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Dissertation Title:
Investigation and Calibration of Close-loop Proportional Dimming Lighting Device

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Abstract

This research aimed to find the optimal dimming lighting control plan for the preset model. Computer simulation was performed to analyze the illuminance relationship between the office workplace and the photo-sensor. The result of the analysis shows the location of the photo-sensor should be placed at the 0.75 meters east and 3.75 meters north to the southwest corner based on the square room (6.1 meters) with a single south facing window. For the data recorded by the photo-sensor and the dimming level calculated based on the result of the simulation, the optimal lighting control plan is concluded. The main future aspect of the research is applying the method to other building models to investigate flexibility for the method used in this project.
# Content

Acknowledgement ........................................................................................................... 1

Introduction ......................................................................................................................... 2
  Background ..................................................................................................................... 2
  Objective ......................................................................................................................... 5
  Thesis Organization ....................................................................................................... 5

Literature Review ................................................................................................................. 6
  Description of dimming control ...................................................................................... 6
  Open-loop dimming control ......................................................................................... 7
  Close-loop dimming control ......................................................................................... 9
  Parameters to affect close-loop dimming control ....................................................... 10
  Computer simulation software ..................................................................................... 15

Methodology ...................................................................................................................... 18
  Preset Model .................................................................................................................. 18
  Procedure of using DAYSIM ....................................................................................... 22
  Further DAYSIM procedure after first simulation .................................................... 26
  Procedures for finding the dimming control plan ....................................................... 27

Result and Analysis ......................................................................................................... 32
  Illuminance contour ..................................................................................................... 34
  Daylight Autonomy ..................................................................................................... 36
  Analysis for the result of DAYSIM .............................................................................. 38
  Optimal Photo-sensor location .................................................................................... 42
  Dimming control case one ............................................................................................ 46
  Dimming control case two .......................................................................................... 47
  Dimming control case three ......................................................................................... 48
  Optimal dimming setting .............................................................................................. 49

Conclusion and Recommendation .................................................................................... 50

Reference .......................................................................................................................... 52
Figure 1 example of open-loop dimming control .................................................. 8
Figure 2 example of close-loop dimming control .................................................. 9
Figure 3 model of the building ................................................................................. 19
Figure 4 top view ........................................................................................................ 20
Figure 5 front view ...................................................................................................... 20
Figure 6 side view ........................................................................................................ 21
Figure 7 analysis point ................................................................................................ 23
Figure 8 normal lighting plan ...................................................................................... 26
Figure 9 contour example ........................................................................................... 33
Figure 10 illuminance contour (sunlight, 09:30 1st December) ......................... 34
Figure 11 illuminance contour (sunlight + electric, 09:30 1st December) .. 35
Figure 12 daylight autonomy ...................................................................................... 36
Figure 13 illuminance contour from fixtures ............................................................. 38
Figure 14 comparison of the dimming level ................................................................. 41
Figure 15 indicator point location ............................................................................... 42
Figure 16 dimming level against illuminance ............................................................. 44
Figure 17 upper part of dimming level against illuminance ....................................... 45
Figure 18 optimal dimming control plan after choosing the upper point .... 46
Figure 19 second dimming control plan ..................................................................... 47
Figure 20 auto-generated dimming control plan ......................................................... 48
Figure 21 optimal dimming control plan ..................................................................... 49
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Introduction

Background

Since Thomas Alva Edison has the invention on the light bulb, the lighting devices have already played an important role in our lives: allowing people in work at night and allow the people to build the high rising building which most of the area don’t have windows. Lighting device has helped us a lot to go through the development of the human society and bring us to the age of the information technology. However, the reflective about the human development in the age of information technology have bought the human to think about the sustainable development. In the view of the sustainable development, people have a review on energy use of the building and find out how many energy they have wasted and what the distribution of the energy consumption is. Through many years of researches, people have found the HVAC system and the lighting device have owned the most percentage in the energy consumption in a commercial building. In Hong Kong, the electric lighting has covered 20 to 30 percent of the total electricity use for a commercial building. The idea of the sustainable development has aroused the people to find a way to minimize the energy consumption while still providing a prompt environment to the users in the building. One of these ideas to reduce the energy consumption in the lighting device aspect is using the window and controls the lighting devices at the same time.
In the aspect of saving energy in the lighting system, installing the windows can allow the sunlight to enter the building and illuminate the workplace to a certain level. However, the sunlight entered the area may not always satisfy the minimum requirement of the working purpose for the area. In this moment, the lighting device can act as an aid to light up the area to the requirement level. With a prompt control scheme, the energy consumption of the lighting system in the whole building can be reduced by approximately 20 to 40 percent.\(^2\)

Although the data have suggested a prompt control scheme can help the building owners to save 20 to 40 percent of the money used in the lighting system. The uniform control scheme is impossible to be drawn as the parameters used in each control scheme are different in each building. Some parameters include the lighting devices used in the building, the building geometry, the interior design of the room, the climate around the building and even which kinds of lighting control the users wanted. This thesis is investigation and calibration of close-loop proportional dimming lighting device which will perform how to find out the optimal lighting control scheme for the preset model.

