U_o) are not considered, and the results did not provide the optimal number of sensors to be employed. To optimise power consumption (PC) and visual comfort simultaneously through the optimisation-based control strategy, the previous work developed a visual comfort model to represent U_o. However, the model did not consider daylight and the results of U_o need further improvement. This research proposes: (1) a new optimal light sensor placement method (OLSPM) by using combined particle swarm optimisation (PSO) and fuzzy logic controller (FLC) denoted as OLSPM-PSOFLC, and (2) a new visual comfort metric called illuminance uniformity deviation index (*IUDI*) and incorporated with multi-objective PSO (MOPSO) for solving energy consumption and visual comfort problem. The OLSPM-PSOFLC is developed to determine the optimal number and position of light sensors by considering PC while satisfying average illuminance level (E_{av}) and U_o. To ensure both PC and U_o in the room are always at the optimum levels, the *IUDI* with MOPSO is developed. Before the proposed methods are implemented, retrofitting lighting system is implemented first to determine the best lamp technology to be installed in terms of technical and economic metrics. An actual office room is considered for carrying out the proposed methods. The comparative results showed that the OLSPM-PSOFLC significantly reduced the number of sensors, energy consumption, carbon dioxide emission, payback period, and life cycle cost were 66%, 23%, 23%, and 30%, respectively, compared to the multi-sensor. Meanwhile, based on the comparative study of the *IUDI* and CVRMSE, the *IUDI* showed superior performance with 6% and 27% improvement of U_o and energy savings, respectively. Based on their superiority, the newly developed methods can be potentially implemented for all types of rooms and are very useful methodologies towards sustainable commercial buildings.

ABSTRAK

Lampu elektrik bagi bangunan komersial di Malaysia menggunakan 21% daripada jumlah tenaga elektrik. Oleh itu, pengurangan tenaga adalah perlu untuk mencapai bangunan lestari (iaitu tinggi kecekapan tenaga dan keselesaan penglihatan) dengan melaksanakan peletakan pengesan cahaya yang optimum dan kawalan berasaskan pengoptimuman. Walau bagaimanapun, dalam kajian terkini berkaitan dengan peletakan pengesan cahaya tidak mengambil kira prestasi tenaga dan keseragaman pencahayaan (U_o) dan ianya tidak memberikan keputusan yang optimum kepada bilangan pengesan untuk dipasang. Bagi mengoptimumkan penggunaan kuasa (PC) dan keselesaan penglihatan serentak melalui kawalan berasaskan pengoptimuman, kajian terdahulu membangunkan model keselesaan penglihatan bagi mewakili U_o. Walau bagaimanapun, model tersebut tidak mengambil kira cahaya matahari dan keputusan U_o perlu ditambah baik. Kajian ini mencadangkan: (1) peletakan pengesan cahaya yang optimum menggunakan gabungan pengoptimuman kumpulan zarah (PSO) dan pengawal logik kabur (FLC) singkatannya OLSPM-PSOFLC dan (2) metrik keselesaan penglihatan baru dipanggil indeks sisihan keseragaman pencahayaan (*IUDI*) dan digabungkan dengan pelbagai objektif PSO (MOPSO) untuk menyelesaikan masalah penggunaan tenaga dan keselesaan penglihatan. Sebelum melaksanakan kaedah-kaedah yang dicadangkan, pemasangan semula sistem lampu perlu dilakukan dahulu untuk menentukan teknologi lampu yang terbaik untuk dipasang dari segi metrik teknikal dan ekonomi. Sebuah bilik pejabat sebenar digunakan untuk menjalankan projek yang telah cadangkan. Keputusan perbandingan menunjukkan OLSPM-PSOFLC mencapai bilangan pengesan, penggunaan tenaga, perlepasan karbon dioksida, tempoh bayaran balik dan kos kitaran hayat yang rendah iaitu 66%, 23%, 23%, dan 30% berbanding pelbagai pengesan. Selain itu, berdasarkan keputusan perbandingan *IUDI* dengan CVRMSE, *IUDI* menunjukkan prestasi terbaik dengan penambahbaikan dari segi keselesaan penglihatan dan penjimatan tenaga dengan 20% dan 67%. Berdasarkan prestasi yang baik, ianya berpotensi untuk dilaksanakan di pelbagai jenis bilik dan metodologi yang sangat berguna menuju ke arah bangunan komersial yang lestari.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Surface/Plane Area
$\boldsymbol{C}$	Illuminance Centre Point Matrix
c_1 and c_2	Acceleration Constants
$C_{x,y}$	Grid Centre Point
d	Dimming Level of Luminaires
$\mathbf{d}$	Dimming Level of Luminaires Vector
d_{av}	Average Dimming Level of Luminaires
d_{Em}	Dimming Value at E_m
d_i	Dimming Level of Luminaire of i^{th} Zone
$d_i^{\min}$ and $d_i^{\max}$	Minimum and Maximum Dimming Level of Luminaire of i^{th} Zone
$\boldsymbol{E}$	Illuminance Matrix
$\boldsymbol{E}_a$	Artificial Lighting Illuminance Matrix
E_{av}	Average Illuminance Level
$\boldsymbol{E}_d(t)$	Daylight Illuminance Levels Matrix
E_{err}	Illuminance Error
E_i	Illuminance value for i^{th} Zone in Matrix $\boldsymbol{C}$
$\boldsymbol{E}_i$	Illuminance Matrix of i^{th} Zone
$\boldsymbol{E}_{i,fd}$	Illuminance Level Matrix During All Luminaires in i^{th} Zone Are Fully Dimming
$E_i^{\min}$ and $E_i^{\max}$	Illuminance Value for Lower and Upper Bounds in Matrix $\boldsymbol{C}$
$E_{j,k}$	Illuminance Value on the Measurement Point
E_m	Maintained Average Illuminance Level
$E_{\max}$	Maximum Illuminance Value
E_{measured}	Measured Illuminance Value
$E_{op,i}$	Optimum Value of Illuminance for i^{th} Zone
$E_{r,i}$	Illuminance Value of i^{th} Zone in PSO Process

