DESIGN AND SIMULATION OF A FUZZY LOGIC BASED CIRCADIAN SMART LED LIGHTING SYSTEM AND ITS POTENTIAL FOR HEALTHCARE FACILITIES

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by

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LIST OF SYMBOLS

m	metre
nm	nano-metres
θ	angle in degrees
Φ	Luminous Flux
E_V	Illuminance
L_V	Luminance
I_V	Luminous Intensity
ρ	Reflectance Index
CO_2	Carbon Dioxide
lx	lux
Hz	Hertz
\$	Arbitrary Currency
MYR	Malaysian Ringgit Currency
V	Voltage
mA	milli amperes
π	Mathematical Constant Pi = 3.142
ms	milli-seconds
μs	micro-seconds
ns	nano-seconds
k	kilo

γ	Non-linear colour correction factor
λ	Wavelength
h	Planck's Constant = 6.63×10^{-34} Js
c	Speed of Light = 3.00×10^{8} m/s
k_B	Boltzmann's Constant = 1.38×10^{-23} J/K
J	Joules
K	Kelvin
C	Celsius
T	Temperature
cd	Candela
mcd	milli-candela
A	Surface Area
A_L	Surface Area of luminaire projecting light
A_S	Surface Area where light reaches
lm	Lumens
α	Calibration Factor for Illuminance
β	Relative CIE Y luminance used in coding

LIST OF ABBREVIATIONS

LED	Light Emitting Diode
CCT	Correlated Colour Temperature
STS	Spectrally Tunable Source
FLC	Fuzzy Logic Controller
IEEE	Institute of Electrical and Electronics Engineers
PID	Proportional-Integral-Derivative
GDP	Gross Domestic Product
ECM	Energy Conservation Measures
ROI	Return on Investment
SBS	Sick Building Syndrome
SP	Sustainability Program
EM	Energy Management
ALOS	Average Length of Stay
BOR	Bed Occupancy Rate
ROC-BOR	Rate of Change of BOR
BTR	Bed Turnover Rate
RGB	Red, Green and Blue
ipRGC	intrinsically photosensitive Retinal Ganglion Cells
SCN	suprachiasmatic nucleus
NIF	Non-Image Forming

TLM	Temporal Light Modulation
TLA	Temporal Light Artefacts
SSL	Solid-State Lighting
HID	High-Intensity Discharge
UV	Ultra-Violet
CIE	International Commission on Illumination
CRI	Colour rendering index
CQS	Colour Quality Scale
CIBSE	Chartered Institution of Building Services Engineers
BRFSS	Behavioral Risk Factor Surveillance System
SACL	Stress Arousal Checklist
AC	Alternating Current
DC	Direct Current
PWM	Pulse Width Modulation
SMPS	Switching Mode Power Supplies
PAR	Project Authorisation Request
RAM	Risk Assessment Matrix
JA	Joint Appendix
FOV	Field of Vision
RPi4	Raspberry Pi 4
RGBC	Red, Green, Blue and Clear

IR	Infra-Red
CSV	Comma-Separated Value
CIE	International Commission of Illumination
SPD	Spectral Power Distribution
RPNC	Raspberry Pi No-IR camera
rgb	red, green, blue —linear RGB
IESNA	Illuminating Engineering Society of North America
ZCM	Zero-Crossing Method
FFT	Fourier Fast Transform
MSA	Motion Sensing Algorithm
CPU	Central Processing Unit
SMT	Surface Mounted Technology
NRZ	Non-Return Zero
PLM	Pabon-Lasso Method
ADC	Analogue to Digital Converter
IT	Information and Technology
AI	Artificial Intelligence
IEC	International Electrotechnical Commission
OLED	Organic Light-Emitting Diode
QLED	Quantum Dot Light-Emitting Diode
UCS	Uniform Colour Space

BMS	Building Monitoring System
BAS	Building Automation System
TM	Trademark
WiFi	Wireless Fidelity
RF	Radio Frequency
NA	Not Applicable
w.r.t	with respect to
IoT	Internet of Things

LIST OF APPENDICES

REKABENTUK DAN SIMULASI SISTEM PENCAHAYAAN SIRKADIAN LED PINTAR BERASASKAN LOGIK KABUR DAN POTENSINYA KEPADA FASILITI KESIHATAN

ABSTRAK

Penyelidikan bukti konsep ini memperkenalkan reka bentuk sistem kawalan pencahayaan berasaskan logik kabur untuk menerangi ruang dalaman menggunakan teknologi pencahayaan *light emitting diode* (LED) dengan mereplikasi pencahayaan sirkadian luar ke ruang dalaman. Penyelidikan lampau menyatakan pencahayaan sirkadian mempengaruhi kesihatan penghuni dengan menentukan corak tidur dan bangun mereka. Pereka dahulu mereplikasi pencahayaan luar dengan menggunakan arkitektur kawalan gelung tertutup klasik, yang memerlukan pemodelan matematik dinamik sistem yang mendalam. Sistem kawalan berasaskan logik kabur pula berkos rendah, teguh, mudah alih dan senang diaplikasi untuk sistem kawalan bukan linear kompleks tanpa pemodelan sistem. Satu metodologi peraturan autonomi bagi pencahayaan *Correlated Colour Temperature* (CCT) dan pencahayaan ruang (lux) dengan menggunakan matriks asas peraturan kabur 7×5 dan operasi gubahan max-min Mamdani diaplikasi. Reka bentuk telah dinilai dengan mensimulasikan prototaip berskala kecil untuk menganalisis prestasi sistem yang menunjukkan output sistem bersepadan dengan nilai kromatik cahaya luar dan sisihan daripada lengkung badan hitam berada dalam julat ± 0.003 menggunakan semakan Duv CCT. Sistem beroperasi tanpa lajakan (0.0%), masa naik dan keadaan stabil masing-masing dicapai pada lelaran 1 dan 4. Potensi aplikasi di wad hospital dibincangkan bersama penunjuk kesihatan yang menunjukkan peningkatan kecekapan fasiliti. Kerja masa depan boleh bereksperimen dengan sensor spektrometrik dan aplikasi di situasi sebenar.