Before showing how to find this optimal lighting control scheme, we must understand
what kinds of lighting control we can perform to help the building owners to decrease the energy consumption in the lighting aspect.

Basically, the lighting devices will response to the reading of the photo-sensor to perform two different kinds of lighting control: switching and dimming. In the function of switching the lighting device, the system will switch on or off the lighting device when some criteria are met. For example, the photo-sensor have detected the illuminance of the area is lower than a certain level or the motion sensor have detected someone enter the area. In those situations, the sensor will send out the signal to the control unit and switch on the lighting device to illuminate the area. However, this control is not suitable for controlling the lighting device which compensates the lack of illuminance provided by the sunlight. It is because the switching control only involves the function to switch on or off the fixture in a specific lighting output.

When the lighting output is too high, the system will cause unnecessary lighting level for the workplace to waste more energy and even make occupies to complain due to the comfortableness. When the lighting output is too low, the system may not be able to provide the suitable lighting level to compensate the lack of illuminance provided by the sunlight.
Objective

To provide the suitable illuminance level to the environment, the idea of dimming control comes up and replaces the method of switching control. By using the dimming control, the photo-sensor will transfer the reading to the control unit. The control unit will then configure the lighting output of the electrical light source according to the signal received. The study of this configuration will be the focus of this thesis. The objective for this thesis is investigating the dimming control system and finds the optimal plan for the preset model.

Thesis Organization

The remaining of this thesis will be divided into four parts. Chapter 2 discusses the essentials of the dimming lighting control and the literature review on the computer simulation software that used in the study. Chapter 3 discusses the method to find the control scheme and describes the building model and parameters used in the thesis. Chapter 4 discusses the research and data analyzed in the study. Chapter 5 summarizes the work that have been performed and the future scope of the thesis.
Literature Review

In this chapter, it would be focus on the description of dimming lighting control system, the literature review about the similar research on finding the optimal control plan of the system and the computer simulation software which help us in the investigation.

Description of dimming control

As the previous chapter mentioned, the control schemes for the internal lighting system are mainly focus on the dimming lighting control. The major reason is using the dimming lighting control can adjust the lighting output of the lighting device to compensate the lack of illuminance produced by the sunlight entered the area while minimizing the energy consumption of the lighting system.

Readers may be confused about what the illuminance is. The illuminance is a term to describe how many lights have fallen onto a given workplace, the unit is normally lux mean the lumen flux per square meters. To put this simple, the human may have difficulties to perform certain tasks in an area which the illuminance is too low. For example, the readers may have difficulties to read the hard copy of this thesis if illuminance on the hard copy (workplace) is too low. The illuminance is basically the indicator to tell the readers if the light sources are enough to read this hard copy or
perform other tasks. Basically, different area have different illuminance requirement because of the working purpose. For example, the corridors are considered to have at least 100 lux illuminance in the daytime and 20 lux in the night time. The offices are considered to have 500 lux for the medium office work. As a result, the lighting control scheme would be based on the illuminance requirement for the area. In other word, the lighting device would start to increase the dimming level (increase the output power) when the sunlight enters the area cannot provide the required illuminance level.

**Open-loop dimming control**

After the description of the illuminance, readers may have a general idea why would the engineers use the dimming lighting control system. To understand how to find the optimal plan of the control scheme, the review on the dimming control should also be performed. The dimming control can be classified into two types: the open-loop dimming and the close-loop dimming. In the open-loop dimming control, the engineers will consider the nighttime signal of the sensor are always zero and the system will only adjust the lighting output in proportion to the daylight signal from the photo-sensor.
Figure 1 is one of the examples to the open-loop dimming control system: we can see that the dimming level of the system has a proportional relationship with the photo-sensor signal. At the zero photo-sensor signals, the system will set the dimming level (lighting output) to the maximum. Once the photo-sensor has received a higher illuminance signal, the system will dim down the system with respect to the photo-sensor signal increased. There is a daytime constant set point in the bottom and the system will stop decreasing the dimming level of the system because the target workplace has already reached the minimum requirement in the illuminance level.
Close-loop dimming control

In the close-loop dimming control, the engineers will find out both nighttime constant set point and daytime constant set point for the photo-sensor signal to develop the proportional relationship between the dimming level of the lighting device and the photo-sensor signal. In other words, the close-loop dimming control is similar to the open-loop dimming control but the close-loop dimming control includes the nighttime constant set point. It means the system will continuously set the lighting output in the maximum value if the photo-sensor have detected the illuminance are below certain value.