E_{set}	Illuminance Value Set Point
E_v	Illuminance
$\boldsymbol{E}_T(t)$	Total Distributed Illuminance Matrix
$EC_{existing}$	Energy Consumption of Existing System
$EC_{proposed}$	Energy Consumption of Proposed System
$f_o^{\min}$ and $f_o^{\max}$	Minimum and Maximum of o^{th} Objective Function
$gbest^{(t)}$	Global Best Position
h	Vertical Distance from Luminaire to Working Plane
$iter_j$	Current Iteration Number
$iter_{max}$	Maximum Number of Iterations
l	Length of the Room
$L_{op,i}$	Optimum Position of Light Sensor for i^{th} Zone
K	Room Index
lm	Lumen
n	Particle Number
n_l	Number of Lamp for Each Luminaire
N	Number of Sensor
N_{av}	Normalised Illuminance Values of Average
$N_{j,k}$	Normalised Illuminance Values of j,k Point
Nl	Number of Luminaire
Np	Number of Grid
NP	Total Number of Measurement Points
Nz	Number of Control Zone
p	Maximum Grid Size
$pbest^{(t)}$	Local Best Position
PC	Power Consumption
P_i	Total Power of Luminaires in i^{th} Zone
P_{Rated}	Power Consumed
$P_{x,y}$	Interior Point
ρ_c	Surface Reflectance Factor for Ceiling
ρ_f	Surface Reflectance Factor for Floor
ρ_w	Surface Reflectance Factors for Wall

q	Longer Dimension of the Area
r	Discount Rate
R^2	Coefficient of Determination
r_1 and r_2	Random Numbers between 0 and 1
$\mathrm{R_a}$	Colour Rendering Index
t	Lifetime
μ_o	Membership Function of o^{th} Objective
μ^k	Membership Function of k^{th} Non-dominated Solution
U_o	Illuminance Uniformity
$U_{o,\min}$ and $U_{o,\max}$	Minimum and Maximum Illuminance Uniformity
Uh	Higher Value Set Point of Uniformity
$v^{(t)}$	Current Velocity of the Particle
$v^{(t+1)}$	New Velocity of the Particle
w	Width of the Room
$\omega_{\max}$	Maximum Value of Inertia Weight
$\omega_{\min}$	Minimum Value of Inertia Weight
$x^{(t)}$	Current Position of the Particle
$x^{(t+1)}$	New Position of the Particle
η	Luminous Efficacy
$\Delta \boldsymbol{d}$	Dimming Level Deviation Vector
$\lvert \Delta E_i \rvert$	Absolute Deviation of Illuminance of i^{th} Zone
$^{\circ}$	Degree
Φ_n	Nominal Lumen Output for Each Lamp
Φ_v	Luminous Flux
ACO	Ant Colony Optimisation
$ALCC$	Annualised Life Cycle Cost
ANN	Artificial Neural Network
BC	Billing Cost
BEMS	Building Energy Management System
BES	Building Energy System
BF	Ballast Factor