DESIGN AND SIMULATION OF A FUZZY LOGIC BASED CIRCADIAN SMART LED LIGHTING SYSTEM AND ITS POTENTIAL FOR HEALTHCARE FACILITIES

ABSTRACT

This proof-of-concept research introduces a fuzzy logic-based lighting control system design to illuminate indoor spaces using Light Emitting Diode (LED) lighting technology by replicating outdoor circadian lighting to building indoor spaces. Past research shows circadian lighting affects occupants' well-being by dictating their sleep and wake patterns. Previous works on replicating outdoor lighting had designers using classical closed loop control architecture, which required extensive mathematical modelling of the system dynamics. Fuzzy logic-based control systems costs less, robust, portable, and easily applicable for complex non-linear control systems without the need for system modelling. A methodology of autonomous regulation of lighting Correlated Colour Temperature (CCT) and space illuminance (lux) is applied using a 7×5 fuzzy rules base matrix using Mamdani max-min compositional operation. The design was evaluated by simulating a small-scale prototype to analyse the controller's performance. Simulation results show the system output matched outdoor chromaticity values and the deviation from blackbody curve was within ± 0.003 range using CCT Duv check. The system performed at no overshoot (0.0%), rise time and steady state reached at 1st and 4th iteration, respectively. Potential application at hospital ward are discussed by correlating with healthcare's practise and parameters which showed increased facility efficiencies. Future works may experiment with spectrometric sensors and real time applications.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Lighting is essential in built environments. Lighting enables humans to see, way-find and execute tasks amongst others (Perumal and Baharum, 2022). Building designers and engineers compensate the lack of natural lighting and illumination into indoor spaces by providing artificial lighting through lighting devices (Boubekri, 2008). Circadian lighting is a lighting that follows the natural lighting characteristics through the day that affects the human being's sleep and wake patterns (Boyce, 2003; Rossi, 2019). Some researchers also refer daylighting effects to circadian effects. The key difference is, however, the daylighting concept is usually utilised in the morning hours for alertness and energy savings, whereas circadian lighting envelops daylighting concept or a 24 hour cycle and dwells into the unseen by eyes effects of light frequency contents. In other words, circadian lighting regulates human's biological clock or circadian rhythm, for that matter. We may experience declines in physiological processes, neurobehavioural performance, and sleep if there is a lack of synchrony or circadian disturbance.

One of the key parameters of lighting is the CCT of lighting that impacts an occupant's well-being. Disruption to the human being sleep and wake cycles affects one's well-being. The circadian variations throughout a day also varies the CCT of the lighting (Zumtobel, 2017). LED lighting is a modern lighting application based on low-power consumption technologies (Chew et al., 2017).

The relationship between lighting and industries exists on a macro level. Economists measure a country's development progress by its annual Gross Domestic Product (GDP) numbers (Fei et al., 2011). The productivity of industrial sectors, including anything from light and medium industries to heavy industries, such as steel mills and manufacturing plants, contribute to the country's GDP. These industries mostly use electricity as a primary source of energy. In other words, the amount of electrical energy used by industries to power their plants influences a country's development level.

Natural energy sources include coal, natural gas, nuclear reactions, sunlight, wind energy, and also through derivatives of hydro-potential conversions (hydroelectric). In an electrical energy generation chain or process, energy is harvested from natural energy sources and converted into electrical energy through generators. Subsequently, heavy equipment and machines consume the generated electrical energy to create mechanical power at the back end of the chain through another conversion level, mostly by electrical motors (Wildi, 2001). More importantly, the energy production, conversion and consumption processes emit carbon-containing gases into the atmosphere, resembling greenhouse gases (Hardisty et al., 2012). These slowly increasing gases play an essential role in global warming and other environmental issues (Soon et al., 1999). The growth of carbon-containing gases (greenhouse gases) in the atmosphere is partly to blame for the rise in global surface temperature. The greenhouse effect is depicted in Figure 1.1, which displays heat trapped in the environment due to carbon-related gases that prevent heat dispersion to the outer atmosphere.

While nations, engineers, and scientists are still debating the long-term consequences, the exponential increase in energy use impacts the earth's natural ecology and, eventually, its destruction (Lovell et al., 2009). As a countermeasure, developing countries are enforcing and adopting Energy Conservation Measures (ECM) to combat greenhouse gas effects. ECM methods vary from zero-cost to high-cost. Furthermore, they are applied to industrial processes to reduce electrical energy consumption, hence

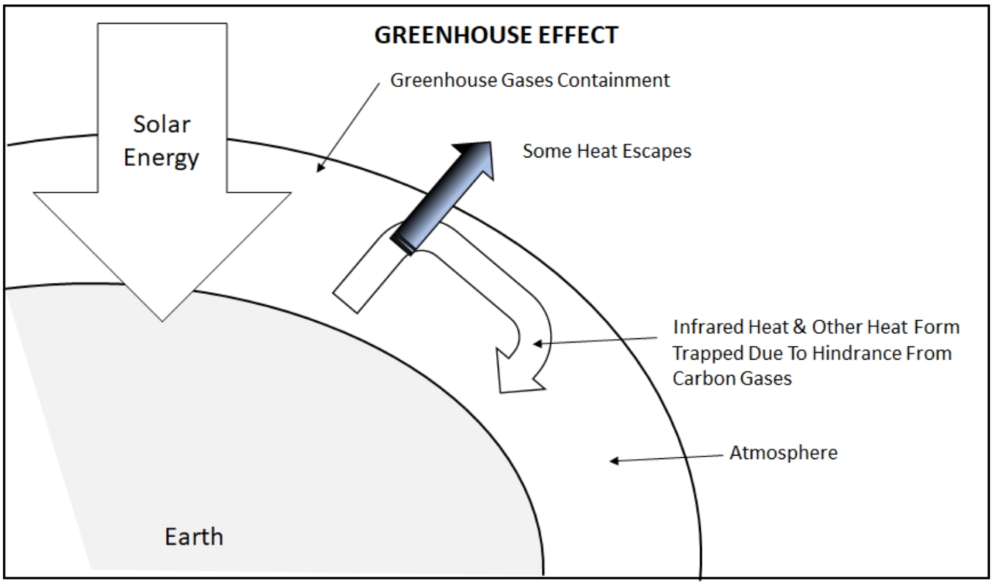

Figure 1.1 Greenhouse Effect.