Figure 2 example of close-loop dimming control

Figure 2 shows the example of the close-loop dimming control: we can see the idea is
similar to the open-loop dimming control. However, the proportional relationship between the dimming level and the photo-sensor signal is not start from the zero photo-sensor signals but the nighttime constant set point. The engineers will consider having a nighttime constant set point because the photo-sensor signal is influenced by both sunlight and lighting device. As a result, the photo-sensor would have a signal from the lighting device though the daytime is over and no sunlight enters the area.

**Parameters to affect close-loop dimming control**

In this thesis, the investigation will consist both electric lighting and sunlight. As a result, the control scheme for the dimming lighting control is expected to be close-loop control system. Therefore, the consideration and limitation for the close-loop dimming control should be taken into account. One of the key elements is the ratio of the photo-sensor signal to the workplace illuminance. This ratio is mainly affected by three parameters: the spatial distribution of the photo-sensor, the location of the photo-sensor and the spectral response of the photo-sensor. To study the relationship and have a prompt design on the control scheme, we should have a review on those parameters.
**Spatial distribution**

The first parameter is the spatial distribution of the photo-sensor. The spatial distribution is basically which direction the photo-sensor should face. In 2000, Mistrick, Chen, Bierman and Felts have conducted a research on the analysis on six kinds of photo-sensors. [5] Mistrick et al. have suggested the sensors have a steady performance when the photo-sensor is facing downward when the photo-sensor is located at the ceiling of the area. In 2005, Choi, Song and Kim have investigated the characteristics of the photo-sensors. [6] Their result has shown the pattern of detection is uniform when the photo-sensor is facing downward while the other aiming angle will cause the pattern have a distortion and may not be able to detect the light come from some specific angle. From these two researches, we can understand the direction for the photo-sensor is usually designed to be downward when the photo-sensor is located at the ceiling.

**Location**

The second parameter is the location of the photo-sensor. As the researches mentioned before, the photo-sensor is always located at the ceiling instead of the workplace. There are two reasons for this arrangement: the installation and the response from electrical lighting.
In the area of installation, the installation on the ceiling is easier to be designed as the lighting devices and the controllers are normally installed on the ceiling. If the photo-sensor is also installed in the ceiling, the designer can save the time, cost to establish the wiring, wireless control between the controllers and the photo-sensor. If the photo-sensor is installed on the workplace (normally 2.5 feet above the ground for the office), it means the photo-sensor is installed on the desk or a stand which is specific for the sensor. This may cause trouble on the floor plan design or the work of the occupancy. When the sensor is installed on the desk, the worker may always remind themselves not to cover up the photo-sensor or the photo-sensor would receive a wrong message to light up the area. When the sensor is installed on a specific stand, it means the stand will always occupy a set area and lower the efficiency of the floor plan design. In both case, the designer will require extra work on the wiring for the system if the interior design is changed.

In the area of the electric lighting response, the photo-sensor on the workplace receive amount of the illuminance provided from the downlight lighting devices which typically used in offices. In this situation, the ratio of the photo-sensor signal from the sunlight to the workplace illuminance may have chances to be smaller than the ratio for the electric light in the evening and cause the close-loop dimming control failed. In the
evening, the sunlight enter the area are normally low and electric light would contribute heavily to fulfill the minimum illuminance requirement. In this case, the system will set the lighting output in a high output level. After lighting up the area, the photo-sensor on the workplace will receive a wrong message and consider the sunlight is now enough and try to decrease the lighting output. However, the system will once again receive a wrong message after dimming down the light and decide to increase the power again. In this repeating purpose, the workplace cannot receive a steady illuminance and even cause the sickness to the users.

As a result, the photo-sensor is always designed on the ceiling. Although the surface for installing the photo-sensor is known, the detailed location is still unclear as the ceiling is big compared with the sensor. To study the location, Mistrick and Sarkar have studied how accuracy of the sensors in different position is five classrooms in 2005.\(^7\) The result shows a trend that the representativeness of photo-sensor signal would be increased if the sensor is getting closer to the center of the classroom. However, the result also shows this trend is not always true when the shape of the room is not uniform. Besides, the research is based on the data of the CIE clear sky, CIE intermediate sky and CIE overcast sky. So the trend may be different if the climate model is considered. Because of this, the position of the photo-sensor is first to be analyzed before finding
the optimal dimming control setting.