BREEAM	Building Research Establishment Environmental Assessment Method
BS	Billing Savings
CAD	Computer-aided Design
CC	Capital Cost
CCT	Correlated Colour Temperature
CD	Crowding Distance
CFL	Compact Fluorescent Lamp
CHPED	Combined Heat and Power Economic Dispatch
CO	Convex Optimisation
CO_2	Carbon Dioxide
COR	Competition Over Resources
CRF	Capital Recovery Factor
CSA	Cuckoo Search Algorithm
CSO	Civilised Swarm Optimization
CVRMSE	Coefficient of the Variation of the Root Mean Square Error
EC	Energy Consumption
ECVC	Energy Consumption and Visual Comfort
EE	Energy Efficiency
EED	Economic Emission Dispatch
ELD	Economic Load Dispatch
ES	Energy Savings
EU	European Union
DF	Daylight Factor
DG	Distributed Generator
DLP	Distributed Linear Programming
ELECTRE	ELimination Et Choix Traduisant la REalité
ER	External Repository
ET	Electricity Tariff
EP	Evolutionary Programming
FA	Firefly Algorthm
FC	Fuel Cell

FFNN	Feedforward Neural Network
FL	Fluorescent Lamp
FLC	Fuzzy Logic Controller
FoV	Field of View
GA	Genetic Algorithm
GBI	Green Building Index
GBRS	Green Building Rating System
GEO	Generalised Extremal Optimisation
GHG	Greenhouse Gas
GWO	Grey Woft Optimisation
HJ	Hooke-Jeeves
HS	Harmony Search
HVAC	Heating, Ventilation and Air Conditioning
ID	Ulluminance Deviation
IDM	Illuminance-based Dimming Control Scheme
IESNA	Illuminating Engineering Society North America
IOF	Illuminance-based On/off Control Scheme
IUDI	Illuminance Uniformity Deviation Index
IWO	Inverse Weed Optimisation
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environment Design
LED	Light Emitting Diode
LP	Linear Programming
LSC	Lighting System Control
MD	Mobile Device
MF	Maintenance Factor
MOEA	Multi-Objective Evolutionary Optimisation Algorithm
MODE	Multi-Objective Differential Evolution
MOGA	Multi-Objective Genetic Algorithm
MOPSO	Multi-Objective Particle Swarm Optimisation
MSE	Mean Squared Error
NCO	Non-linear Constrained Optimisation

NGTP	National Green Technology Policy
NSGA II	Non-Dominated Sorting Genetic Algorithm II
OC	Operating Cost
ODM	Occupancy-based Dimming Control Scheme
OOF	Occupancy-based On/off Control Scheme
OLSPM	Optimal Light Sensor Placement Method
OPF	Optimal Power Flow
O&M	Operating
PI	Proportional Integral
PID	Proportional Integral Differential
PIR	Passive Infrared
PoE	Power over Ethernet
PP	Payback Period
PSO	Particle Swarm Optimisation
PV	Photovoltaic
PWM	Pulse Width Modulation
RBFNN	Radial Basis Function Neural Network
RFID	Radio Frequency Identification
RMSE	Root Mean Square Error
ROI	Return on Investment
SA	Simulated Annealing
SIRIM	Standard and Industrial Research Institute of Malaysia
SPDE	Simple Partial Differential Equation
SPEA	Strength Pareto Evolutionary Algorithm
TNB	Tenaga Nasional Berhad
TLBO	Teaching-learning-based Optimisation
UD	Uniformity Deviation
UF	Utilisation Factor
VDC	Direct Current Voltage
VLC	Visible Light Communication
WT	Wind Turbine

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Nowadays, the energy demand has dramatically increased all over the world. In the United States (US), electricity energy consumption increases by approximately 1.6% every year [1]. Meanwhile, Malaysia recorded increased electricity energy consumption year 2010 to 2013 by 18% and increased by approximately 4.5% annually [2]. This phenomenon is reflected in the number of population, economic growth and infrastructure development. Consequently, the increase of greenhouse gas (GHG) emission has serious impacts on the global environment, such as global warming and climate change.

Electrical energy consumption (EC) and carbon dioxide (CO_2) emission of buildings for global and the European Union (EU) [3], [4] is presented in Figure 1.1. Based on the figure, global represents the total energy used with 40% and consequently, CO_2 emission with 30%. For the EU, building energy consumption contributes 40% of the total energy and 36% of the total CO_2 emission. Figure 1.2 shows the electrical energy consumption of Malaysia by major sectors in 2012 [5]. It can be seen that, industrials (45%), commercials (33%), and residential (21%). In 2017, the energy used in the US from the residential and commercial sectors was around 39% of the total energy used [6].

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