carbon-containing gas emissions. The quotation that follows summarises Malaysia's commitment to energy efficiency and conservatory measures.

> *"I would also like to announce here in Copenhagen that Malaysia is adopting an indicator of a voluntary reduction of up to 40% in terms of emissions intensity of GDP by the year 2020 compared to 2005 levels. This indicator is conditional on receiving the transfer of technology and finance of adequate and correspond to what is required in order to achieve this indicator."*
>
> *—His Honourable Prime Minister of Malaysia at United Nations Climate Change Conference (COP15), Copenhagen, on 17th December 2009.*
>
> *Lim and Biswas (2015)*

One of the most common ECM is the rapid use of LED lighting to replace conventional lighting, such as fluorescent lightings. Interestingly, LED lighting has been around since the 1960s, but it became more popular in the late 1990s (Gayral, 2017). In comparison to LED lighting, traditional lighting such as incandescent lighting has a lower efficacy. The ratio of a lighting device's luminance to the unit power it consumes is known as efficacy. Power consumption is the instantaneous rate of energy consumption. Therefore, the high efficacy ratings of LED lightings had the technological world coining the term “energy efficient” lighting devices (IESNA TM-16-05, 2005). More significantly, LED lighting technology for lighting and illumination purposes has a faster Return on Investment (ROI), making it attractive to industries that need lighting 24 hours a day, seven days a week (Kumar et al., 2017).

Moreover, LED lighting technology has advanced to the point where designers build a lighting system that satisfies the end user’s environmental requirements. Shopping malls, typical office buildings, and even factories are already using this technology. The growing popularity of LED lighting has spread to healthcare facilities. Healthcare building owners are already installing LED lighting in general wards, operating theatres, and other clinical rooms (Johnston, 2011). Besides, lighting manufacturers heavily promote LED lighting as a substitute for conventional T8 fluorescent and incandescent lights. The ability to save energy has become a major selling point for manufacturers. Plate 1.1 shows an example of lighting in a hospital ward environment.

Plate 1.1   Lighting in a hospital ward.

Unfortunately, building owners frequently disregard the occupants' visual comfort concerns during the lighting design and installation phases. Official occupant reports and complaints of excessive illumination levels, eye pain, dizziness, and other issues further amplify the comfort concern (ASIS MOH, 2017). These are Sick Building Syndrome (SBS) symptoms associated with interior lighting that require the attention of building owners to address. For this reason, one way in overcoming the comfort issues is through the proper deployment of LED lighting by choosing their appropriate characteristics. As LED has design flexibility in photometric and physical variability, they could be used for precise lighting applications such as circadian lighting (Chew et al., 2017).

The light emanating from the sun or artificial lighting around us is a form of electromagnetic wave called visible light. The visible light takes up a portion in the electromagnetic spectrum at wavelengths in between 380 *nm* to 700 *nm*. Figure 1.2 shows the electromagnetic spectrum constituting the visible light spectrum.

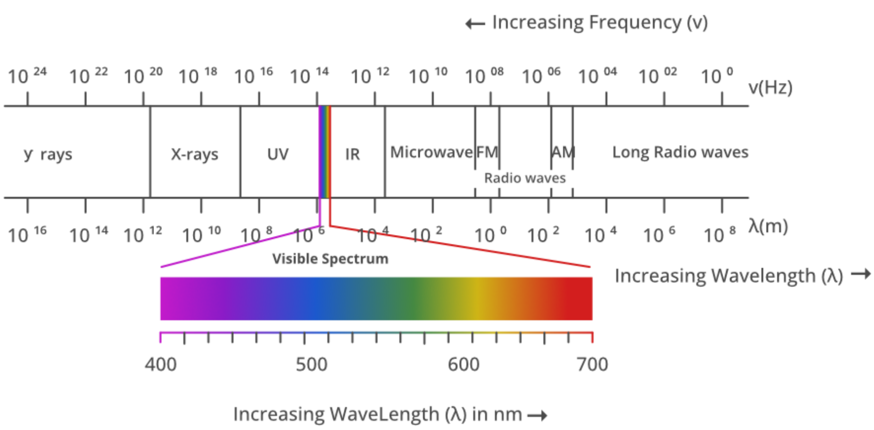

Figure 1.2 The electromagnetic spectrum (adapted from website: www.geeksforgeek.com).

The chroma or colour appearance of the light is determined by the average weightages of each wavelength's intensity present in the light that humans perceive. Light travels in energy packets or quantum. Each packet has its own discrete wavelength property (Gardi, 2018). The abundance of light packets determines the illuminance (brightness) of a particular light source. For example, if the lower wavelength contents, near the 380 *nm* are present, the light appears to be blueish. In contrast, presence of longer wavelength contents, near the 700 *nm*, makes the light that humans perceive as reddish. When mixture of different wavelength intensities occurs non-uniformly, the colour appearance of light is difficult to be guessed without mapping the wavelength-intensity data into mathematical equations to determine the exact colour appearance.