**Spectral response**

The third parameter is the spectral response of the photo-sensor. The spectral response is basically the how well the photo-sensor can detect the light sources from different wavelength. In 2007, Doulos, Tsangrassoulis and Topalis have conducted an experiment to investigate spectral response of five types of photo-sensors. The result shows the pattern of spectral response for all five sensors is very different to the CIE model but most of them have similar peak intensity to the CIE model. And the paper mentioned the manufacturers have provided a correction for the difference in the setting. However, this thesis will not include the consideration of the type of the photo-sensors used in the design and mainly focus on finding the location and dimming control setting for the preset model.
**Computer simulation software**

After the literature review on the parameters that affected the ratio of the photo-sensor signal to the workplace illuminance, this paragraph will be focus on the simulation software used to perform the study. The purpose of using the simulation software in this study is to find out the location of the optimal location of the photo-sensor and the illuminance for the workplace so that the optimal dimming control scheme can be concluded after analyzing the data from the result of the simulation. Some might judge the simulation result cannot reflect the actual condition, so we need to have a literature review on the accuracy of the simulation tools. In 1995, Mardaljevic has conducted the research on the validation for the lighting simulation software. [9] The result indicates the software RADIANCE can have a high accuracy prediction on the internal illuminance under the real sky condition. In 2001, Reinhart and Walkenhorst state another simulation tool based on RADIANCE- DAYSIM can perform a high accuracy simulation while comparing with the measured data in the study. [10] In 2009, Reinhart and Breton have performed a similar research to validate the newer software: 3DS MAX 2009 and DAYSIM 3.0. [11] The result also shows the simulation tools can predict most of the illuminance data when comparing with the measurement. This means the computer software can predict the actual illuminance level under a certain requirement.
The development of the lighting simulation keep blooming, more lighting simulation software is published in these two decades. This development has led people to move their focus to the integration ability between different types of software. It is because the society has changed into a cooperating society; a project will be divided into different parts and handled by various engineers. By using software which have high integration can save up time to analyze the data and fit to the other software. In 2011, Jakubiec and Reinhart have studied the integration ability for three lighting simulation software when integrating with the thermal simulation software DIVA 2.0. \(^{[12]}\) The result shows DAYSIM has the highest integration ability as it can generate an advanced blind and electric light schedules that aid the DIVA 2.0 to perform the thermal and energy use analyst.

Since DAYSIM has the ability to integrate with other software and have a high accuracy in the prediction of the workplace illuminance. The simulation tools used in this study would be DAYSIMS.

In this chapter, it mentioned the information and literature review on the close-loop dimming control system, the parameters that affect the dimming control scheme and the computer simulation software that would be used in the study. The next chapter would
be focus on the methodology to find the optimal dimming control setting and the parameters used in the study including the model of the building and weather files.
Methodology

In the previous chapter, the operation of close-loop dimming control and the accuracy of the computer simulation software have been investigated by the means of literature reviews. In this chapter, it would describe the methodology for conducting the research.

As mentioned before, the objective of this thesis is to investigate the close-loop dimming control system and find the optimal setting in a preset model. It means the parameters of the model should be set and shown before describing the method to find the optimal dimming setting.

Preset Model

In this study, the building model was defined as an office building. It means the recommended illuminance requirement is 500 lux according to the standard of medium office task in the CIBSE. For the research, the designed area would be considered as a room on the middle floor of the building. The ground floor office should not be considered as the target as the reflected sunlight from the ground outside the building will cause a great impact to the photo-sensor signal.
Figure 3 shows the basic model of the research building, the research room is located at the fourth floor to prevent the excess sunlight reflected from the ground enter the research area. Besides, the research room have an overhang to prevent too many direct sunlight enter the area and make the workplace overlit. The dimension of the research area is 20 feet width x 20 feet length x 10 feet height (6.1m x 6.1m x 3.05m). The reflectance of the ceiling, wall and floor is 0.7, 0.5, and 0.3 respectively. In the research area, there is a single window on the southern wall for the room. This window is 5 feet tall and 20 feet length with 2 inches thickness while the window head is in the same level with the ceiling. This window is the only source for the sunlight and the transmittance is 0.7. The window is located at the southern wall as the sunlight is always available from the south in the geometric location of Hong Kong.
Figure 4 top view

Figure 5 front view
After the modeling of the geometric of the research area, the model was exported into different rad files for the use of the DAYSIM software. The exported files contain the geometric information for the building, the reflectance of the interior design and the transmittance of the window.
Procedure of using DAYSIM

In the DAYSIM, different data would be imported to find out the illuminance level of the area. Those data include: the geometric information for the research area and the characteristic for each surface in the area; the climate file which represent the weather data for each day so the DAYSIM can simulation the condition for sunlight enter the research area; the occupancy file for the DAYSIM to calculate the annual metrics such as the daylight antimony and useful daylight illuminance.

As mentioned before, the files exported from the modeling software can provide the information of the geometric information for the research area and the characteristic for each surface in the area. The climate file was found in the website of the energy plus website, this climate file use 1 hour as the time interval to use the weather data in the whole year. It is the result conducted by a research from the City University of Hong Kong. The occupancy file contains the information of the pattern of the workers in the area but not the actual occupancy level at that time slot. As a result, the occupancy file was set with the reference of the format provided in the DAYSIM example. In this occupancy file, the working hours were set to be 09:00 to 18:00. Normally, the occupancy level of these hours was set to be 100 percent. The 12:00 to 13:00 is considered to be lunch hour and the occupancy level was set as 20 percent.
After importing the data, the DAYSIM software allowed the user to set the analysis point for the area. This analysis point is the locations which the users want to obtain the illuminance value. Since the objective for this study is to investigate the close-loop dimming controls system, the illuminance for both the workplace and the ceiling (photo-sensor plane) should be found in the computer simulation. Therefore, two analysis point plan were set: the workplace (2.5 feet above the floor) and the photo-sensor plane (0.5 feet below the ceiling).

![Figure 7 analysis point](image)

The facing directions of these two analysis point are different as the workplace is considered as the plane for the worker to see the document and the light beam come from the upward is the useful light to illuminate the document. In case of the
photo-sensor plane, the direction of the analysis point is facing downward as the review in the precious chapter. Figure 7 is distribution setting of the analysis points for the workplace and the analysis points on the photo-sensor plane also have this distribution. The bottom of figure 7 indicates the south direction and also the wall with window.

There are 144 analysis points which are even distributed on both planes; the result of the simulation can draw an illuminance contour at a certain time and the daylight antimony for the area. The information can help us to design the lighting plan for the area that uses the close-loop dimming control.

After setting the analysis point, the user can move forward to the simulation interface and change the parameters in the simulation. In this project, the default parameters were used to conduct the simulation as the default setting is satisfactory for most runs.

Before obtaining the result and designing the lighting plan with a close-loop dimming controls, a normal lighting plan used in the nighttime should be designed. In the normal lighting plan, the fixtures Vandal Linear 504 from the Eclipse are used.
Lumen method

\[ E = \frac{n \times N \times F \times UF \times LLF}{A} \]

- \( E \) = target illuminance over the horizontal working plane
- \( n \) = number of lamps in each luminaire
- \( N \) = number of luminaire
- \( F \) = lighting design lumens per lamp
- \( UF \) = utilization factor for the horizontal working plane
- \( LLF \) = light loss factor
- \( A \) = area of the horizontal working plane

By lumen method calculation, the minimum account of lighting fixtures should be used is 10 when the light loss factor is 0.7. However, the target area is a square and the light fixtures are difficult to be even disturbed if the lighting plan is set as 5 rows and 2 columns. Therefore, the number of the lighting fixture is set to 12 and the pattern of the lighting plan is 4 rows and 3 columns. Figure 8 shows the fixture distribution of the lighting plan as mentioned before. The spacing of each row is 1.2 meters and the spacing of each column is 1.7 meters while both spacing are counted between the centers of two fixtures.
Further DAYSIM procedure after first simulation

After the first simulation of the DAYSIM, the software would generate both illuminance contour and daylight autonomy. By studying the daylight autonomy of the area, the fixtures would be divided into two types: the control zone fixtures and the dim zone fixtures. The control zone is classified as the area which cannot be reached by the daylight in most of the time. The fixture in this control zone will not be dimmed down so that they can provide sufficient illuminance for the area. In the dim zone, the dimming level of the fixture would be controlled by the close-loop dimming control plan to act as an aid to the sunlight entered the area.
After dividing the lighting plan into two zones, the DAYSIM software would give out three different kinds of result for each analysis point. These three results are the illuminance provided by the sunlight for each hour, the illuminance provided by the dim zone and the illuminance provided by the control zone. The illuminance provided by the sunlight will contain the illuminance of each analysis point with respect to the climate file. The illuminance provided by the lighting plan solely contains the illuminance of the analysis point under the maximum lighting output.

**Procedures for finding the dimming control plan**

To find the optimal close-loop dimming control setting, the relationship between all three sets of results should be found. To perform this, the following procedure would be done in order.

The first step is finding the required illuminance provided by the dim zone on the workplace. As the target illuminance is known and the illuminance provided by both sunlight and control zone are known in this stage. We can find out the required illuminance provided from the dim zone on the workplace under this equation:
Required illuminance provided from the dim zone

\[= \text{Target illuminance} - \text{Illuminance provided by sunlight} - \text{Illuminance provided by the control zone}\]

This required illuminance also indicates the need of the illuminance from the dim zone. If the required illuminance is lower than 0, it means that analysis point have enough illuminance and the need is already fulfill even the lighting devices in dim zone are switched on.

The second step is finding the dimming level for each analysis point on the workplace in different time. After finding the required illuminance, these values would be divided by the illuminance provided by the dim zone under maximum lighting output to obtain the value of Dimming level for each analysis point on the workplace.

\[\text{Dimming level} = \frac{\text{Required illuminance}}{\text{Illuminance provided by the dim zone}}\]

This dimming level indicates the percentages of energy the system should transfer to the fixtures in the dim zone, so the illuminance on that analysis point can meet the target illuminance. However, some of the dimming level is greater than 1, it means the target
illuminance can never be fulfilled even the fixture have the maximum power output. It is because the lumen method can only help us to find the number of the fixtures in the area while the pattern and the characteristic of the fixtures may not be able to provide sufficient illuminance to every point.