In lighting studies, CCT is a single parameter that represents the lighting chroma (colour) (Rea and Freyssinier, 2012). Studies has also shown that distinct wavelength-intensity spectrum configurations influences human's well-being by affecting the natural circadian rhythms of humans. Therefore, to produce a lighting of certain colour through artificial lighting, requires CCT measurements, which can be measured through light sensor, calibrated through spectrometers. When CCT and illuminance (lux) parameters are available, they can be utilised in a control system to process a required output.

Lighting devices alone, such as LED lighting, are considered unintelligent as they need control mechanisms for guidance. By guidance, in the context of this research, they can be defined as colour and brightness intensity. In modern control systems, several intelligent control mechanisms are available, such as Fuzzy Logic Control system. Fuzzy logic is a branch of probability logic theory which uses aggregation (degree of truth) concept to represent fuzziness from measured parameters (Ansari, 1998; Liu et al., 2016). For example, the ambient temperature in an air-conditioned room may be referred as cold, warm, and hot instead of exact temperature measurements. In other words, how cold/warm a room can be linguistically quantified by the degree of truthiness (cold/warm) based on a reference max-min scale. The fuzzily referred parameters may be mathematically mapped to be represented in number form, ranging between zero and one (like probability).

The fuzzy logic concept when applied and processed in a control system, becomes Fuzzy Logic Controller. In the former example given on room temperatures, if occupants desire the room to be warm, when it is cold, the Fuzzy Logic controller directs the air conditioning device in the room to be set to warm temperatures by decreasing the refrigerant flow to its cooling coils or by decreasing the blower fan speed. Internally, the portion of compensation required for the warming effect are fuzzily (input-output weight aggregation) determined and changes over time as the temperature correction takes place.

Manufacturers today, brands such application as Artificial Intelligence, although, there are different levels of intelligence complexity involved for multitude of applications. The difference to conventional control system is not that far, as both applies the concept of error correction or compensation. However, conventional system tends to be more precise in measurements and error calculations as they process actual measurement numbers (King and Mamdani, 1977). The performance of fuzzy logic controller is comparably similar with less cost, faster and easier implementation with added advantage of energy efficiencies. Besides, the conventional system requires extensive mathematical system modelling to determine the compensation (King and Mamdani, 1977; RasemAbuzeid and Shtawa, 2014; Singhala et al., 2014). In some cases, the performance of the fuzzy logic controller performs better than conventional controllers that relates to human expectations such as the room temperature case elaborated (King and Mamdani, 1977). This is because of human's nature to reference certain parameters fuzzily than exact, so is to the perception of light.

Correlating altogether, as circadian lighting is a concept of illumination where indoor lighting follows human beings' sleep or wake cycle, the circadian lighting strategy syncs the indoor artificial lighting to follow the outdoor natural lighting patterns (Rossi, 2019). These carefully engineered systems could significantly impact people's health, alertness, productivity, and more. Furthermore, circadian lighting is a form of occupant visual comfort enhancer, where the CCT parameter is a part of it and plays a substantial role (Boyce, 2003). As human beings have evolved from living outdoors to indoors for decades or centuries, our psychophysiology mechanism are entrained to natural lighting.

Synonymously, the natural lighting affects the sleep and wake cycles of human beings. For example, humans tend to fall asleep at dark lightings and feel awake or alert at bright lightings (Boyce, 2003; Rossi, 2019). Delving in deeper, the characteristic of lighting needs to be understood if one plans to replicate natural lighting-like ambience through artificial lighting. The wavelength-intensity or the lighting spectrum needs to be determined from measuring equipment where shortage or excess of certain wavelength content may be compensated though artificial lighting. The visible light spectrum has two extreme ends which overlaps to a certain extent to infra-red region and ultraviolet region respectively, as depicted in Figure 1.2. In other words, circadian lighting is characterised by the spectrum content (wavelength-intensity) of lighting and each spectrum yields different lighting outlook colours. The single representation of the spectrum is CCT, hence its colour. Therefore, CCT measurement methodology becomes a part of this research. The influence of high intensity of such wavelength extremes existence in spectrums are further reviewed through past works in the research, where and gaps and opportunities are considered to design a smart lighting system.

On the other hand, many businesses have yet to fully optimise LED lighting technology to improve occupant visual comfort (Fong and Hankin, 2009; Gayral, 2017). LED lighting could control CCT and brightness simultaneously to realise the circadian lighting concept. In the healthcare industry, occupant visual comfort is becoming increasingly important. Visual comfort affects patient recovery or rehabilitation time. Furthermore, research shows that accurate lighting parameters through circadian lighting aids in improving staff work efficiency (Zind, 2018).

Hospital wards nowadays are built in a closed environment with controlled and conditioned air circulating. Similarly, in closed settings, lighting is crucial to set the mood right for patients by enhancing the "recovery mood". Artificial lighting is used more often due to the lack of exposure to natural light (daylight). As a result, appropriate lighting applications could potentially increase the quality of healthcare services. Though occupant comfort is a subjective matter of interest where no one person may be satisfied with the comfort level of others, it is hugely important in the healthcare settings such as wards where patient healing or recovery time is critical (Collins, 1993).

In addition, the notion of "occupant comfort" is a broad discussion area where traditionally, "thermal comfort" has been given much attention. Today, other occupant comfort aspects, including illumination and lighting quality, indoor air quality, acoustic quality, and others, are required to be "green-building" certified. (Xuan, 2018). Moreover, buildings achieving such statuses are certified by professional bodies to have successfully conserved electrical energy consumption and thus practices sustainability measures (with CO_2 emission reduction).

According to studies, lighting in buildings consumes about 20%-30% of the energy used by a typical facility (Liu et al., 2016). In healthcare environments, especially hospitals, certain areas need 24 hours of operating lighting. Although the energy usage apportioning for lighting is only a rough estimate and not the emphasis of this research, lowering energy use can be accomplished with LED lighting technologies while maintaining occupant comfort.

The smart circadian lighting that are available in the market are generally open-looped system or tailor-made for residential use. By open-looped system, it means that the final output of the system is not verified of its accuracy. For example, if a lighting space need a CCT of 4000 K, and the open-loop system directs a bulb to shine at 4000 K, it does not necessarily mean the final room ambience would be 4000 K of CCT. The inaccuracy may be due to error introduced into the system such as through external lighting, the intrinsic error embedded into the lighting bulb itself or others. High-end smart lighting devices are tailored-made to suit residential purposes using close-looped systems (Chew et al., 2017). Today the designers are venturing to apply the circadian lighting concept in commercial settings. However, less have focused into healthcare setup and its potential.

The design proposed by this research uses a closed-loop feedback control system to adapt the final lighting output to the desired values. The potentials of such application exemplified through low-cost components at healthcare setup is focused on this research. The link between lighting and human well-being such as patient recovery and staff productivity in healthcare setup is of great importance. This research would discuss on the application of circadian lighting to hospital wards through publicly available healthcare data by correlating manually applied lighting techniques by healthcare staffs to healthcare facility efficiency. In addition, the proposed design could be applied at any types of buildings as well.

The circadian lighting is influenced by the availability of sunshine and hence its sun-path. At any day and time in a year, the weather outlook may be cloudy and stormy hindering sunshine even at morning hours. These are the cases where the design proposed in the system comes handy to compensate the lack of natural lighting through artificial lighting. Generally, when lighting is concerned most people tend to quantify the lighting intensity through illuminance (lux) levels. However, this research also focuses on another lighting characteristic, the lighting chroma or colour, that presents lighting through various wavelength intensity. Different wavelength intensities in lighting dictates the colour appearance of the lighting which influences the alertness and rest in human beings. In addition the system also monitors lighting flickers which have been found to be detrimental to human's health when exposed continuously at high intensities (CEC:JA10, 2016; IEEE 1789:2015, 2015).

1.2 Problem Statements

As a part of its hospital maintenance privatisation plan, the Health Ministry of Malaysia has included Sustainability Program (SP) in its ten-year concession agreement with Facility Healthcare Management and service providers. Within the first five years, a submodule of SP called Energy Management (EM) requires concessionaires to save at least 10% on total energy use per hospital. In addition, the savings must be sustained monthly for the term of the contract. As a result, concessionaires are rapidly installing or retrofitting fluorescent lighting to LED lighting as an energy-conserving strategy at hospitals throughout the country. Furthermore, due to their favourable energy-saving appeal, LED lighting has become the most preferred ECM among other ECMs.

However, installations and retrofitting works have consistently ignored the subject of occupant visual comfort. Additionally, healthcare practitioners manually control lighting parameters such as colour and brightness, which are less efficient and unguided by standards and regulations. Besides, very few staffs are aware of the importance of correct lighting colour applications and their impact. Therefore, this research aims to design and simulate a lighting control system to monitor, automate, regulate, and condition artificial lighting in hospital wards by giving importance to occupant visual comfort through the circadian lighting concept. Lighting CCT, illuminance (lux), and flicker are the comfort attributes focused on in the research. The CCT and illuminance (lux) of lighting can be measured through colour sensors which requires a CCT-spectrum characterisation for accurate readings and evaluations. Regulating indoor lighting comfort parameters benefits healthcare facilities in lowering Average Length of Stay (ALOS) and increasing Rate of Change of BOR (ROC-BOR). In turn, patients recover faster, and staff productivity increases.

1.3 Research Questions

Given the motivation and context of the design needs, the following research questions emerge.

1. How does a photodiode sensor measure lighting spectrums (wavelength-intensity data) and quantify the spectrum into single parameters of CCT and Illuminance for control system measurements?
2. How does a lighting control system determine the compensation lighting,

spectrum wise, through fuzzy logic concept to entrain circadian effects on occupants?

3. How does a program of fuzzy logic-based lighting control system self-regulate CCT, illuminance and monitor flicker rates?
4. How does a lighting control system render LED lighting to output specific colour and brightness specific for hospital ward settings?

1.4 Research Objectives

The objectives of the research and design are as follows.

1. Characterize CCT and Illuminance (lux) response functions of an Red, Green and Blue (RGB) multi-channel photodiode colour sensor (TCS34725) through spectrometer calibration for accurate control system measurements.
2. Design and construct an intelligent adaptive LED lighting controller prototype that replicates circadian lighting and monitors flickers based on International Commission of Illumination (CIE) colourimetry equations and fuzzy logic compensation.
3. Simulate and evaluate the Fuzzy Logic Controller (FLC) closed-loop feedback control system performance using Python-based coding.

1.5 Research Scopes

The scopes of the research and design are as follows.

1. The research and design would be focusing on identifying essential occupant visual comfort for general hospital wards based on literature reviews and government reports.

2. Only CCT, illuminance (lux), and flicker focused among identified visual comfort parameters.
3. A small scale lighting control prototype (hardware) is built to simulate and test automation software using RGB LED lighting strips.

1.6 Research Limitations

The scopes of the research and design are as follows.

1. The research could not survey healthcare patients and staff due to the COVID-19 pandemic.
2. The design does not consider non-lighting-related discomfort introduced by facility's engineering equipments.
3. The design does not consider discomfort from a medical standpoint such as pain due to medical disorders of patients.
4. The research does not test the planned lighting control scheme and design outcome on actual hospital wards due to cost, regulatory approval, and safety issues.

1.7 Research Significances

The outcome and results of this research would address several grey areas on occupant visual comfort in hospital settings. The results obtained from this research design would benefit the healthcare sector in choosing a lighting device and control system to improve healthcare services.

In short, the grey areas and benefits are as follows.

1. Suitability of LED lighting utilisation in healthcare facilities.
2. Human response (safety) and comfort, be it patients or staff, towards LED

lightings.