The third step is identifying the specific analysis point that would be used as the indicator on the workplace. In this step, the dimming level of each analysis point would be studied carefully so that we can find out which point have the highest frequency to obtain the highest dimming level expect the number greater than 1. When the analysis point has the highest dimming level, it means it requires the most energy to meet the target illuminance. If this point has met the requirement, the other points that have a lower dimming level can also meet the target illuminance since the fixture is having a higher energy output than they required.

The fourth step is calculating the illuminance under the dimming condition based on the dimming level of the indicator point on the workplace. After identifying the indicator point on the workplace, the illuminance of workplace indicator point and each analysis point on the photo-sensor plane should be found before investigating the relationship between on the workplace indicator point and each analysis point on the photo-sensor
plane. The equation used would be as follows:

\[
\text{Illuminance in dimming condition} = \text{Illuminance from the sunlight} + \text{Illuminance from the control zone} + \text{dimming level of the indicator point} \times \text{Illuminance from the dim zone}
\]

The fifth step is identifying the point on the photo-sensor which has the closest relationship with the workplace indicator point. In this step, the function “CORREL” in Microsoft Excel would be used. The “CORREL” command is a function to return the correlation coefficient of the Array1 and Array2 cell ranges. If two sets of array have a high correlation, the function will return a high percentage value. We would use “CORREL” to fix the first array as the illuminance of the workplace indicator and vary the second array as the illuminance of each analysis point on the photo-sensor plane. After comparing the return value of the function, the analysis point that has the highest value from “CORREL” was defined as the sensor-plane indicator point.

The final step is studying the relationship between the illuminance of the sensor-plane indicator point understand the dimming condition and the dimming level of the lighting
fixture to produce a close-loop dimming control plan similar to the diagram shown in the literature review.

In this chapter, the parameters used in the preset building model and computer simulation software are shown and the procedure of finding the optimal close-loop dimming control is shown. The next character is the result and analysis, it will show the result obtained from the simulation software and the optimal close-loop dimming control plan concluded by the procedures mentioned in this chapter.
Result and Analysis

In the precious chapter, the methodology of this study was revealed. In this chapter, it will describe the result and analysis based on the simulation and procedure mentioned before.

After performing the computer simulation from DAYSIM, the DAYSIM have produced different kinds of result including the illuminance contour and the daylight autonomy. The illuminance contour gives the users an idea how the light from the sun and fixtures is disturbed to the survey plane and which area on the survey plane cannot fulfill the recommended illuminance at that time. The daylight autonomy gives the users an idea how many percentage of the occupancy hours the recommended illuminance can be fulfilled when the sunlight is the single light source for the area. By analyzing the daylight autonomy, the users can also generate the idea which area would be defined as the control zone which the fixture in that zone would not be dimmed. From the simulation conducted in this study, some of example the illuminance contour and the daylight autonomy are shown as follows:
Figure 9 is an example of the illuminance contour generated by DAYSIM. An illuminance contour contains different kinds of elements including: the illuminance of the area, the fixture in the area and the contour line help indicating the area. The illuminance is shown as the color in the contour; the illuminance value is low if the color is more bluish and the illuminance is high if the color is more reddish. The fixture is defined as the hollow rectangles on the illuminance contour. The black line with the text 500 indicates the contour line of 500 lux, the area inside the black line has reached 500 lux while the area outside the black line has the illuminance that is below 500 lux.
Illuminance contour

Figure 10 shows the illuminance contour using sunlight as the single light source with the climate data at 09:30 in 1st of December. The contour shows illuminance in more than 80% of the room has reached the recommended level (500 lux). In this case, the user may figure out the upper-right corner section (North-east) of the room should be considered as the control zone that the lighting device remains on at whole time. However, this single time slot might not be able to reflect all condition during the occupancy hours. When the users need to get a complete picture about how the sunlight disturbed to the room, the daylight autonomy could be used.
Figure 11 illuminance contour (sunlight + electric, 09:30 1st December)

Figure 11 shows contour at the same time while switching on all fixtures in the area, the contour reveals the illuminance in the whole room can achieve the recommend level when all fixtures in the room are turned on. It means the illuminance of the fixture can compensate the lack of illuminance provided the sunlight in this time slot.
Daylight Autonomy

Figure 12 daylight autonomy

Figure 12 is the daylight autonomy for the workplace, the idea of the daylight autonomy is showing the percentage of the research area that the target illuminance level can be fulfilled in the occupancy hours. In this contour, it shows the inner half of the room is the major area that cannot reach the target illuminance (500 lux). This result leads to the consideration of the control zone should be the inner half of the room instead of the corner of the office. As a result, the fixtures in the inner half area are now considered as the control zone. This control area contains two rows of fixtures, these two rows of fixture remains turned on and have 100% power output. As a result, the dim zone is
defined as the outer half section of the room and the investigation of the close-loop
dimming control is focus on two rows fixtures in the dim zone.