3. Patient recovery time improves from the correct lighting application.
4. Staff productivity increased; SBS through lighting system reduced.
5. Energy conservation and efficiency are observable through lighting at healthcare facilities.
6. An intelligent lighting design and control system for healthcare facilities involves minimal human intervention in the setting.

All the above would benefit the Ministry of Health, hence the Government of Malaysia, in providing quality healthcare service to the public and making good use of taxpayers' money in existing or new healthcare facilities installations.

1.8 Thesis Organisation

This thesis has several chapters, with each chapter (except Chapter 1 and Chapter 5 has a subsection of introduction and summary. Chapter 1 (this chapter) – Introduction presents the background and problem statements of the research. Both will highlight the motivation for designing an intelligent adaptive lighting controller. The chapter continues with the statements on research objectives, scopes and limitations. A final section concludes the chapter by featuring the significance that this research can offer to the healthcare industry.

Chapter 2 – Literature Review describes lighting parameters and explores occupant visual comfort parameters. Reviews of previous research on occupant visual comfort and human reactions to lighting follow. A shift in focus to lighting requirements in the healthcare context ensues. Since this research uses the Python scripting tool for software programming and statistical analysis, certain fundamentals are covered. Finally, a study of past technical articles on lighting control systems, such as fuzzy logic control systems and LED lighting technology, concludes the chapter.

Chapter 3 – Research Methodology is the gist of the thesis. It explains how to construct spectrometer hardware for calibration and lighting parameters measurements. This chapter introduces the equations to calculate lighting parameters. The process of converting measurement values to other colourimetry dynamics and dimensions is detailed. A section devoted to motion-sensing presents the techniques to detect motions through a camera. Next, a novel method of correlating illuminance to corresponding correlated colour temperature is detailed based on the literature review findings on the Kruithof curve. The chapter also details the architecture of a fuzzy logic control system before clarifying ways to control LED lighting strips based on the device datasheet.

Chapter 4 – Results And Discussion reveals and discusses the output and outcome of the design. The chapter starts with a picture presentation of constructed hardware and proceeds to tabulate measurement values. The simulation results follow them to highlight the results of the control system automation software. The performance of the control system is analysed and discussed. Finally, the chapter concludes by displaying the simple prototype of LED lighting strips rendering the desired outcomes. This chapter also connects the application of FLC to the lighting strategy in hospital wards through the discussions section. An additional discussions subsection describes the integration of the design to the Building Automation System (BAS) or Building Monitoring System (BMS) for large scale applications.

Lastly, Chapter 5 – Conclusions And Recommendation is a wrap-up chapter to revisit research objectives and report the outcomes. Based on the outcome, the chapter specifies achievements, recommendations, suggestions for future works and applications.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The earth's atmospheric layers filter direct sunlight. The residue of the filtration radiates around us as natural lighting. Natural lighting's contents change when the planet spins in a twenty-hour cycle. Furthermore, natural lighting is also known as broadband lighting because it aggregates various light source spectrums (Rossi, 2019). Besides, morning, noon, and night are all time-terms used to describe natural lighting at different periods of the day colloquially. After sunrise, the brightness of natural lighting increases, whereas as the evening advances and sunset approaches, the light dims. In addition, natural lighting intensity, spectrum characteristics, and colour vary by location during the day.

Humans perceive lighting through the retina cells in the eyes, which has cone cells sensitive to wavelength peaks of RGB colours. Another type of cells called rod cells located at the retina guides our vision in the dark. Also, rod cells are sensitive to motions. Human eyes also have a fifth receptor called intrinsically photosensitive Retinal Ganglion Cells (ipRGC) (Boyce, 2003). The suprachiasmatic nucleus (SCN) activates these ipRGC cells, which are the gateway to Non-Image Forming (NIF) effects of lighting in our bodies (Boubekri, 2008; Boyce, 2010; Rossi, 2019). Furthermore, SCN is the trendsetter to dictate circadian rhythm in human beings. The Hypothalamus region deep inside the brain accommodates the SCN. Significantly, NIF effects are the primary factor influencing the synthesis of melatonin and cortisol hormones in humans.

Human bodies need cortisol hormone to function throughout the day, whereas melatonin is a sleep-inducing hormone. Figure 2.1 depicts the relative hormonal markers in the human body for a 24 hours cycle (Rossi, 2019). Figure 2.1 indicates the hormonal fluctuations in humans where cortisol concentrations are higher in the morning as compared to night. Similarly, the melatonin concentrations in humans are lesser in the morning as compared to night hours.

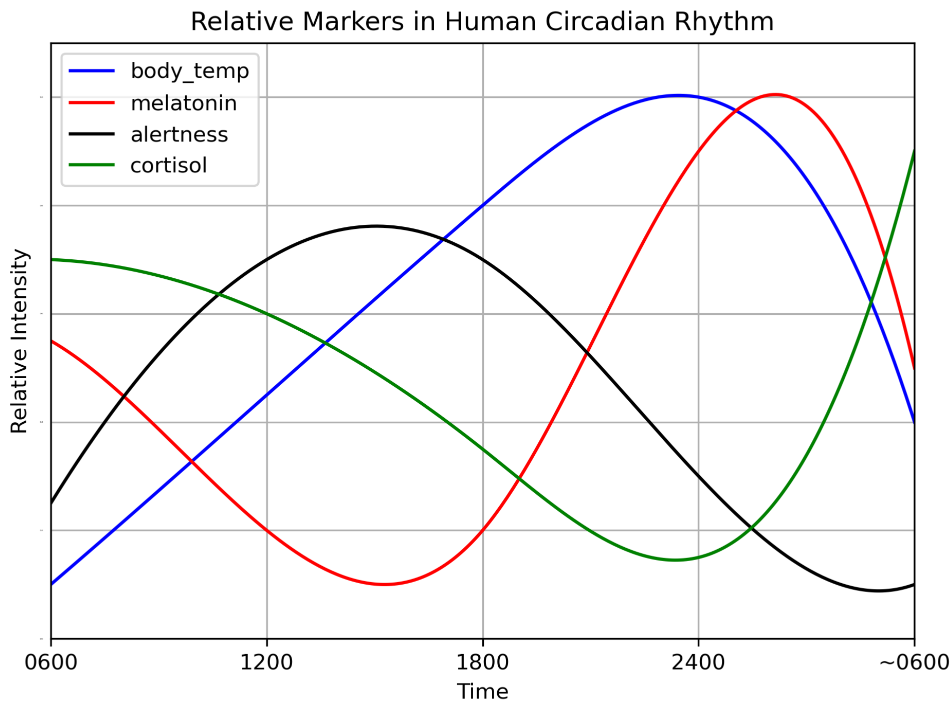

Figure 2.1 Relative markers of the human circadian rhythm.

The year 2017 marked a milestone achievement in chronobiology research that led to discovering the mechanism that governs the biological clock in all living things. Researchers discovered the molecular level mechanism between the human circadian clock and natural lighting (Rossi, 2019). The Nobel Prize-winning findings prove that circadian clocks are present in humans. Thus, giving importance to circadian lighting.

In addition, humans have adapted from living outside to living indoors. Hence, humans now spend more time indoors than outside (Boyce, 2003). Given that we humans have spent centuries accustomed to natural outdoor lighting, the issue that emerges in the field of chronobiology is whether indoor artificial lighting is sufficient for health. Lighting and illumination offered in a healthcare setting affect patient rehabilitation and staff productivity. Various studies exist to resolve the issue by establishing a connection between interior lighting, patient recovery times, and staff productivity.

On another note, Boyce and Raynham (2009) define lighting flickers as rapid and repeated shifts in light intensity. The flicker frequency and intensity variations of a lighting waveform decide whether or not it becomes visually perceptible. Furthermore, flicker occurs when the lighting source and the viewer move around each other, known as the stroboscopic effect. A flicker is a form of Temporal Light Modulation (TLM). Temporal Light Artefacts (TLA) are unintended lighting effects induced by changes in light output (Rossi, 2019). The average human brain does not sense flickers explicitly, but it processes them subliminally. They affect visual and cognitive abilities. There are health issues concerning flickers, leading to detrimental incidents in some cases (Iacomussi et al., 2015).

Subsequent sections discuss and identify the properties of lighting comfort parameters and further dissect the impacts of lighting on humans and healthcare based on past research and studies. Ending sections discuss lighting control methodologies and flicker detection methods applied by past researchers.

2.2 Lighting Devices

Researchers divide lighting sources into two categories, namely natural lighting and artificial lighting. Moreover, natural lighting comes from the sun, while artificial lighting comes from various man-made lighting equipment or materials. The following are examples of typical lighting.

i. Natural Lighting
   a. Light radiating from sunlight
ii. Artificial Lighting
   a. Through by-product of chemical combustions
   b. Solid-State Lighting (SSL) (e.g. LED lightings)
   c. Incandescent
   d. Fluorescent
   e. High-Intensity Discharge (HID)
   f. Others

Each type of lighting source has its own set of characteristics, such as size, application, power consumption, and cost (Taylor et al., 2000). Their medical applications include surgical lights, examination lights, Ultra-Violet (UV) photo lights, and common area lightings. Of particular interest is the LED lighting, which this thesis focuses on in detail.

Incandescent lights use the heating concept to produce light. Lighting through heating is inefficient since it loses almost 60% of the energy consumed as heat (Taylor et al., 2000). Lighting manufacturers introduced a new technology in fluorescent lighting to counter the heat loss issues from incandescent lightings. The newer technology uses the concept of electrons discharge from electroplates to produce light when free electrons hit on inner fluorescent layers. However, the energy efficiency of fluorescent lighting is still lower as compared to LED lightings, which boasts higher efficiency.

2.2.1 LED Lighting Fundamentals

Today, LED lighting has become popular due to its better energy efficiencies (Boubekri, 2008; Rossi, 2019; Taylor et al., 2000). It is not a relatively new device. One way or another, it has been used for decades all around the world. What is new is having achieved greater emission power over the years and producing white light (IESNA TM-16-05, 2005). Its advantage is that it uses less energy as compared to incandescent and fluorescent lamps. Moreover, due to heat loss, the non-LED materials suffer at high temperatures by degrading and carbonising. On the other hand, conduction becomes superior at higher temperatures for LED lighting due to its semiconductor properties.

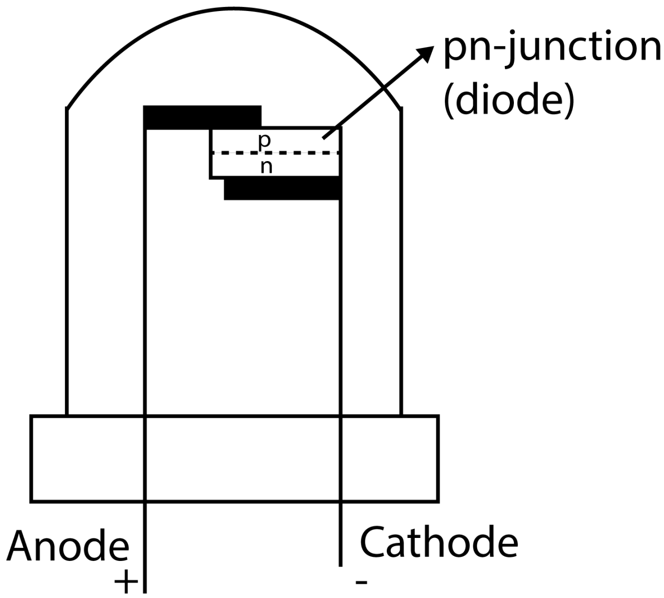

Figure 2.2 The basic construction of LED.