Since the lighting plan is divided into two zones, the DAYSIM should generate three set
of results that indicate the illuminance from the sunlight, fixtures from control zone and
fixtures in dim zone respectively. Since all the result are produced as the text file, this
result should be transfer into the excel file and further analyzed in the excel files.

The objective of this study is the investigation of the close-loop dimming control and
finding the optimal plan for the preset model, and the method for finding the optimal
plan is to study the relationship between three sets of data generated by DAYSIM. The
detail procedures were mentioned in the methodology and the actual values could not
be attached as the data from the sunlight is massive (365 days x 24 hours x 144 analysis
points) but cannot be represented as the raw data or graphical presentation.
Analysis for the result of DAYSIM

After performing the first two tasks, the results have shown some of the region would have the dimming level always greater than 1. It means that analysis point would require the fixtures in the dim zone to produce 100% of light. As a result, the system would not be dimmed down and it causes us to have a review in the illuminance provide from both dim zone and control zone.

![Image](Image)

Figure 13 illuminance contour from fixtures

Figure 13 shows the illuminance contour based on the electric lighting, it shows the electrical lighting can provide most of the area to have the recommended illuminance
(500 lux). However, the perimeter region and some of the zone could not able to have 500 luminance in the case of all fixtures are switched on. To have an actual dimming control, these point should be omitted and not to be considered as the indicator point for the workplace. In order of find the actual location for these analysis point. The illuminance data from both zone fixtures are combined to generate the below table.

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Table 1 illuminance plan from fixture
This table indicates the illuminance plan in numerical numbers instead of illuminance contour from the DAYSIM. The bottom left point is defined as point 1 and the point on its upper one is point 2 while the point at the upper right corner is point 144. From the table, the readers can see the perimeter area cannot fulfill the recommended illuminance when using the fixtures as the single source. It is because the lighting profile of the fixture is not ideal as the concern of the lumen method. As a result, those analysis points with the purple background would not be considered as the indicator point for the workplace.

After performing the third step by finding the highest dimming level which is smaller than 1 from each time slot and comparing the frequency of getting this highest dimming level for each analysis point. The analysis shows the seventeenth point in the workplace have the highest frequency of getting the highest dimming level. The analysis also shows the dimming level of the dim zone is usually zero between 09:00 to 17:00. It means the fixtures in the dim zone can always be switched off in that period. From these, we could have a validation on using the seventeenth point as the indicator point by comparing the dimming level of the seventeenth point and the maximum dimming level for each analysis point in the remaining time slot: 17:30.
Figure 14 is the comparison of the dimming level of the seventeenth point and the maximum dimming level from each analysis point at 17:30 for each day. It shows the seventeenth point cannot meet each point (142 out of 365 value matches the maximum dimming level) on the maximum dimming level curve but the pattern of two lines is similar.

After finding the indicator point on the workplace, the next step is finding the correlated point on the photo-sensor plane by comparing the illuminance of the seventeenth point on the workplace and the illuminance of analysis point under the dimming level of the seventeenth point. After the analysis by using the “CORREL” function in excel, the system has identified the twentieth point on the photo-sensor plane has the closest
relationship with the seventeenth on the workplace, the value returned from the system is 0.8346571.

**Optimal Photo-sensor location**

Figure 15 shows the location of the analysis points in the area. The red point (seventeenth point) is the workplace indicator point while the orange point (twentieth point) is the photo-sensor plane indicator. In this moment, the users may not able to
know the location of these two points. To describe the location of these two points, some of the setting of the analysis should be clarified. Firstly, the spacing between the analysis points is 0.5 meters in both x and y direction. Secondly, the first analysis point has a 0.25 meters offset with the southwest corner of the room in both x and y direction. These two statement has pointed out the workplace indicator is in 0.75 meters east and 2.25 meters north to the southwest corner while the photo-sensor indicator is in 0.75 meters east and 3.75 meters north to the southwest corner.

After determining the indicator point on the photo-sensor plane, the relationship between the illuminance of the indicator point from the photo-sensor plane and the dimming level of lighting fixture can be drawn and producing the close-loop dimming control diagram as Figure 2.

In the close-loop dimming control graph, we would define the dimming level from the workplace indicator point as y-axis and the illuminance from the indicator point on the photo-sensor plane as x-axis.
Figure 15 is the control graph drafted with the data from the illuminance on the photo-sensor indicator point and the dimming level of the workplace indicator point. The general shape of the close-loop dimming control can be seen but the setting is not accuracy as there are too many points on the graph while the dimming control graph should contain a single line with the daytime and nighttime constant set points.