In solid-state device studies, the usage of the p-n junction has been taken advantage of to produce lights or photons (IESNA TM-16-05, 2005). They are optimising energy cost and information transmissions. In the p-n junction of semiconductors, as shown in Figure 2.2, there are two types of charge carriers, electrons (in the n-layer) and holes (in the p-layer). Electrons are negatively charged particles on the atomic scale.

In contrast, holes are positively charged spaces waiting to be filled by electrons to stabilise the atomic structures separated by a differing potential material barrier in between. Electrons would have enough energy to cross over the barriers when an adequate voltage shunts across the junction (forward-biasing). Figure 2.3 depicts the process. The quantum of energy to get the electrons travelling to the holes section are called the bandgap in atomic-scale studies. This process is known as carrier injection through forward-biasing. The electrons exhibit energy called the conduction band, and it is the greatest in the semiconductor atomic structure. The holes exhibit energy called the valence band.

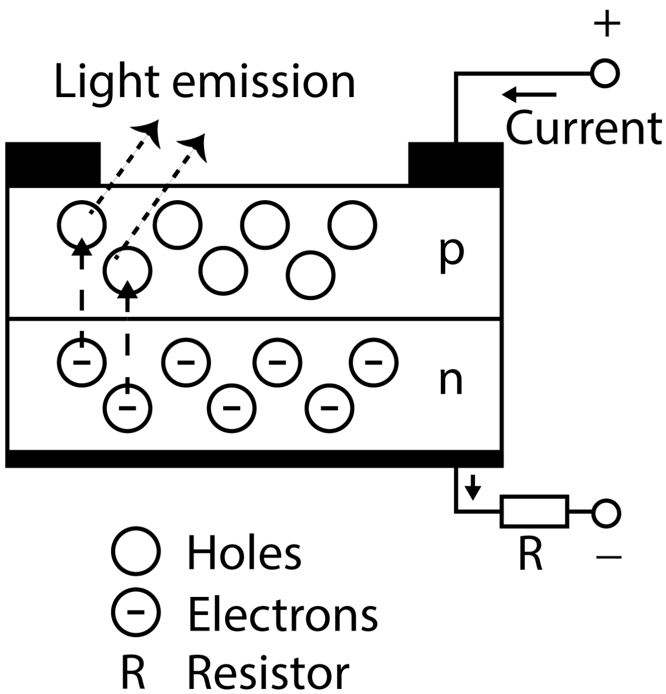

Figure 2.3 Light emission through the pn-junction's electrons transfer.

When bonding between holes and electrons occurs, the atomic structure expels residue energy. Emission of the residue energy is in the form of light in the semiconductors. Humans perceive the energy emission as visible light (referring to the electromagnetic spectrum - Figure 1.2 on page 5. Controlling the forward biasing voltage, materials impurity, and the bandgap of the semiconductors produces different forms of light emission in terms of colours. In the electromagnetic spectrum, visible light is a sub-spectrum, and its colours range from red to violet. Each colour exhibits different energy levels of specific wavelength properties. The lighting intensity is proportional to the number of packets of identical wavelength spectrum (photons) emitted.

Objects tend to reflect, refract and diffract the natural night into different colours as our eyes perceive (Taylor et al., 2000; Zumtobel, 2017). Meaning, objects around the light perceiver may absorb certain light packets and reflect only the residue. For example, if a white light is shined toward an red apple fruit, the rest of the colours are absorbed by the material except for red, which is reflected back into human eyes, making the apple look red. Therefore, in lighting spaces, the objects present in them filters the natural light. Thus, the importance of compensating the lack of certain colours (frequencies) are important to replicate the outdoor natural lighting. If the lighting source is unidirectional straight to the apple, this means that there will be no red colours at all in the room. In reality, lighting radiates in a steradian angles which covers a huge surface area. Table 2.1 summarises this section.

2.2.2 Advancement of LED Lighting

Today, LED lighting is readily available in the electronics market and comes in various sizes, shapes, colours, and fixtures. LED lighting manufacturers are offering lamps at different CCT ratings, which correlate to their lighting colour appearances. Starting with simple LED diodes and progressing to Organic Light-Emitting Diode (OLED)s and Quantum Dot Light-Emitting Diode (QLED)s, the technology has

Table 2.1 Summary table for LED lighting fundamentals.

Author (Year)	Findings	Gaps/ Opportunities
Taylor et al. (2000)	LED lighting has low power consumptions and design flexibility compared to conventional lightings. They are used in medical applications.	Using LED lighting in the research to optimise energy consumptions.
IESNA TM-16-05 (2005)	LED operates by releasing packets of energy quantum having fixed frequencies. The frequency of the energy carried signifies the colour appearance of lighting if the frequency falls within the visible light spectrum.	By controlling the forward biasing voltage of the LED, the colour appearance in a lighting space can be varied. The colour appearance of lighting dictates the circadian lighting approach in this research.

advanced rapidly in tandem with advances in electronics and semi-conductor areas. Furthermore, engineers use LEDs in display electronics such as monitors, televisions, smartphone displays and others by taking advantage of its design flexibility and low-power consumption traits. In addition, newer LED bulbs or devices are WiFi-enabled, making them remotely controllable and integrated into smart home systems.

Figure 2.4 shows some available modern lighting luminaires in the lighting and illumination branch. They are colour-tunable and brightness-dimmable types. Table 2.2 summarises some of the popular smart lighting available in the market. The products listed are single devices (bulbs). Some of them have features to be networked in a system, meaning, multiple bulbs could be linked in a network to respond together. Of the many devices, Philips Hue is one of the earliest smart lighting product which gave user additional control on lighting. Parameters such as CCT, brightness, auto on-off, and others are programmable through the device's built-in controller.

Moving forward, many manufacturers produced similar devices such as listed in the