If we want to find the actual dimming control setting, we have to fix two points in the area that the dimming level is between the 0 and 1. The line drawn according to these two points will represent all the points in the area that the dimming level is between the 0 and 1. So the root mean square error of this line should be the smallest to perform the
optimal dimming control. The first thing for this analysis is defining the upper point from the data, so the upper part of the diagram is enlarged to produce Figure 16.

![Figure 17 upper part of dimming level against illuminance](image)

In figure 16, there are two points at the top. The higher one indicates 160.2616 in the illuminance and 0.8634 in the dimming level. The lower one indicates 161.0557 in the illuminance and 0.8607 in the dimming level. In the research, the higher point is chosen as the higher point is closer to the centerline of the data set.

After defining the upper of the control, three control settings are generated. The first one is the optimal control setting and the graph is shown below:
Figure 18 optimal dimming control plan after choosing the upper point

Figure 17 shows the optimal setting of the dimming control after fixing the upper point in the coordination 160.2616, 0.8634. This dimming control setting has the lowest root mean square error in the x-axis among and the value of this root mean square error is 4.2390. In this case, the fixture in the dim zone will start to dim down when the photo-sensor has detected the illuminance is above 154 lux and the fixtures will be completely switched off when the photo-sensor has detected the illuminance is above 195 lux. In this case, the dimming control plan can cover more than 78% of the conditions in the analysis data.
Dimming control case two

Another setting is generated by choosing the fixing the upper point in the coordination in 160.2616, 0.8634 and fixing the lower point in the coordination in 190.7405, 0.3431.

The root mean square error in this case is much higher, the value is 11.6153. However, this setting always provides the area enough illuminance to the workplace as the photo-sensor is set to require many illuminance from the sunlight to activate the dimming sequence. In this case, the fixture in the dim zone will start to dim down when the photo-sensor has detected the illuminance is above 152 lux and the fixtures will be completely switched off when the photo-sensor has detected the illuminance is above 210 lux. In this case, the dimming control plan can cover up to 99% of the conditions in the analysis data.
Dimming control case three

The final one is the dimming control plan based on the trend line features in Microsoft Excel. The root mean square error in x-axis of this control plan is the lowest, the value is 4.1885. Although this control plan has the lowest root mean square error in the x-axis, this plan has not covered half of the dimming condition. Therefore, the occupancy may suffer from the insufficient illuminance in above half of the time. In this case, the fixture in the dim zone will start to dim down when the photo-sensor has detected the illuminance is above 151 lux and the fixtures will be completely switched off when the photo-sensor has detected the illuminance is above 195 lux. In this case, the dimming control plan can cover 38% of the conditions in the analysis data.

Figure 20 auto-generated dimming control plan
Optimal dimming setting

Based on the comparison among all three dimming control plan, the first one is chosen as the optimal dimming setting as this setting has covered almost 80% of the dimming condition and have a relatively low root mean square error in x axis. Figure 21 is the optimal dimming control plan for this preset model. The nighttime set point is set as 154 lux and the daytime set point is set as 195 lux.

![Figure 21 optimal dimming control plan](image)

From the analysis, the optimal dimming control plan is concluded based on the procedures mentioned in the methodology. The conclusion of this paper would be summarized in the next chapter.
Conclusion and Recommendation

The dissertation mainly is to investigate the close-loop dimming control and find an optimal dimming control plan for the preset model. In order of find this optimal control plan, various computer simulations were performed to find the lighting plan for the use of dimming control system and the illuminance provided from the lighting plan. The results of the simulation indicated the relationship between the analysis points between the workplace and the sensor plane is the key element to develop the optimal dimming control plan. By finding the relationship and illuminance under the dimming condition, the optimal dimming control plan can be drawn.

This thesis could be used an introduction for the readers who have never contacted the lighting simulation software to find the optimal lighting control plan by performing the computer software. Besides, the method can be used to perform the early lighting design to find the location for sensors through simulation instead of performing the site experiment and testing to speed up the lighting design process. However, the method used in the study has not considered the actual characteristics for the photo-sensor. Besides, many parameters were omitted and the method has only been used for the preset model which is a square building with a single window facing south.
As a result, many modifications can be performed to increase the truthfulness of this method about finding the optimal dimming light plan. Firstly, the preset model can change to the actual model in the real life. Secondly, the analysis point can be set closer to widen the research data base and increase the accuracy for the method. Thirdly, the efficiency of the optimal dimming control plan can be calculated by comparing the energy output for each dimming hour and the lighting plan with 100% lighting output. The close comparison was not shown in this paper as the time for conducting the analysis is quite limited. Finally, the error for omitting the parameters such as neglecting the analysis point that does not reach the recommended illuminance should be solved in the future review. Those errors can be corrected if the knowledge of the researcher is good and the time for the research is sufficient.
Reference


[10] C. Reinhart and O. Walkenhorst, "Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds", Energy and Buildings,
